Appendices

Appendix I – Impacts of renewable energy on habitat, wildlife, water and soil and their mitigation strategies

Solar Energy

Solar energy generation has been growing rapidly worldwide and in Australia. In 2021, a record 168 GW of solar power was installed worldwide, and the global fleet reached 1 terawatt in early 2022 (Meban, 2022). The Australian Energy Market Operator projects, in the draft 2024 Integrated Systems Plan, that solar energy (along with wind) will become the bulk source of electricity in coming years with seven times as much wind and solar capacity (AEMO, 2023).

The development of large-scale solar projects will have significant land requirements. This has raised concerns, in Australia and elsewhere, about large-scale solar farms negatively impacting ecosystems, notably fragile desert ecosystems (Gibbens, 2022) and competing with agricultural land (Taylor, 2021).

In this section, we focus on the ecosystem impacts of large-scale solar farms and describe the Mitigation and Conservation strategies that can be implemented to mitigate impacts.

Description of large-scale solar energy technology

Large scale solar farms (often referred to as ‘utility-scale solar’) usually consist of arrays of PV solar panels[1]. Electricity generated by utility-scale solar farms is distributed through power lines to homes and businesses. The solar panels are stationary and often mounted in the ground (Solar Choice, n.d.). Ideally, the surface for large scale solar should be flat and flood-free land.

There are different types of solar panels, such as monocrystalline, polycrystalline, and thin film. These all vary in composition, efficiency, and cost. Both monocrystalline and polycrystalline panels are made of silicon wafers, covered by a glass sheet. The main difference between monocrystalline and polycrystalline panels is that the former is composed of one pure crystal of silicone, while the latter is composed of fragments of silicon crystals moulded together. Thin-film panels are made of a diverse range of materials, such as amorphous silicon, cadmium telluride or Copper Indium Gallium Selenide (CIGS).

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[1] Solar thermal systems use mirror to attract sunlight, and a fluid (such as oil or molten sodium) to capture heat. The heat is subsequently used to heat water and produces steam to power turbine or electricity (ARENA, n.d.). PV has been proven to be cheaper than solar thermal. As a result, they are more widely used . In this section, we will focus on the impacts of PV rather than solar thermal.

Impacts

Raw material sourcing, processing, and manufacturing

The production of solar panels will increase demand for materials, such as silicon, glass, copper, silver, indium and tellurium. The mining and processing of those materials have a range of negative impacts on water, soil, habitat, and wildlife. Large quantities of water are required for mining and processing operations, which can lead to water scarcity, particularly in arid regions (IEA, 2022b). Water contamination can also occur through acid mine drainage[2] and improper wastewater and tailings management (IEA, 2022b). Additionally, mining can lead to soil erosion which can have impacts on both soil and water quality (IEA, 2022b).

Mining operations have impacts on habitat and wildlife, notably by driving loss and fragmentation of habitats. A study by Sonter et al. (2020) found that the large-scale deployment of renewable energy could pose new threats to habitat and wildlife, as areas that contain materials used in renewable energy technologies are frequently located in areas of high biodiversity.

Manufacturing

The manufacturing of solar panels has been associated with environmental impacts, mainly on water quantity and quality. For each energy unit of the solar module (measured in kilowatts peak [kWp]), 3.7 to 5.2 cubic meter (m^3) of water is used (Yang et al. (2015). The production of solar cells from crystalline silicon can impact water quality, as it generates wastewater containing harmful substances (fluorine) and metals (silicon-containing chromium). While chemical and biological methods can be used to remove fluorine, residuals can remain in wastewater (Qi & Zhang, 2017). For chromium, physical, biological and chemical methods can be used, noting that the chemical method – which is the most commonly used - generates hazardous waste sludge (Qi & Zhang, 2017).

Construction and installation

The construction phase encompasses a range of activities that can negatively impact on water, soil, habitat and wildlife, including removal of vegetation, land grading[3], addition of gravel, use of heavy machinery as well as use of dust suppressants and herbicides to control dust emissions and vegetation on the site (Hernandez et al., 2014; Lovich & Ennen, 2011; Macknick et al., 2014; Tawalbeh et al., 2021; Turney & Fthenakis, 2011). Impactful activities are also carried out beyond the site, notably the development of roads to transport materials and the digging of trenches for transmission line networks (Hernandez et al., 2014; Lovich & Ennen, 2011; Macknick et al., 2014; Moore-O'Leary et al., 2017).

Vegetation removal, land grading, development of access roads and use of heavy machinery can lead to soil erosion and compaction – in turn impacting on water quality by increasing sediment load and turbidity and limiting the infiltration of precipitation (Hernandez et al., 2014; Macknick et al., 2014; Turney & Fthenakis, 2011). In arid regions, the construction of large-scale solar farms could also disrupt ephemeral streams[4] (Lovich & Ennen, 2011; Moore-O'Leary et al., 2017).

Habitat and wildlife can be impacted in various ways. On the site, the removal of vegetation may lead to habitat destruction and displacement of wildlife (Nordberg et al., 2021), while the use of dust suppressant and herbicides can damage plants and wildlife (Hernandez et al., 2014; Lovich & Ennen, 2011). Soil disturbance triggered by activities such as land grading, may affect secondary plant succession[5], which will negatively impact the restoration of the site after decommissioning (Lovich & Ennen, 2011).

Beyond the site, the development of access roads coupled with increased traffic for the transportation of materials, and the digging of trenches for the transmission line networks, can have impacts including:

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[2] It is the runoff of acidic water from mines. This is due to water having been in contact with rocks containing sulfur-bearing minerals.

[3] Site grading is an engineering process that adjusts the slope and soil elevation around a construction site before building occurs (Stovall Construction Inc., 2020).

[4] Temporary streams with minimal or no surface water for the majority of the year.

[5] Type of ecological succession (the evolution of a biological community's ecological structure) in which plants and animals recolonise a habitat after a major disturbance—such as a devastating flood, wildfire, landslide, lava flow, or human activity (e.g., farming or road or building construction)—significantly alters an area but has not rendered it completely lifeless (Encyclopaedia Britannica).

- Habitat fragmentation, preventing the movement of species and genes through the landscape (Hernandez et al., 2014; Lovich & Ennen, 2011; Macknick et al., 2014; Moore-O'Leary et al., 2017), affecting predation strategy, food availability (Turney & Fthenakis, 2011).
- Arrival of exotic species (Guerin, 2017; Hernandez et al., 2014; Macknick et al., 2014).
- Killing and entrapment of animals on roads (Lovich & Ennen, 2011).
- Industrial noise impacts, which can alter wildlife activity patterns, increase their stress and weaken their immune system among other things (Lovich & Ennen, 2011).

In recent times, a new technology – floating photovoltaics systems – has emerged. In Box 1 below, we provide insights on the potential impacts related to the installation of floating photovoltaics on water bodies.

Box 1: Floating photovoltaics systems (FPVSs)

In the last decade, there has been growing interest in installing solar panels on water bodies (Hooper et al., 2021), with medium and large size FPVSs installed in Japan, South Korea, India and the USA (Rosa-Clot et al., 2017). While initially installed on freshwater systems, such as lakes or reservoirs, there is growing interest in installing them at sea (Hooper et al., 2021; Rosa-Clot et al., 2017).

FPVSs offer advantages to ground mounted PV on two fronts. Firstly, they do not require large land-use change (da Costa & da Silva, 2021). Secondly, they are more energy efficient, due to water bodies naturally cooling the panels (Golroodbari & van Sark, 2020). Notwithstanding those advantages, FPVS are likely to have impacts on the water quality and local habitat of the water bodies they are built on (de Lima et al., 2021). Indeed, the installation of FPVS on water is likely to modify the impact of wind and sun on the body of water, which would then impact its thermal structure (Exley et al., 2021).

At the construction and installation phase, FPVSs may have negative effects on habitat and wildlife, notably by generating sediment suspension (which may prevent the growth of aquatic plants needing sunlight) and spreading invasive species, particularly in marine environments where the infrastructure may be towed from ports where non-native species are often present (Hooper et al., 2021). In addition, the anchoring of the infrastructure is also likely to have impacts on the seabed (Hooper et al., 2021).

At the operation phase, FPVSs can have either negative or positive impacts on water, habitat and species. The nature of the impacts is highly dependent on: i) the size of the system compared to the size of the water body, ii) the design of the system, and iiii) environmental parameters, such as the climate, water depth etc (de Lima et al., 2021)

In some cases, FPVSs were found to have positive impacts on water quality and quantity, by reducing evaporation, which may be particularly important in water scarce regions (Abdelal, 2021), and minimising the presence of algal blooms (Hooper et al., 2021). It can also have positive impacts on wildlife, as floating structures can be utilised by fish (Hooper et al., 2021).

In other cases, FPVSs can have negative impact on water quality and wildlife. They can cause decreases in water temperatures, which may modify animal behaviours, food web dynamics and species interactions among other things (Exley et al., 2021). They can also intercept solar radiation. This may impact the timing of phytoplankton bloom, as well as their growth, which may, in turn, affect the food web and species composition (Exley et al., 2021). Finally, it was also found that in some circumstances, FPVSs may increase anoxia[1] as well as the regeneration of phosphorus and heavy metals from sediments, which can negatively impact wildlife for the former and water quality for the latter (Exley et al., 2021). However, in other circumstances it may decrease both anoxia and the regeneration of soluble phosphorus and heavy metals (Exley et al., 2021).

As such, it appears the FPVSs have the potential to have positive and/or negative impacts on water, habitat, and species, and that a careful design of the project that considers the specific environmental conditions of the project is necessary.

Operation

During the operation, impacts on water, vegetation and wildlife are noted:

- Water is mainly used for the cooling and cleaning of panels as well as dust suppression (Hernandez et al., 2014; Nordberg et al., 2021; Tawalbeh et al., 2021). While water use during operation is insignificant compared to water use during the manufacturing phase (Tawalbeh et al., 2021), it could negatively affect water quantity in semi-arid and arid regions (Nordberg et al., 2021).
- Vegetation (if any) may be regularly mowed or controlled with herbicides (Lovich & Ennen, 2011; Turney & Fthenakis, 2011). The presence of panels can modify the micro-climate, which may have a positive or negative impact on vegetation (Turney & Fthenakis, 2011). In positive cases, the reduction of mean temperature below the panels can increase moisture in comparison to open landscapes, which can benefit some plant and animal species (Nordberg et al., 2021) and improve soil moisture in arid environments, which can facilitate vegetation restoration (Wu et al., 2022)
- Solar panels reflect horizontal light, which may create a 'lake effect'. Flying aquatic insects can confuse the solar panels with a water body and collide (Moore-O'Leary et al., 2017; Nordberg et al., 2021). This could also be the case for some types of birds; however, findings are currently inconclusive (Nordberg et al., 2021). Even if the lake-effect was confirmed, bird mortality due to solar panels would remain minimal compared to other infrastructures (Nordberg et al., 2021; Walston et al., 2016).

Decommissioning and disposal

If not managed appropriately, solar panels disposed in landfills can release heavy metals (e.g. lead, cadmium) that have the potential to contaminate soil and leach into groundwater (Sustainability Victoria, 2022). In Australia, it is estimated that approximately 100,000 tonnes of PV panels will enter the waste stream by 2035, initially from decentralised installations (rooftop, PV), but from large solar farms as well (Florin et al., 2020).

Mitigation and Conservation Strategies

There are a range of mitigation and conservation strategies available to project proponents at different stages of the project. We will focus on four themes: habitat and vegetation protection and management; resource use, reuse and recycle; land surface and soil alteration.

Habitat and wildlife protection

Mitigation and conservations strategies often relate to the protection of habitat and wildlife but can also have positive impacts on water and soil.

Planning

During the planning phase, the siting of the project is an essential step to protect habitat and vegetation. Habitat impacts can be avoided by solar energy being integrated in the built environment (e.g. rooftops, parking lots etc) or developed in degraded landscapes (e.g. overgrazed livestock properties, industrial zoned land, landfills, spent mines or contaminated sites) (See Box 2 below for an example of a solar farm developed on an industrial zoned land) (Hernandez et al., 2014; Macknick et al., 2014; Moore-O'Leary et al., 2017; Nordberg et al., 2021; Tawalbeh et al., 2021). When located in degraded landscapes, solar panels could provide habitat benefits by adding structures such as shelters, nesting and perching sites for prey species (Nordberg et al., 2021; Wu et al., 2022).

To support the identification of sites where impacts on habitats will be lower, regional conservation plans can be developed (Bennun et al, 2021; Stoms et al, 2013). If such spatial documents are not available, proponents may have access to biodiversity sensitivity maps (Bennun et al., 2021; Moore-O'Leary et al., 2017; Stoms et al., 2013). For example, The Nature Conservancy in the U.S., developed a mapping tool (The Resilient Connected Network) to help proponents identify areas where solar farms would have the least impacts on habitat and biodiversity.

Box 2.: Bomen Solar Farm: siting on industrial zoned land

This is a 120 MW solar farm established near Wagga Wagga, in rural NSW, Australia. It is supported by a 10 MW/40 MW-hour (MWh) battery storage facility. The solar farm was developed by Renew Estate and Spark Infrastructure. Spark Infrastructure acquired the project from Renew Estate in April 2019. The solar farm is powering the equivalent of 36,000 homes, and Westpac entered a Power Purchase Agreement with Bomen Solar Farm, which should deliver 45% of Westpac's clean energy. The project has been operational since 2020.

Several characteristics of this project are worth mentioning:

- The solar farm is located on 250 hectares of land zoned industrial - currently used for agricultural purposes - which avoided habitat destruction.
- Habitat restoration efforts were made, including the planting of 50,000 trees.
- Local initiatives for sheep grazing and bee keeping for a honey farm were invited

See Appendix II for further details on the drivers of change, factors of success and challenges in developing the project.

Once the site is identified**,** design strategies can be put in place to protect habitat and vegetation, along with the wildlife they shelter. This can be done by ensuring that the placement of panels, roads, cables and other associated infrastructures does not encroach on important habitat and a buffer is maintained between the panels and those areas of importance. Additionally, panels and other infrastructures can be placed and designed in such a way that they do not fragment habitat and enable the passage of wildlife through the site (e.g. maintaining vegetation strips or wildlife corridors (Guerin, 2017; Sinha et al., 2018), as well as wildlife-friendly fencing (Nordberg et al., 2021)). Bennun et al. (2021) identify areas that should be avoided, which include threatened or vulnerable areas, areas that shelter threatened or vulnerable species, nesting, roosting or foraging, areas that facilitate species movements (e.g. rivers, forest edges, migratory corridors etc). Measures can also be taken to improve habitat and enhance vegetation on the site. For example, new vegetation can be added to the site (e.g. planting vegetation between panels or around the site), along with habitat features (e.g. nestboxes) (Macknick et al., 2014; Nordberg et al., 2021; Sinha et al., 2018). Examples of such measures are presented in the 'Design' sections of Boxes 3, 4, and 5 below.

In order to design effective approaches, it is preferable to adopt an ecosystem-based approach rather than a species-based approach - focusing beyond the conservation of a specific species to an integrated approach that accounts for the interdependence between species - (Techera, 2016) as utility-scale solar farms impact entire trophic levels rather than single species (Moore-O'Leary et al., 2017). Some approaches, such as repatriation and translocation programs, land acquisition and road fencing, usually target single species (Hernandez et al., 2014)

Finally, biodiversity offsets can be purchased to compensate for the loss of habitat (Kreitler et al., 2015; Sinha et al., 2018). Biodiversity offsets consist in compensating for the loss of biodiversity in one area by generating equivalent gains in another area (BBOP, 2018). Biodiversity offsets have been scrutinised for a range of reasons, including the ethics of trading biodiversity losses in one area for gains in another; technical problems related to the was offsets schemes are applied in practice; and governance challenges in terms of monitoring and ensuring offset policies are implemented in the long term (Maron et al., 2016). The use of biodiversity offsets can be controversial, they are not always an effective strategy for the conservation of biodiversity (Thorn et al., 2018) and should only be used as a last resort when other options have been exhausted.

Construction and installation

At the construction phase, habitat and vegetation protection and management activities envisioned during the planning phase can be implemented. Additionally, other activities can be conducted to avoid and minimise impacts. In a recent report, Bennun et al. (2021) detail a range of scheduling and operational/abatement measures:

- **Carefully scheduling construction activities**: Avoiding the scheduling of construction in periods that may have high impacts on the species present on site, by considering their seasonal and nocturnal/diurnal activities, as well as their patterns of movement.
- **Managing vehicles**: Limiting vehicle movements as much as possible, limiting speed, avoiding the use of unauthorised roads, and washing vehicles when they enter the site.
- **Training personnel and implementing processes**: Organising regular toolbox talks about the habitat and vegetation protection and management measures put in place on the site and putting processes in place to deal with issues related to habitat and vegetation during construction.

In addition, conducting regular biological monitoring can provide insights on the effectiveness of the measures and may identify modifications to improve outcomes (Sinha et al., 2018).

Finally, restoration activities can be started during the construction phase, in areas that were only used temporarily.

Operation

During the operation phase, biological monitoring can continue to identify impacts and modification strategies (Sinha et al., 2018).

Decommissioning and disposal

During the decommissioning and disposal phase, the ecosystems should be restored on the site. The success of restoration depends on several factors (Moore-O'Leary et al., 2017).. Firstly, not all types of ecosystems can be restored. Secondly, the position of the site within the broader landscape may impact the restoration process. For example, if adjacent natural ecosystems remain in place, they may facilitate the restoration of the site. Thirdly, the practices adopted during construction will influence restoration. For example, sites where the topsoil has not been removed have higher chances of restoration, Finally, the effect of climate change on the distribution of species may also affect the restoration process and should be considered, Currently, for most projects, plans to conduct restoration appear to often remain unclear, which may affect the restoration success (Moore-O'Leary et al., 2017; Oudes & Stremke, 2021). Emphasis should therefore be placed on developing high quality restoration plans.

Box 3: Better Energy

Better Energy (BE) is a Danish renewable energy company operating in Denmark, Sweden Poland and Finland. BE aims to develop solar projects that include the protection of groundwater, the restoration of wetlands and the improvement of biodiversity.

Siting

In its siting process, BE considers a range of technical and legal factors, as well as environmental impacts and benefits to local communities. Generally, BE develops its solar projects on sites with a low nature value, which are primarily agricultural land. Once the site has been identified, internal and/or external biodiversity and environmental experts conduct an initial biodiversity assessment of the site and surrounding landscape. This initial assessment informs BE on how they should protect biodiversity when developing the site, and what they could do to enhance it further. Additionally, BE consults with the local community early in the projects, where they may gather additional insights from local inhabitants on the local biodiversity.

Design

In the design process, BE considers how to avoid or minimise impacts on the site by locating panels at a distance from existing natural and wildlife areas within and beyond the site, and protecting areas that are essential for wildlife movement, such as migration paths through the development of wildlife corridors. Beyond avoidance, BE also explores how to encourage biodiversity on the site. While the activities that will be implemented on site will vary from site-to-site, the following activities can be considered:

- Wetland restoration: BE can install solar panels on drained lowland areas that will then be restored to their wetland state stopping the drainage of the area.
- Creating new habitats: BE also focuses on the creation of new habitats for wildlife, notably through the development of hedge rows and windbreaks composed of trees and bushes that can provide shelter and food for wildlife. Additionally, other types of habitat features can be added, such as rocks and water bodies, which can be beneficial to amphibians.
- Native grasses and grazing under solar panels: The main purpose of the solar panel field is to generate energy, which leads to limitations in terms of the activities that can be conducted in this area to improve biodiversity. Indeed, vegetation can only reach a certain height and the area is shaded by the presence of the panels. However, certain activities can still be conducted, notably sowing the area with native grasses and using it for sheep grazing.
- Removal of nutrient rich topsoil: As mentioned above, solar projects are often developed on sites that were often fertilised for agricultural purposes. As a result of this agricultural activity, the topsoil on the site is often rich in nutrients, which may prevent the development of grassland ecosystems that prefer nutrient poor soils. To facilitate the development of these grassland areas, BE mechanically removes the nutrient-rich topsoil to expose the nutrient-poor sandy soils. This technique is expensive and has only been piloted on small areas to measure its effectiveness.

Construction and installation

BE aims to minimise impacts on habitat and wildlife in the construction phase by avoiding leveling the ground, when possible. Native grasses are also planted before the start of the construction, so as to minimise the damage of machinery and workers on the soil. Additionally, small machinery, notably excavators, is utilised during the construction phase.

Operation

Native grasses present under the panels are grazed by sheep, rather than being controlled through the use of herbicides. Additionally, a review of the site is conducted regularly. This review enables BE to assess the activities that provide positive biodiversity outcomes and the ones that may not be performing as well. This, in turn, enables BE to make adjustments to the activities, in order to reach better biodiversity outcomes.

See Appendix III for further details on the drivers of change, factors of success and challenges in developing the project

Box 4: The Nature Conservancy

The North Carolina Chapter of the Nature Conservancy (TNC NC) provides advice to solar developers on siting, design and practices that are beneficial to wildlife on solar developments. The support they provide is through the following channels.

Project planning

Guidelines: TNC NC has developed high-level guidance on solar siting and design and identified six main principles that underpin the development of wildlife and habitat friendly developments (The Nature Conservancy North Carolina, n.d.):

- "Avoid areas of high native biodiversity and high-quality natural communities"
- "Allow for wildlife connectivity, now and in the face of climate change"
- "Preferentially use disturbed or degraded lands"
- "Protect water quality and avoid erosion"
- "Restore native vegetation and grasslands"
- "Provide wildlife habitat"

Siting: TNC has conducted a spatial analysis of the most biodiverse and resilient parts of the landscapes in the US: the Resilient Connected Network. They encourage solar developers to use the mapping tool that resulted from this analysis, to identify sites that are preferable – from a wildlife and habitat standpoint – for the development of solar projects. At a national level, TNC provides a siting map called "Site Renewable Right," and completed a more thorough analysis called 'Power of Place' that identifies areas that should be excluded for development due to biodiversity values and determines the amount of energy that can be supplied by the remaining land under various scenarios.

Design: The North Carolina Chapter of the TNC provides guidance on the design of solar developments that focus on the following aspects:

1. Adapting the conservation measures to the context: It encourages solar developers to think about the 'matrix' they are in and to design measures that are relevant to that specific context. For example, if the development is located in a forested ecosystem with a large number of animals, they may want to consider wildlife friendly fencing. If the site is located in an agricultural matrix, the focus may be on pollinator vegetation that can provide pollination services to adjoining agricultural land.

2. Wildlife-friendly fencing: This type of fencing has large holes that enable animals to pass through the fence. TNC works with developers to implement this type of fencing to monitor animal movements with wildlife cameras. This showed that many medium size mammals were using the fence.

3. Wildlife corridors or passageways: For larger facilities, The North Carolina chapter of the TNC advises the provision of unfenced passageways to facilitate the movement of larger animals who cannot use the wildlife friendly fences. These types of passageways have been implemented on some sites, but no monitoring has been conducted at this stage.

4. Habitat features and pollinator vegetation: The TNC also encourages developers to protect existing habitat features on the site, such as wetlands or riparian areas, to provide habitat refuges to help animals move through the site and to plant vegetation that favours the presence of pollinators.

The development of positive relationships between solar developers and the North Carolina Chapter is a key success factor. Presenting solar developers with options that will mitigate impacts on wildlife and habitat while not requiring large amounts of time and financial investment. For example, wildlife-friendly does not cost more than a chain link fence but is likely to facilitate the movement of some mammals through the facility.

See Appendix IV for further details on the drivers of change, factors of success and challenges in developing the project.

Box 5: Lightrock Power

Lightrock Power (LP) is a solar farm developer based in the United Kingdom (UK), whose objective is to go beyond industry best practice for wildlife and biodiversity by developing projects that further enhance biodiversity outcomes.

Project planning

Initial surveys: LP conducts a suite of surveys to develop a baseline of the existing habitat and ecology of the site. These initial surveys enable LP to identify species that may be at risk of being disturbed by the project, as well as the opportunities that exist to create additional habitat on the site. Additionally, LP consults with environmental organisations, such as the Royal Society for the Protection of Birds (RSPB), who often do a site visit and provide recommendations for on-site mitigation and regeneration activities.

Design: Building on this initial phase, LP designs the solar project. While each project has its own needs and specificities, some of the biodiversity considerations that appear to be involved in one way or another in most projects are:

- Enhancing existing habitat, notably hedgerows, which are sometimes not continuous and do not act as an effective wildlife corridor. The project will then work on 'gapping up the hedgerow' to make sure it completes its function.
- Adding floristic diversity by sowing a wildflower mix in the five metres field margin, which can be attractive to certain species, such as dormice that in turn make food for raptors.
- Enabling grazing under solar panels by sowing a neutral mix grass interspersed with native wildflowers that will be conservation grazed by sheep from October to March.
- Providing habitat features, such as bird, bat, and barn owl boxes.

For each project specific features are adapted to the local ecology of the site. For example, one of LP's site is located in an area near a small population of an endangered species of bumblebee that requires a specific type of habitat. As a result, the project design incorporates habitat creation for this specific bumblebee needs, so as to try to increase its population in the local area.

Construction

LP works on the design and planning of solar projects but does not implement them. However, LP works with companies that do implement some measures related to wildlife and habitat protection at the construction and operation phases. At the construction phase, an environmental management plan is developed that specifies measures to be taken to protect wildlife and habitat during the construction. For example, areas that provide habitats, notably water bodies or hedgerows, could be fenced off.

Operation

During the operation phase, regular toolbox talks are provided to employees to make them aware of the ecology of the site and the species they may be able to spot. This enables employees, such as electricians who may be on site regularly to provide information about the species present on site. In addition to these more 'ad hoc' observations, ecologists assess the sites periodically. This monitoring process feeds back into LP's design and planning process, as it provides information on whether the interventions were successful or not and what improvements could be put into place in the next iteration of solar projects.

See Appendix V for further details on the drivers of change, factors of success and challenges in developing the project

Resource use, reuse and recycle

We will present strategies to reduce the use of three types of resources along the supply chain: i) the PV panel materials, ii) water and iii) wood and cardboard. There are two primary strategies for minimising the use of panel materials and water: i) reducing the use of raw materials for solar panels (notably through recycling at the decommissioning and disposal phase) and ii) water efficiency during raw material sourcing and processing, the manufacturing of panels, and construction and operation. Cardboard and wood in the construction and installation phase can also be reduced.

Raw material sourcing, processing, and manufacturing

Panel materials

Responsible sourcing and processing practices for solar energy can reduce the negative impacts on water, soil, habitat, and wildlife. This can be achieved by increasing traceability, sourcing materials from lower risk countries and adhering to standards and certifications. Standards and certifications, notably the Initiative for Responsible Mining Assurance (IRMA), require mining companies to minimise their environmental impacts, notably avoiding contamination due to waste materials, biodiversity protection and water management (see Box 16 on Responsible Sourcing – while the focus is on responsible sourcing for batteries, the information provided will be broadly relevant for solar energy). Certification scheme also exist at the manufacturing phase. One example is the *Cradle to Cradle Certified Product Standard*[6], which aims to be "the global standard for products that are safe, circular and responsibly made"[7], with participants including SunPower, Solarwatt and SoliTek. The Standard rates products along five categories: i) water and soil stewardship, ii) material health, iii) product circularity, iv) clean air and climate protection and v) social fairness.

Construction and installation (and operation)

Water

Many strategies implemented at the construction and installation phase can reduce the use of water for cleaning and cooling the panels at the operation stage:

- Reducing the intensity of site grading and housing the cables above ground rather than in ground trenches can reduce dust emissions, which, in turn, will reduce the amount of water needed to clean the panels (Sinha et al., 2018).
- Orienting the panels to enable 'self-cleaning' reducing the use of water to clean them (Guerin, 2020).
- Implementing water retention and recuperation infrastructures on site (Oudes & Stremke, 2021).
- Using treated effluent for the cooling of water for solar farms in proximity to urban centres (Carter & Campbell, 2009).

Wood and carboard

Solar panels are often transported to the site in wood and cardboard packaging. Trials were made using those materials as mulch on site. Guerin (2020) found that it reduced water evaporation rates and increased the infiltration rate of water in the soil.

Decommissioning and disposal

Panel materials

Solar farms can reduce their impacts on ecosystems by reusing or recycling solar panels. Reuse markets are still immature due to regulatory barriers in Australia, in particular reused panels are ineligible for renewable energy certificates, making them less financially attractive (Salim et al., 2023). Coupled with reductions in panel cost, these policy settings have the perverse outcome of incentivising early retirement and replacement with new panels.

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[6] The other four criteria are: material health, material reutilisation, renewable energy and carbon management and social fairness.

[7] 'Cradle to Cradle Certified, version 4.0', Cradle to Cradle Products Innovation Institute, n.d., https://c2ccertified.org/the-standard/version-4-0.

There has not yet been a high level of demand for PV recycling but this will change as panels installed in the early 2000s reach their end-of-life (Weckend et al, 2016). In Australia, recycling options are emerging; for example, Reclaim are using a combination of mechanical processing and pyrolysis to break down solar panels into their components and recover materials like aluminium, copper, glass, plastics, silver, lead and silicon (Reclaim PV Recycling, 2021). In New South Wales, the *Circular Solar Trial* project is being funded by the Environmental Protection Authority (NSW EPA) to support PV industries in developing a novel solar panel recycling process and activate end-markets for recovered solar panel glass. One of the main objectives of the project is to send all the recovered materials to local manufacturers to make new products. Box 17 provides an overview of the different avenues for manufacturers, policy makers and recyclers to reduce the demand for raw materials, as well as their associated challenges.

Land surface

Planning

Several options can be envisioned to diminish the land area used by solar farms and to minimise land-use competition, which should be determined at the planning stage:

- **Agrivoltaics** is the technique of pairing photovoltaics (PV) with open field crop production, meeting both food and energy demands at the same time (Andrew et al. 2021). **Solar grazing** is a method of vegetation control, moving livestock such as sheep onto solar sites during the grazing season. Solar grazing is a mutually beneficial arrangement for both solar companies and the local farmers (Kochendoerfer and Thonney 2021). See Box 6 below for further details about Agrivoltaics.
- **FPVS** are considered as an alternative to land-based solar farms. However, as they are likely to have impacts on the ecosystems, they are most likely best placed on artificial water bodies (Bennun et al., 2021). See Box 1 for further information.
- **Hybrid power systems**: Another way to minimise the land surface is to develop hybrid power systems, such as wind-solar for example (Hernandez et al., 2014; Tawalbeh et al., 2021).

Box 6: Agrivoltaics

Agrivoltaics (or Agrisolar) is the practice of installing solar PV on agricultural land (Mellon, 2021). It covers a wide range of approaches, the most common being incorporating solar panels with crop or livestock farming.

Large-scale solar projects can often conflict with meeting agricultural needs. The Food and Agriculture Organisation (FAO) estimates that food production will need to increase by 70% to support the estimated world population of 9.1 billion people in 2050 (FAO, 2009). Agrivoltaics could be a way to allow for the simultaneous production of renewable energy and agricultural products. Some potential benefits include:

- Additional source of income for landowners – either through leasing their land or selling the energy generated (if the system is privately owned) (Stark, 2022).

- Increased water conservation – panels can increase moisture retention and reduce irrigation requirements by up to 20% (Elamri et al., 2018).

- Certain crops benefit from increased shading – one study found that berries and fruit trees increased crop yield due to a decrease in solar radiation by 30% (Laub et al., 2022). However, the evidence base is still emerging and this may only be true for certain crops under specific conditions. Indeed, a recent review of the literature on agricultural yield in agrivoltaic systems found that yields often decrease as the ground covering ratio increases (Dupraz, 2023).

Some examples of agrivoltaics include:

Numurkah Solar Farm (Victoria): the 128MW solar farm provides free grazing opportunities around the solar panels for farmers and 'lawnmowing' services for the solar farm (Hill, 2023) . Without the sheep, mowing the 1,200-acre farm can take up to seven weeks.

Domaine de Nideolères Vineyeard – Pyrénées-Orientales, France: The Escudié family have owned the Domaine de Nideolères vineyard for eight generations. The effects of climate change have led to the early ripening of the grapes, distorting the resulting wine's flavour profiles. In 2018, they installed 7,800 photovoltaic modules over 4.5 hectares of their vineyard. In collaboration with Sun'Agri, a French agrivoltaics company they carried out experimentation that produced the following results (Sun'Agri, 2021):

- 20% reduction in the plot's water consumption.

- Reduced impacts of heatwaves on the vineyard during the summer of 2019.

- Improved flavour profiles of the resulting wine.

- Installed sensors also allow for panel adjustment depending on the sun and the needs of the vines (Deboutte, 2021).

Agrivoltaics is still at an early stage in Australia and there is still limited data. There can be significant upfront costs and complex mounting systems which limit the potential for small-scale projects at this stage (Davey, 2022), further awareness is required amongst farmers (Rauline, 2021) and it is not suitable for all crops (e.g. wheat). The suitability of agrivoltaics needs to be determined on a case-by-case basis. Nonetheless, agrivoltatics may, under certain conditions, allow for energy and food production to occur together.

Soil alteration

Several strategies can be employed at the construction and installation and operation phases, to reduce the impacts of solar farms on soil, or to enhance soil quality.

Construction and installation

At the construction and installation phase, techniques can be implemented to minimise soil disturbance. Sinha et al. (2018) identified the following:

- Preparing sites using the disk-and roll technique[8]
- Mowing or sashing vegetation instead of grading.
- Housing cables above ground rather than in trenches

The adoption of these techniques could provide positive outcomes by: i) reducing erosion due to wind and water, ii) enhancing the likelihood of natural regeneration occurring as the seed bank will be less impacted and iii) reducing dust emissions (Sinha et al, 2018).

Additionally, strategies can be adopted to improve the soil. For example, the use of wood and cardboard packaging as mulch, already described in the resource use section, can also have positive impacts on soil, notably by improving pH, and increasing moisture and organic carbon content (Guerin, 2020).

Operation

Sowing crops or maintaining a vegetative cover under the panels can improve soil health by: i) increasing water retention and infiltration as well as soil carbon levels, and ii) reducing surface run-off which, in turn, reduces soil erosion (Nordberg et al., 2021).

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[8] The disk-and-roll site preparation method "contours the land without changing the macro-level topography and existing drainage patterns" (Sinha et al., 2018, p10).

Wind Energy

Wind is a major source of clean energy. Internationally, total installed wind energy capacity is at 837 GW, which prevents roughly 1.2 billion tonnes of CO_2 from entering the earth's atmosphere annually – the same as the total annual emissions of South America (Global Wind Energy Council, 2022). In the next five years, 557 GW of new global energy capacity is expected to be added by wind energy (Global Wind Energy Council, 2022).

In Australia, wind energy accounts for almost 12% of the country's overall energy capacity and a third of the renewable energy generation (Clean Energy Council, 2022). There are over 100 wind farms around Australia. With the passing of the Offshore Electricity Infrastructure Act 2021 (Cth). In AEMO's draft 2024 Integrated Systems Plan, wind farms are projected to outstrip solar farms for the remainder of the decade and 70 GW of capacity installed by 2050 (AEMO, 2023).

Concerns over wind farms appear to primarily centre on their negative impacts on avian wildlife, notably birds and bats mortality. In Australia, for example, there have been calls to stop the development of a large wind farm on Robben Island, Tasmania, due to the projected impact it would have on several migratory bird species (Morton, 2019).

This section of the report looks at the potential impacts of onshore (and to a lesser degree offshore) wind farms on the local environment across its lifecycle, as well as highlighting the mitigation strategies adopted by projects to minimise or manage these impacts.

Description of the technology

Wind energy technology harnesses the power of the wind to turn propeller-like turbine blades around a rotor, spinning a generator and creating electricity in the process (IRENA, n.d.). It is deployed in two forms: onshore and offshore wind farms. Onshore wind farms consist of a series of turbines (made up of a nacelle, rotor, blades, and tower); a collector substation; a network of access roads that have cables running between the turbine and the substation; and a high-voltage power line connecting the substation to the energy grid (Bennun et al., 2021).

Impacts

Raw material sourcing and processing, and manufacturing

Depending on the design of the wind farms, a wide variety of raw materials are required which mainly includes aluminium, steel (iron-ore) and zinc for the tower; carbon-fibre and fibreglass for the blades; cement for the foundations, buildings, and tower; cobalt, graphite and lithium for the battery; copper for the generator; and rare earth elements for the magnets (Bennun et al., 2021).

Wind energy technology generally requires many of the same raw materials as those found in solar panels, with significant overlaps in the impacts in the raw material sourcing and processing. Notably, wind turbines require large amounts of rare earth elements, particularly for the magnets located in the nacelle. (Hoffs, 2022). The mining of these rare elements pose a series of human and environmental health risks For example, 9 per cent of the global production of rare earth elements has been outsourced by China to Myanmar, where militia groups implement crude, unregulated and illegal mining practices that destroy ecosystems, devastate local communities, and pollute drinking water (Global Witness, 2022; Hoffs, 2022). Upstream impacts from material processing are an emerging area of research. Namely, the impacts caused by producing rare earth magnets. However, it is difficult to quantify the impact as it is not tackled by the wind energy Life Cycle Assessment (LCA) literature (UNEP, 2016).

Manufacturing the components for wind farms also requires significant consumption of energy and currently generates greenhouse emissions to create the turbines, tower, and foundation (Chowdhury et al. 2022; Ardente et al. 2008; Guezuraga, Zauner & Pölz 2012) in hard-to-abate sectors such as cement and steel (although technological innovation is underway to develop alternatives).

Construction and installation

The construction of onshore wind farms can lead to impacts on water, soil, habitat and wildlife.

Impacts on water systems from wind energy developments are not very well documented. However, good practice guidelines that have been produced by environmental agencies in Northern Ireland and Scotland highlight that the construction of onshore wind farms can impact the quantity, quality and flow regimes of groundwater (Department of Environment Northern Ireland 2015; NatureScot 2019) if not appropriately managed.

Soil erosion and compaction can be caused by a range of activities, including the removal of plants for the excavation of foundations and the creation of roads, as well as the use of heavy machinery during construction (Dhar et al, 2020; Nazir et al, 2020). Soil contamination can also occur if oil and wastewater seep into the soil (Nazir et al., 2020).

The construction of wind farms can impact habitats and wildlife as the physical footprint of the plant itself as well as support facilities and access roads can lead to displacements due to disturbance, migration barriers, lack of access to feeding and roosting ground, and habitat loss and degradation (Bennun et al. 2021; Dai et al. 2015; Hastik et al. 2015). Recent studies suggest that wind farms may have less biodiversity in plant and animal communities than natural areas, with more non-native plant and less rare species (Agha et al., 2020; Keehn & Feldman, 2018).

Operation

During operation, the main concerns relate to the risk of collision by birds and bats, either due to blade strike or barotrauma – particularly for bats (Gasparatos et al., 2017; Peste et al., 2015; UNEP, 2016). Additionally, operation and maintenance activities may affect the roosting and feeding activities of some animals (Gasparatos et al., 2017; Peste et al., 2015; UNEP, 2016)[9]. Finally, wind turbine activities may deter birds from using the area the area, thereby narrowing their habitat (Dai et al., 2015). Box 7 below provides additional information on wind farm related bird mortality in the Australian context.

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[9] Predatory species like raptors are particularly affected, as they not only suffer from high collision rates but also have fewer offspring annually (Thaker et al., 2018; Watson et al., 2018). Higher collision rates coupled with lower breeding rates can lower the predator density in the area, which has a cascading effect on the rest of the ecosystem (Thaker et al., 2018).

Fatality rates can also vary depending on the positioning of the wind farm in the environment (e.g. topography, winds etc.) (Hastik et al., 2015). Turbine design can also have impacts. For example, birds like to nest on – old - turbines that have lattice towers (Saidur et al., 2011). Species-specific factors are also at play, like species type, migration movements and whether they are active during the daytime or are nocturnal species (Hastik et al., 2015; UNEP, 2016).

Box 7: Wind farms related bird mortality in Australia

The impact of turbines on Australian bird mortality rates, while the source of much controversy concerning wind energy, is lacking in peer-reviewed literature (Morton, 2019). That said, expert estimates suggest it may be on average 1-2 birds per turbine per year, depending on the site (Morton, 2019), and a total of 2,000 to 8,000 birds being killed annually across all wind farms in Australia (Parliament of Australia, 2015). A Victorian study conducted from 2003 to 2018 estimates that there is a rate of between 0.1-6.2 bird deaths per turbine, per year of operation, for each species covered in the study (Moloney et al., 2019).

Furthermore, it is worth noting that positive impacts of onshore wind farms on some animals have also been noted. This could be due to a decrease in traffic and predators and an increase in resource availability (Gasparatos et al., 2017). Greater access to shrubs and permanent grasslands (which can occur when wind farms are constructed on previously open agricultural landscapes) will also provide food and shelter for some land animals (Helldin et al., 2012).

So far, we discussed the impacts of onshore wind farms. Box 8. below provides further insights on impacts of offshore wind at the construction and operation phases.

Box 8: Impacts of offshore wind at the construction and operation phases

Description of the technology

Offshore wind farms can be either bottom-fixed turbines, where the turbines have an underwater structure fixed to the seabed in water depths up to approximately 60m, or floating turbines, where the structure is anchored to the seabed in deeper waters through cables (Bennun et al., 2021). Offshore wind farms are comprised of the turbine and tower components that sit above the water and the components for the structure below the surface, including the sub-structure, foundations and scour protection materials. Off-shore wind have infrastructure to transmit electricity to the grid from the turbines both offshore (buried cables, the substation) and onshore (substation, construction port, export cable, and transmission lines) (Bennun et al., 2021).

Construction and installation

Constructing the foundations for the turbines and putting the turbines in place can have a range of impacts including (Dai et al., 2015, 2017; UNEP, 2016):

-Increased water turbidity

-Damage to benthic flora and fauna due to object falling on the seabed

-Decrease in the amount of light penetrating water

- Underwater noise, which may impact mammals using sound to communicate, navigate and find food.

Operation

Offshore wind turbines may impact seabirds and other migratory species. While some research has found that many birds avoided wind avoided offshore wind farms, it also acknowledged that the small percentage of birds who did not may still amount to a significant number of individuals (Shankleman, 2014). A 2016 study carried out on an offshore wind farm in the North Sea found 767 dead birds between 2003 and 2007, which would be equivalent of around 150 mortalities per year (Huppop et al., 2016). The authors highlight that, as the number of wind farms increase, measures to avoid bird strikes should be implemented.

Maintenance activities (e.g. replacing parts and lubricating the turbines), can result in wastewater and/or oil polluting the water (Dai et al., 2015).

Notwithstanding these negative impacts, some research has also documented positive impacts from offshore wind sites. For example, floating structures or bottom-mounted structures can create new habitats by becoming an artificial reef that attract fish to the area (UNEP, 2016).

Decommissioning and disposal

As wind energy increases, the waste streams generated by wind turbines, notably blades, pose major challenges for waste management systems. Tens of thousands of tonnes of waste from blades will need to be managed by 2050 at the global scale (Majewski et al., 2022). Blades are usually made of a composite resin that makes the separation of individual components difficult. Additionally, the blades decrease in value, even when they have been decommissioned successfully (Wind Energy Technologies Office, 2021). Those factors make blades hard to recycle. Current decommissioning and disposal practices only allow 30% of materials used in turbine blades to be reused as new composite materials (Majewski et al., 2022). If no commercially viable solution is developed soon, many turbine blades will end up in land fill at their end of life.

While no literature was identified describing the specific ecosystem impacts of disposing of blades in landfill, blades do contain toxic materials. If those materials were to be leached into the environment, this could have impacts on soil and water quality, as well as on the habitats and wildlife that depend on this land and water.

Mitigation and Conservation Strategies

In this section we focus on three themes that emerged as important for wind energy: habitat and wildlife protection, land surface, and resource use, reuse and recycle.

Habitat and wildlife protection

Planning

The majority of the negative impacts of wind energy on habitat, wildlife and vegetation can be avoided or reduced at the planning phase through the appropriate macro and micro siting of wind farms (US Department of Energy, n.d.; European Union Science for Environment Policy, 2015; Gasparatos et al. 2017). Macro-siting is the identification of a site for a wind farm whereas micro-siting is the layout of the turbines within the wind farm.

A strategic planning approach to macro-siting at a large scale (e.g., a region) can avoid impacts on habitat and wildlife by identifying sites that are away from conservation areas and ecologically significant sites that constitute high quality habitat for wildlife (Gartman et al., 2016a). To assist with the macro-siting of wind farms, data-analysis tools can be used, including land suitability analysis, multicriteria analysis, as well as different methods to generate indices and scores that indicate suitability and compatibility (Stoms et al., 2013). One example of a map developed to help streamline decision-making processes related to wind energy developments is the **Nebraska Wind and Wildlife Working Group Map and Guidelines** (see Box 9).

Box 9 Nebraska Wind and Wildlife Working Group Map and Guidelines

In the U.S., the state of Nebraska has one of the greatest potentials for wind energy due to its availability of open land, with 2.2 million hectares or 11% of the region defined as low-impact suitable land, equating to 66–110 GW capacity (Hise et al., 2022). Conversely, there is opposition to wind farm developments in Nebraska.

The Nebraska Wind and Wildlife Working Group Guidelines (the Guidelines) aim to standardise negotiation processes between project developers and the relevant government agencies (The Nebraska Wind and Wildlife Working Group, 2016). The Guidelines complement existing processes including the coordination and consultation with the state and federal agencies such as the Nebraska Game and Parks Commission (NGPC) and the U.S. Fish and Wildlife Service (USFWS).

The Map

A series of spatial datasets and data on species biodiversity and wildlife concentrations was used to develop the Nebraska Biodiversity and Wind Energy Siting and Mitigation Map (the Map). This planning and siting tool identifies the areas where wind energy is likely to have the most adverse impacts on biodiversity. Consequently, it can recommend siting mitigation measures. It is now part of the voluntary guidance for wind development in Nebraska (University of Nebraska-Lincoln, 2016) and addresses the **refrain** and **reduce** steps of the MCH.

Developers and planners can use this Map when considering new sites for wind projects. It is recommended that developers and planners consult with the biologists at the Nebraska Game and Parks Commission (NGPC) and the U.S. Fish and Wildlife Service (USFWS) at the earliest stage of the development to select suitable sites for projects (The Nebraska Wind and Wildlife Working Group, 2016).

The Map was developed from spatial layers with various indicators associated with threatened species, landscapes, wetlands, and waterways. It aims to support and facilitate decision-making among stakeholders on land-use and locations/designs of wind farms, and the development of mitigation measures (e.g., buffer distances from wind turbine and infrastructure) and costs. The Map can accurately demonstrate the relative sensitivity of wildlife habitats to wind projects, and the best location for projects to mitigate impacts (The Nebraska Wind and Wildlife Working Group, 2016). The three levels of sensitivity on the map are:

Minimum Mitigation Areas – lower concentration of sensitive species and fauna, lower impacts to wildlife, mitigation recommended for some sites including forests, wetland, and grasslands

Moderate Mitigation Areas – higher impacts on site than for minimum mitigation areas

Maximum Mitigation Areas – avoiding development is recommended, high sensitivity very vulnerable sites, mitigation will not compensate the impacts to the site

Best practice is to develop wind energy projects in '**Minimum Mitigation Areas**'. The data suggests that, by doing this, there will be fewer impacts on wildlife and biodiversity overall compared with developing projects in other areas. As it is unlikely that any mitigation measures would adequately compensate for the impacts to biodiversity in '**Maximum Mitigation Areas**', avoiding development in these areas is recommended (The Nebraska Wind and Wildlife Working Group, 2016b; University of Nebraska-Lincoln, n.d., 2016).

The Guidelines

Accompanying the Map are the 'Guidelines for Avoiding, Minimizing, and Mitigating Impacts of Wind Energy on Biodiversity in Nebraska' (the Guidelines) (The Nebraska Wind and Wildlife Working Group, 2016). The Guidelines have made various improvements on the previous development guidelines. This includes development of the Map, pre- and post-construction guidelines, and mitigation guidelines for wind energy developers and operators. The previous development guidelines and assessment processes were limited to the site's condition and impact during the pre-construction phase. The updated Guidelines acknowledge the importance of assessing the long-term (more than five years post-construction) effects of wind farms on biodiversity, as well as cumulative impacts. The Nebraska Wind and Wildlife Working Group (2016) recommends site assessments including bird/plant surveys at both pre- and post-construction phases. As uncertainty remains on these impacts, future research efforts are also suggested in the Guidelines.

Micro-siting can identify ecologically sensitive areas on a site and create avoidance zones around them, as well as arrange the turbines to limit the risk of collisions with avian species, notably by providing wildlife corridors (Bennun et al, 2021) While general recommendations exist on the types of arrangements that may reduce collisions, those are only based on limited observation (see, Bennun et al, 2021).

Construction and installation

The construction phase presents conservation opportunities and the potential to mitigate impacts on habitat, wildlife, and vegetation. For example, barriers or screens can be constructed on the site to limit the disturbance zone of the project (Gartman et al., 2016a; Gasparatos et al., 2017; Saidur et al., 2011). To mitigate impacts on wildlife, wind turbines should be installed away from bird migration corridors, construction should be avoided near bird protection zones, and the turbines should be designed with patterns or different colours to make them more visible to wildlife (McLendon, 2019; UNEP, 2016).

Operation

Projects should develop wildlife-friendly operational procedures, mainly to minimise the risk of collision with avian species.

Electromagnetic fields, acoustics and visual deterrents can be used to redirect wildlife away from wind farms (Gartman et al., 2016b). For example, a study conducted in Norway demonstrated that painting the turbine blades black to increase visibility reduced annual fatality rates by 70%, particularly for raptors like the white-tailed eagle (May et al., 2020). However, it should be noted that there is a risk of eventual habituation and reduced effectiveness of these measures (Gartman et al., 2016b).

The use of technology can also assist in reducing avian mortality. Coastal wind farms in Texas have been using avian radar technology to detect birds and shut down the wind turbines automatically if it perceives the birds to be in danger (Saidur et al., 2011). Further, endangered species are sometimes fitted with GPS transmitters that wind farms can use to track and adjust operations (McLendon, 2019). Additionally, systems using new technologies, such as distributed computing, IoT devices and artificial intelligence are increasingly harnessed to reduce bird mortality on wind farms (Gradolewski et al., 2021; Rogers, 2022). See Box 10 below for a description of the IdentiFlight system installed at the Cattle Hill Wind Farm in Tasmania.

The area can also be modified to be less attractive to specific species (Bennun et al., 2021; Gartman et al., 2016b). For example, activities can be conducted to reduce food availability for specific species, such as removing dead animals that could attract scavengers, or reducing habitat features for small mammals so as to avoid attracting raptors (Bennun et al., 2021) Inversely, *offsite* areas can be enhanced for these species by, for example, promoting the availability of prey through habitat management or the creation of roosting and breeding sites (Bennun et al. 2021).

Box 10: Cattle Hill Wind Farm

The Cattle Hill Wind Farm in Tasmania is using an aerial monitoring and detection system called IdentiFlight to reduce collisions with the Tasmanian wedge-tailed eagle, which is listed as endangered in the state. Construction of the 144 MW wind farm was completed in 2019 and started to power the grid in 2020 with 48 turbines, each standing 170 metres (Cattle Hill Wind Farm, n.d.; Vorrath, 2021). The approval of the project was conditional on the Identiflight camera technology. An 18-month trial was implemented (Rogers, 2022).

How does it work?

16 towers mounted with IdentiFlight units have been installed on-site which can shut down any of the 48 turbines. Fifteen towers are 7 metre tall, and one tower is 10 metre tall. The proprietary technology combines machine learning and AI technologies that are connected via an artificial neural network (IdentiFlight, n.d.). The technology works within seconds by detecting and photographing flying objects, using algorithms to identify the object. Once an eagle is detected, the technology tracks its flight path, recording height, speed, angle of approach and other data, while collecting images at ten frames per second. If an eagle's speed and flight path indicate a risk of collision with a wind turbine, a signal is sent to temporarily shut down that turbine (Rogers, 2022). Another signal is sent to restart the turbine once the eagle is no longer at risk.

A recent American study found that the use IdentiFlight led to an 82% reduction in the fatality rate at a study site in Wyoming, U.S.A. (Top of the World Wind power Facility) compared with the control site situated 15km away (McClure et al., 2021). Since installing the system in November 2019, Cattle Hill Farm has registered eight Tasmanian wedge-tailed eagle mortalities and zero White Bellied Sea Eagle, while a collision risk modelling exercise undertaken in 2010 predicted 14 eagle mortailites in four years (Cattle Hill Wind Farm, 2023).

Recent developments

In 2023, an additional 30 metre tower was installed on Cattle Hill Wind Farm to improve the visual coverage of a forested area present on the wind farm, where a number of eagle mortalities occurred. Since this additional tower was set up, no additional mortality was recorded. Additionally, a neural network was developed to identify the white bellied sea eagle. The IdentiFlight technology can now identify either species.

Birds and bat mortalities on wind farms have been a source of ongoing community concerns, including at Cattle Hill Wind Farm. We have noted elsewhere that there are few long-term studies on bird and bat mortality from wind farm projects. As such, the long term monitoring of birds and bats mortalities – and the independent verification of outcomes – will be essential to build community trust in their effectiveness.

Decommissioning and disposal

During the decommissioning and disposal phase, reclamation planning can be implemented to increase conservation outcomes. Land reclamation aims to restore a fully functioning ecosystem comparable to the one that existed before the site was disturbed (Dhar et al., 2020). However, reclamation presents multiple challenges, including reconstructing landforms, developing the right conditions to establish suitable vegetation, and rebuilding microbial and soil ecosystems (Dhar et al., 2020).

Resource use, reuse and recycle

These conservation and mitigation measures can help reduce ecosystem impacts upstream of the wind farm by reducing the need for mining new materials, and downstream by avoiding blades from ending up in landfill. Additionally, some strategies here relate to the management of waste and water during the construction phase. These strategies therefore belong to the reduce step of the MCH.

Raw material sourcing, processing, and manufacturing

The conservation and mitigation strategies for wind energy at this stage of the lifecycle are similar to those for solar energy. Namely, the focus is on responsible sourcing and processing of materials through mining standards and certification schemes, that increase the traceability of materials. These standards and certification schemes also have a focus on processing techniques, with environmental protection measures in place to avoid waste contamination and water pollution (Box 16 on Responsible Sourcing – while the focus is on responsible sourcing for batteries, the information provided will be broadly relevant for wind energy).

Construction and installation

The impacts on habitat, wildlife and vegetation that occur during the construction of a wind farm can be reduced through sustainable circular economy building practices. This would involve minimising the infrastructure and materials used, minimising transportation of materials, and recovering and reusing materials such as the turbine base materials, cables, and track stones (NatureScot, 2019). Specific practices that can be implemented to manage waste and water at the site include (NatureScot, 2019):

- Reusing excavated rock materials to improve roads and levees.
- Where woodland removal is necessary, selling any merchantable timber for economic benefits, and leaving tree stumps and roots in place to avoid soil destabilisation and run-off into waterways, and using any residual tree materials (e.g., mulch) to help support habitat restoration.
- Implementing sustainable drainage practices, such as collecting and treating water run-off and wastewater.

See Box 11 below for an example of the integration of sustainable building practices in a wind energy project.

Box 11: Midelt Wind Farm

Located in Draa-Tafilalet, Morocco, the Midelt Wind Farm, developed by Enel Green Power (EGP), Moroccan Agency for Sustainable Energy, Nareva Holding and Platinum Power (Power Technology, 2024) incorporated sustainable construction practices in the construction phase of the project lifecycle. The 210 MW windfarm is part of Morocco's Integrated Wind Farm program. The aim of the program is to build a wind farm network with a combined 850 MW (Enel Green Power, 2018). The actions implemented at the Midelt Wind Farm focused primarily on the reduce step of the mitigation hierarchy. Some of the practices adopted were (Enel Green Power, 2019, 2021, 2023):

-Using excavation materials to upgrade levees and roads,

- Reusing wood pallets as signs on the site,

- Developing a waste recycling system for metal, pallets, and lubricants,

- Reusing greywater and wastewater used to manufacture concrete and wash vehicles.

Enel Green Power has developed a Sustainable Construction Site model to formalise the sustainable practices used in their projects. This model is replicated on sites across the world. For example, the Cohuna Solar Farm (operational) and the Girgarre Solar Farm (under construction) (Victoria, Australia) followed the Sustainable Construction Site Model (Enel Green Power, n.d.-a, n.d.-b).

Decommissioning and disposal

While the market for steel scrap and recycling for wind towers is relatively established, the management of the blades at the end of life stage remains a concern. However, global blade manufacturer commitments to making their businesses carbon neutral and zero-waste has spurred several research developments and demonstration projects for recovery, repurposing and recycling of blades, notably in Europe and the US.

For example, the National Renewable energy Laboratory (NREL), USA, is conducting research on designing clean energy technologies that reduce the number of materials used for blades and generators (NREL, 2020). Siemens Gamesa Renewable energy (SGRE), a European engineering company, has developed a RecyclableBlade technology using a new resin to overcome the challenge of recovering the materials used in turbine blades. At the end-of-life the resin can be separated from the components of the blade – including fiberglass, wood, plastic, and metals – by soaking the blade in a solution. The components can then be recovered for secondary use in the automotive industry or consumer goods (e.g. flatscreen casings) (Stone, 2021). These types of blades were used for the first time in 2022 at the Kaskasi offshore wind farm which is located in the German North Sea (Frangoul, 2021).

An increasing number of companies are beginning to offer composite recycling (for blades), though this is not currently cost-competitive. The main commercially available technology is cement co-processing, with blades as an input, and mineral components reused in cement (WindEurope; Cefic and EuCIA, 2020).

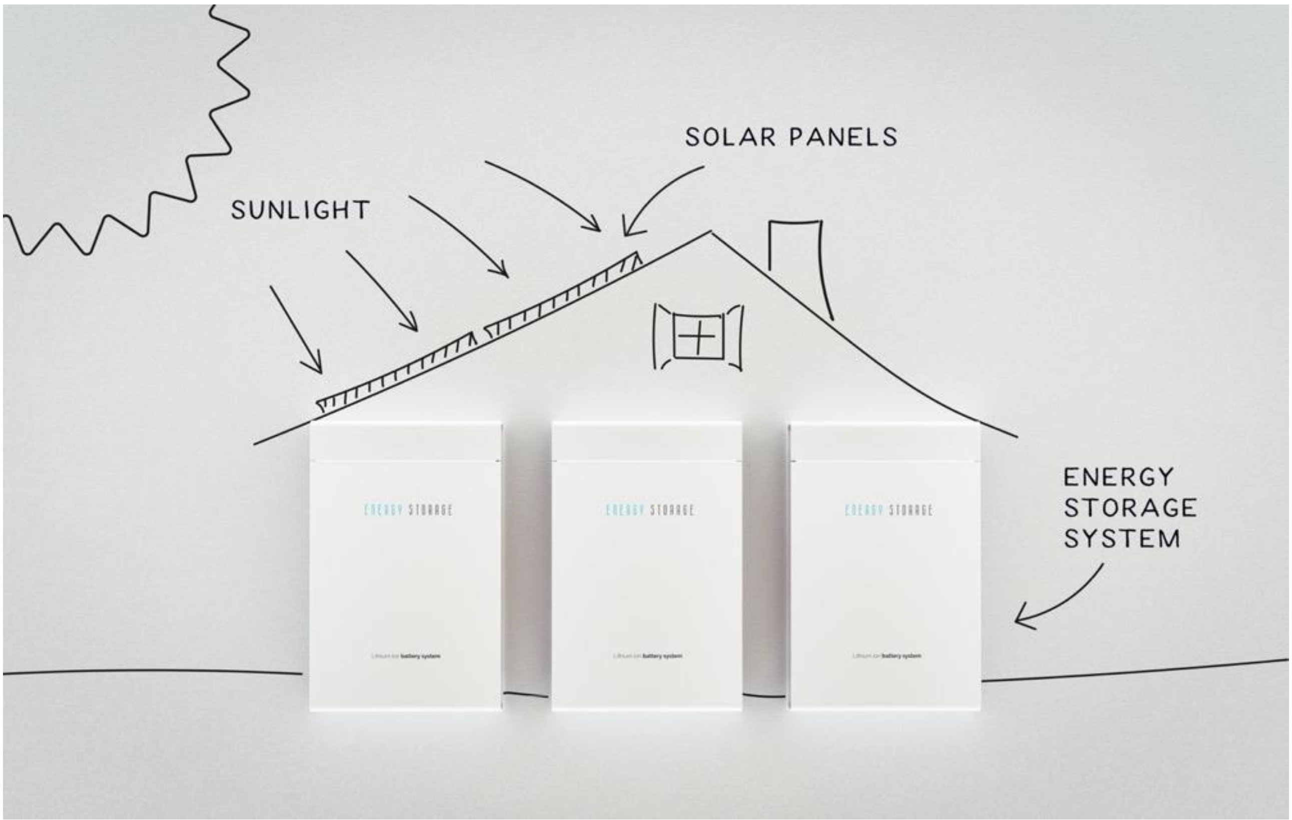
Lastly, some projects focus on the repurposing of blades. Several demonstration projects across Europe use them for playgrounds, street furniture, or building structures like bridges, walkways, bike shelters, etc. but this is often an example of downcycling (WindEurope; Cefic and EuCIA, 2020).

Land surface

Planning

The strategies to manage the impacts of wind farms on land surface are focused on how to minimise the land footprint of projects, and therefore belong to the refrain and reduce steps of the MCH. Studies have suggested that since the overall impact on land use is low for wind energy, many activities like agriculture, aquaculture, and grazing can continue to occur among operating turbines (Dhar et al., 2020). Another opportunity is to retrofit solar farms at existing wind farms, which can help minimise the land footprint of the renewable energy infrastructure as well as reduce costs. In Australia, AECOM (2016) analysed 10 wind farms to find that 414 MW of solar capacity could be co-located without exceeding a 5% curtailment in overall power production. This planning measure presents significant economic and environmental opportunities.

Battery Energy storage systems



Battery energy storage systems (BESS) are unique in their ability to hold and reinject surplus electricity produced by renewable energy technologies back into the grid. As such, they are fast becoming an essential feature as low-cost variable wind and solar energy become the bulk sources of energy – ‘firming’ the supply and security of the energy system (IRENA, 2019a; Roos, 2021).

Large-scale and local (or ‘distributed’) energy storage systems are on the rise in Australia. In 2022, CEP Energy began construction on what will be “the world’s biggest large-scale battery” (Morton, 2021). Located in the Hunter Valley, NSW, and costing AUD 2.4 billion, this BESS will have a power capacity of up to 1.2 GW which is eight times greater than the 100 MW / 129 MWh Tesla Li-ion BESS at the Hornsdale Wind Farm, South Australia (Morton, 2021). At a local level, batteries a critical component of electric vehicles (Evs) and battery storage systems ‘behind the meter’ in households and ‘neighbourhood’ battery systems in ‘front of the meter’ to support a local area are also growing. AEMC predicts that by 2050, 45% of Australia’s electricity demand will be supplied by distributed energy resources (AEMC, n.d.).

However, there are very serious environmental impacts from BESS, especially in the mining and mineral processing which often occurs in countries. Aside from the negative impacts caused by mining, these raw materials have the potential to leach into the environment, particularly at the decommissioning and disposal phase if not handled appropriately. Some of the toxic materials that are contained within batteries include acid, lead, nickel, lithium, cobalt, cadmium, alkaline, mercury and nickel metal hydride (Azo Clean Tech, 2008). However, it is difficult to have a comprehensive understanding of the environmental impacts that batteries can have because battery chemistries vary significantly according to their design (Macoun, 2022).

In addition to the impacts of BESS on the environment across their lifecycle, various mitigation and conservation strategies are highlighted including improving supply-chain governance, alternative battery chemistries and recycling and circular economy to reduce mining.

Description of technology

Batteries store energy using chemicals, which absorb and release the energy on demand. A battery consists of five major components – an anode, cathode, electrical current collector, electrolyte, and separator (Borah et al., 2020) – with the main difference in batteries being their chemical makeup. Lithium-ion (Li-ion) batteries are most widely used battery on the market, mainly due to their steep decline in costs over the years and their application in EVs (IEA, 2024). Other types of batteries exist, such as lead-acid, nickel-cadmium, nickel-metal hydride, and vanadium redox flow (Díaz-Ramírez et al., 2020). Some of the main minerals and metals that are mined for batteries include lithium, nickel, cobalt, graphite, manganese, alumina, tin, tantalum, magnesium and vanadium (Chamber of Minerals and Energy of Western Australia, n.d.)

The environmental impacts caused by batteries vary. For example, the vanadium redox flow battery (VRFB) was found to cause the least amount of environmental damage, while the nickel metal hydride (NiMH) battery caused the most (Díaz-Ramírez et al., 2020). VRFBs do not degrade with cycling and store energy in a non-flammable, liquid electrolyte (Skyllas-Kazacos and McCann, 2015) whereas NiMH batteries contain a relatively large amount of the toxic chemicals harmful to humans and ecosystems (Parvez Mahmud et al., 2019). However,

Batteries can be arranged in different ways, sizes and for different applications. Smaller-scale batteries can operate in homes and businesses to store power from, for example, a rooftop PV system, but can also be operated as a collective referred to as a Virtual Power Plant (VPP)[10]. BESS are being deployed as utility-scale storage systems which have a typical capacity from several megawatt hours (MWh) to hundreds of MWh (IRENA, 2019b) – and larger batteries are emerging. Utility-scale storage systems have widespread applications and benefits, such as providing grid services, such as frequency regulation; deferring network augmentation to meet peak demand, grid reinforcement during peak demand periods; storing excess electricity from cheaper, cleaner renewable energy; and providing cheaper, more reliable electricity to isolated communities at the end of electricity distribution lines (IRENA, 2019b).

Impacts

The impacts of BESS on ecosystems are primarily concentrated in two stages: the raw material sourcing, processing, and manufacturing phase; and the decommissioning and disposal phase. Installation at the utility-scale is a relatively small component of the construction process for wind and solar farms.

Raw material sourcing, processing, and manufacturing

Sourcing

The extraction of critical battery minerals, and the waste this generates, has widespread impacts on water, soil, habitats and wildlife. This is largely because the mining governance regimes of countries that have abundant reserves of battery-minerals normally fail to meet international sustainability standards (Future Battery Industries CRC, 2020).

Water management is one of the key environmental challenges associated with raw material sourcing for battery materials. Mining can lead to unsustainable water table reduction and the depletion of water resources, exacerbating droughts and desertification (Brooks, 2021). The mining of critical battery metals like cobalt, copper, lithium, nickel, silver, and rare earths is responsible for pollution and heavy metal contamination of water, which can have detrimental health effects on mining workers, local communities that rely on the water for drinking, and natural ecosystems. Of particular concern are the mining practices associated with Li-ion batteries (see Box 12) considering that lithium demand is expected to increase tenfold between 2020-2030 to meet the global demand for batteries (Kaunda, 2020; Gielen & Lyons, 2022).

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[10] A VPP aggregates and stores the electricity produced by thousands of individual DER systems, which can then be reinjected into the grid to manage frequency and voltage imbalances, disruptions or disturbances to the local power supply, and to help stabilise the electricity network (ARENA, 2021).

Box12: Lithium-ion batteries

Li-ion batteries dominate the market for rechargeable batteries (IEA, 2024). Lithium is the lightest metal and the least dense solid element, and it has a high electrochemical potential. These qualities make lithium very valuable for Evs because it has the highest charge-to-weight ratio, which is especially desirable for transportation applications (Goonan, 2012).

However, the processes involved in extracting and producing lithium often require large amounts of groundwater because the highest concentration of lithium is found in continental brines in desertic areas (Flexer, Baspineiro and Galli, 2018). Evaporative lithium extraction is a popular and controversial method to access this lithium, which involves pumping water from large salt lakes into evaporation pools that are then left to evaporate into lithium carbonate over a period of several months (Wanger, 2011; Katwala, 2018). For the precipitation process to be effective, the brine must lose up to 95% of the water in the pools (Brooks, 2021). Reports have estimated that roughly 1.9 million litres of water must be pumped to produce a tonne of lithium using this extraction technique (United Nations Conference on Trade and Development, 2020). Evaporative lithium extraction has diverted water away from communities and farming, particularly in the 'Lithium Triangle' region of South America between Argentina, Bolivia and Chile which contains ~50% of the global lithium resources (Dominish et al., 2019; Future Battery Industries CRC, 2020; United Nations Conference on Trade and Development, 2020). In Chile, for example, conflict ensued between mining companies, authorities and Indigenous communities in the village of Antofagasta de la Sierra, where mining companies entered people's land without consent and police persecuted the locals when they protested the developments (Blair et al., 2022).

Evaporative lithium extraction is also associated with pollution because toxic chemicals can enter water supplies (Smith et al., 2022; Wanger, 2011; Katwala, 2018). For example, in 2016 in Tagong, a Tibetan town near the Ganzizhou Rongda Lithium mine, lithium that leaked into the local waterways decimated the fish population and there were reports of yak and cow dying from drinking the water. This was the third time this had happened in the area in the space of seven years (Katwala, 2018).

Mining critical battery metals can also destroy the structure of soils and cause soil contamination (Brooks, 2021; Dominish et al., 2019). Opening a mine requires large amounts of soil to be removed or sealed for roads, which causes soil erosion, soil destabilisation and, consequently, natural disasters such as landslides (Manhart et al., 2019). The production of heavy metals such as lead, zinc, cadmium, mercury, chromium, arsenic, copper, and nickel also pollute soil, which is persistent and can be irreversible without implementing complicated intervention measures. Soil contamination poses risks to humans and ecosystems, which can occur through ingestion or contact with the soil, spreading pollutants through food chains, and drinking contaminated ground water that has mixed with the soil. This can also drastically reduce food quality which can lead to food insecurity (Wuana & Okieimen, 2011). In China, mining activities are one of the most significant causes of heavy metal contamination, which has generated approximately 1,500,000 hectares of wastelands across the country (Li et al., 2014).

Additionally, the mining dust and fine particles, released during mechanical excavations and targeted explosions, is toxic. When it is released into the atmosphere, it affects miners and local communities when it is inhaled, as well as fauna and flora. If cobalt and graphite powder spill out of a mine, soils may become contaminated which causes flow-on impacts on ecosystems (United Nations Conference on Trade and Development, 2020).

The threats posed to habitats and wildlife will continue to increase as more (dense) mines target materials for renewable energy and battery storage production. These new threats to biodiversity could be considerable if there are no strategic planning mechanisms in place. Research has found that there is a high density of current and future global mining areas that also overlap with conservation areas and priority areas, including Protected Areas and Remaining Wilderness areas (Sonter et al., 2020). One mining practice that is beginning to receive more attention is deep seabed mining (see Box 13).

Box 13: Deep seabed mining

The deep-sea is unique, largely unexplored terrain that hosts rich ecosystems full of biodiversity. Within these ecosystems mineral resources are also an integral centrepiece, contained and located around structures such as hydrothermal vents that serve as shelters and steppingstones for marine fauna and flora (Orcutt et al., 2020). Some of the main mineral resources in the deep-sea include massive sulphide deposits forming around hydrothermal vents, and polymetallic nodules and crusts that contain primary metals like copper, manganese, nickel and cobalt (Hylton, 2020).

Deep-sea mining of mineral resources has raised concerns because of the likely impacts it will have on biodiversity and ecosystems (Orcutt et al., 2020; Hylton, 2020). This is linked to the use of mining equipment to dredge the ocean floor and the sediment plumes that are created by the mining operations, which smother fauna in the disturbed areas and surroundings (Jones et al., 2018). Notably, recovery from any mining disturbances in the deep-sea will be extremely slow. This is most likely to happen if mining activities disturb and remove important parts of the habitat (e.g. vent chimneys, corals and nodules) (Jones et al., 2018).

These concerns have led to the signing of a global moratorium to ban seabed mining by scientists, communities, members of the fishing industry, political leaders, NGOs, and from multinational companies like BMW Group, Samsung SDI, Google and Volvo Group (WWF, 2021). Some proponents have argued that if it could operated sustainably the overall environmental impact could be lower as there are very rich mineral deposits in the ocean that could offset some of the new mines that will be developed to meet demand.

Processing

At the processing stage, procedures such as cyanidation, amalgamation, or flotation, are used during the concentration process, which uses toxic reagent chemicals to extract different metals and minerals from ores (Manhart et al., 2019). This can result in toxic chemicals like copper and lithium cyanide being released along with mining residues into ecosystems.

Manufacturing

During the manufacturing stage large amounts of water is used for several purposes: to prepare reactive materials and the electrolytes; deposit reactive materials onto electrodes, to charge and remove impurities from electrodes; and to wash the production equipment, manufacturing areas and finished battery cells. As a result, wastewater from materials such as cobalt, copper, lead, manganese, mercury, silver, zinc etc. can seep into and pollute waterways if not managed appropriately (United States Environmental Protection Agency, n.d.). Heavy metals can also cause soil contamination during the battery manufacturing stage. One study conducted in Africa analysed the soil located around battery manufacturing and recycling plants and found that the lead leaching into the soil around the plants had reached toxic levels. This caused elevated blood lead levels in young children in the local communities adjacent to the plants, which were using the soil for agricultural purposes. Disturbing contaminated topsoil can also release lead into the atmosphere and cause similar detrimental health effects when the lead is inhaled (Gottesfeld et al., 2018).

Battery manufacturing also uses harmful chemicals (Sharma & Manthiram, 2020). Hydrogen fluoride is an extremely corrosive chemical found in batteries. It can dissolve in clouds, fog, rain, dew or snow, which can then be deposited as wet acids (e.g., acid rain, acid fog) into the environment. Hydrogen fluoride also readily mixes in waterways (DCCEEW, n.d. - b). These toxicity concerns therefore extend beyond the battery manufacturing factory and pose serious impacts to surrounding communities and ecosystems.

Decommissioning and disposal

Hazardous materials contained in batteries – such as lead, sulphuric acid, cadmium, copper, cobalt and nickel – are responsible for impacts at the decommissioning and disposal phase, as they can leak from battery casings buried in landfill at their end-of-life which contaminates soil and ground water (Gottesfeld et al., 2018; Zhao et al., 2021). This could consequently impact habitats and wildlife.

Significant quantities of end-of-life waste will increase as demand for batteries increases. This raises concerns about material recovery, as current recycling processes are not always compatible with recovery. Though recycling consumer batteries is well developed, the process for large EV and BESS is complicated because there are currently non-standard design and disassembly procedures (Zhao et al., 2021).

Mitigation and Conservation Strategies

Resource use, reuse and recycle

Raw material sourcing, processing, and manufacturing

Responsible sourcing and processing practices for BESS are essential to reduce the negative impacts on water, soil, habitat and wildlife. This can be achieved by increasing traceability, sourcing materials from lower risk countries and adhering to standards and certifications. For example, Cobalt Blue (see Box 14) is an Australian mining company that strives to assess and implement best-practice standards for cobalt production. Considering that the majority of the world's cobalt is mined in the Democratic Republic of Congo, where child labour and human rights issues are common and persistent (United Nations Conference on Trade and Development, 2020), transparency in the supply chain is essential. Box 16 provides further details on responsible mining for solar, wind and BESS.

Box 14: Cobalt blue

Mining companies are looking into better managing the waste generated from mining and processing operations. For example, inert waste rock can be used in roads. Cobalt Blue is a cobalt development and technology company that advances and develops cobalt mining and refining operations in Australia (Cobalt Blue 2022). Cobalt Blue ensures that the refined waste and waste rock from its mining operations are stored in Integrated Waste Landforms rather than a tailings dam.

At the manufacturing phase, low toxicity practices can be implemented. For example, one study recommended that low toxic salts be used as an alternative to lithium hexafluorophosphate, a toxic substance that is commonly used as an electrolyte in Li-ion batteries (Sharma & Manthiram, 2020). The same study suggested that iron and manganese-based cathodes should be prioritised over cobalt and nickel-based cathodes, as they are as less toxic and less energy-intensive (Sharma & Manthiram, 2020). To reduce risks to habitats and wildlife from toxic manufacturing practices, sodium would be preferable to lithium, and polyethylene – which is derived from natural gas – should be replaced with cellulose separators, which require far less land to produce (Sharma & Manthiram, 2020).

Decommissioning and disposal

To manage negative impacts there is a need for developing and mainstreaming alternative batteries, long-lived products along with an efficient recycling system for resources (Smith et al., 2022). For example, VRFBs are emerging as a mature, cost-effective and sustainable alternative for stationary energy storage, namely because they have a long lifecycle, are highly efficient, easily recyclable and do not contain toxic metals such as cadmium, zinc, lead and nickel (Arevalo-Cid et al., 2021; Larcher & Tarascon, 2014). Sodium is being investigated by researchers as a cost-effective, sustainable alternative to lithium, mainly because of its abundance in the Earth's crust and high concentration in sea water (Larcher & Tarascon, 2014).

Recycling the components of batteries and other e-waste is crucial to mitigating harmful impacts on the environment as it reduces the amount of raw materials that are being mined and restores ecosystems that have been harmed from mining and toxic contamination. However, recycling is made difficult because of the different chemistries of batteries. Processes like bio-hydrometallurgy are being explored as a sustainable solution that uses bacteria (e.g., *Acidithiobacillus ferrooxidans*) to metabolise and leach metals from batteries (Farnaud, 2021; Larcher & Tarascon, 2014), as well as using certain plants to recover cobalt and nickel efficiently and naturally from contaminated soils and water (Dodson et al., 2012; Larcher & Tarascon, 2014). While these novel methods have great potential, they are still in their infancy and remain experimental.

Some other initiatives aimed at improving the recycling of batteries are included in Box 15. Box 16 discusses responsible sourcing practices, and Box 17 discusses initiatives to reduce demand for the raw materials, While they have a particular focus on batteries, they are likely to be relevant for other renewable energy, notably solar and wind.

Box 15: Battery recycling initiatives

ABRI

In 2008, a non-for-profit association was established in Australia called the Australian Battery Recycling Initiative (ABRI), whose mission is to promote the responsible collection, recycling, and disposal of batteries at end of life. The members of ABRI include recyclers, battery manufacturers, research institutions, government bodies and environment advocacy groups (ABRI, 2022). Recycling can significantly reduce primary demand for new raw materials, and thus contributes to managing environmental impacts of battery systems caused by mining.

Some of the services that ABRI offer includes online or face-to-face training to explain best practices around battery safety and packaging for transport, as well as advocacy and public policy work alongside policymakers and regulators to improve standards and industry integrity, and achieve environmental, safety and sustainability outcomes (Australian Battery Recycling Initiative, n.d.).

Birmingham Extreme Robotics Lab, University of Birmingham

The Reuse and Recycling of Lithium-Ion Batteries (ReLiB) is a project being conducted in the UK involving a consortium of 50 scientists and engineers as well as 14 industry partners. Led by the University of Birmingham, they are working together to improve Li-ion battery recovery, specifically from eVs.

Of interest is the work being conducted by researchers at the Birmingham Extreme Robotics Lab who are using robotics technology to remove, dismantle and recover potentially explosive Li-ion battery cells from eVs (IER, 2020; Harper et al., 2019). The novelty of this technology is that these robots were originally developed for nuclear power plants and are resistant to high levels of radiation. Automating the recovery process using these state-of-the-art robotics, computer vision and artificial intelligence eliminates the health risks posed to humans, reduces costs and improves the separation process, thereby enhancing the purity of the recycled materials (Harper et al., 2019). Recycling batteries in this way reduces the need for primary materials and enhances material supply and efficiency (Jacoby, 2019).

Box 16: Responsible Sourcing

Responsible sourcing practices are beginning to be adopted in the renewable energy sector, but many manufacturers have been primarily concerned with securing mineral supply at a stable price. EV manufacturers have had the most public scrutiny on their supply chains because of child labour and forced labour in cobalt sourced from Democratic Republic of Congo (Amnesty International, 2017). However, there are also risks in solar and wind supply chains (Dominish et al., 2019).

Consumer-facing companies are leading industry efforts to adopt responsible sourcing practices following increasing pressure from consumers and investors and have an important role to put pressure on their upstream suppliers (RAID and CAJJ, 2021).

Increasing traceability

Understanding the supply chain is the first step to understand risk of environmental impacts from mining for renewable energy technology manufacturers. Transparency in the supply chain is challenging owing to the complex supply chains and multiple actors, including mine operators, traders, smelters and component manufacturers. For example, although the majority of cobalt is mined in DRC, most of this is processed in China where it is blended together during the refining process (RAID and CAJJ, 2021).

Many manufacturers, particularly EV manufacturers who have faced challenges to secure supply of metals such as cobalt and lithium, are moving towards purchasing directly from mines and supplying the raw materials to their component manufacturers.

Sourcing from lower risk countries

Manufacturers are increasingly looking to secure the supply of minerals for their batteries from “low sovereign risk” countries like Australia, Canada, the EU and US (Dominish et al., 2019). Additionally, the EU and US have policies to encourage onshoring of critical minerals production. For example, providing subsidies, financing and de-risking incentives to lithium companies (Riofrancos, 2022).

This strategy is not a guarantee of responsible practices. Mining projects may still have risks of environmental and human rights impacts and it cannot be assumed that the regulation and enforcement of environmental (and labour) regulations is sufficient in these countries. Mining projects are also more likely to affect disadvantaged communities in these countries. For example, in the US large proportions of nickel, copper, lithium and cobalt reserves are located in close proximity to Native American reservations (Block, 2021).

A strategy of shifting sourcing to these countries in the "global north" does not address the existing harms within supply chains (Riofrancos, 2022). Shifting investment away from existing mining regions could also lead to adverse impacts. For example, removing cobalt from the DRC from the supply chains of lithium-ion batteries reduces the economic opportunities for the local community. Instead, downstream consumers of these metals can help to drive improvements concerning the environmental and human rights impacts of the mining operation.

Certification and standards schemes

A best practice approach for responsible minerals sourcing is a commitment to source from mines that follow strict environmental and human rights standards via independent, third-party certification and standards schemes. The *Standard for Responsible Mining* is a standards scheme that was launched by the **Initiative for Responsible Mining Assurance (IRMA)**. Standards must not only address environmental and biodiversity risks, but also factors relating to human rights and labour impacts.

In 2018, IRMA launched the *Standard for Responsible Mining* and their own independently verified certification scheme. The standard is applicable to all minerals with best practices organised in four principle areas:

1. Business integrity
2. Planning for positive legacies
3. Social responsibility, and
4. Environmental responsibility

The IRMA standard and assessment system was developed through a multi-stakeholder consultation process that recognised and built upon the principles contained in existing certification and standards schemes. For instance, the environmental responsibility principle outlined in the *Standard for Responsible Mining* has the following requirements (IRMA 2018):

- **"Waste and Materials Management**: To eliminate off-site contamination, minimise short- and long-term risks to the health and safety of communities and the environment, and protect future land and water uses.
- **Water Managemen**t: To manage water resources in a manner that strives to protect current and future uses of water.
- **Air Qualit**y: To protect human health and the environment from airborne contaminants.
- **Noise and Vibratio**n: To preserve the health and well-being of nearby noise receptors and the amenity of properties and community values, and to protect offset structures from vibration impacts.
- **Greenhouse Gas Emission**s: To minimize climate change impacts through increased energy efficiency, reduced energy consumption and reduced emissions of greenhouse gases.
- **Biodiversity, Ecosystem Services and Protected Area**s: To protect biodiversity, maintain the benefits of ecosystem services and respect the values being safeguarded in protected areas.
- **Cyanid**e: To protect human health and the environment through the responsible management of cyanide.
- **Mercury Managemen**t: To protect human health and the environment through the responsible management of mercury."

See Appendix VI for further details on the drivers of change, factors of success and challenges in developing the project.

Box 17: Reducing raw material demand

There are several strategies that can minimise demand for primary minerals and reduce the need for new mining, before looking to responsible sourcing practices. In many cases these strategies will be essential to ease pressure on the supply of raw materials for the energy transition, particularly for metals where there are potential supply challenges. For example, a recent study on lithium demand found that recycling systems, reuse of end-of-life EV batteries for storage and the design of transportation systems with lower lithium intensity are required in order to balance lithium supply and demand over the next century (Greim et al., 2020). The following section outlines examples of these strategies to minimise primary metal demand.

Improving material efficiency

Improving the efficiency of material use in the manufacturing of renewable energy technology can reduce the demand for new metals. This can be done by using less material compared to the amount of energy produced or stored, and by extending the products life.

For solar PV and wind power, material use has already improved significantly since these technologies became commercially available. For example, the amount of silver used in solar panels has decreased significantly, falling from 521 mg per cell in 2009 to 111 mg per cell in 2019, and is forecast to level out at around 80 mg per cell (CRU Consulting, 2020). The average size of a new wind turbine has also increased over time, which reduces the material use as less tower are needed for the same sized wind farm. For example, the average capacity of a new turbine installed in the US in 2020 was 2.75 MW, up from approximately 1.5 MW in 2005 (Wiser et al., 2021). Lithium-ion batteries have also had significant improvements in efficiency and cost since commercialisation. However, there is also a trend towards larger sized batteries in EV passenger vehicles.

Reducing demand for technology

Renewable energy systems should be designed to reduce the overall demand. This is particularly important for electric vehicles where electrification provides an opportunity to redesign the transport system through policies that reduce dependency on private vehicles, such as the promotion of car sharing and use of public transport. A recent scenario of EV uptake found that a 10% reduction in the distance travelled by car by 2050 makes it easier to reach decarbonisation targets, and a reduction in the global car fleet by 145 million cars in 2050 would reduce emissions by 2.25 gigatons and reduce battery demand by 433 gigawatt hours per year (BloombergNEF, 2022).

Increased use of recycled content

To significantly reduce primary demand for the key minerals used in renewable energy supply chains it is necessary to reuse minerals from recycled sources. However, this does not come without challenges. For example, modelling undertaken by UTS, for lithium-ion batteries used in electric vehicles, found that "*recycling has the potential to reduce primary demand compared to total demand in 2040, by approximately 25% for lithium, 35% for cobalt and nickel and 55% for copper*" (Dominish et al., 2021, p.i). This modelling was based on a scenario of EV uptake and battery capacity reflected in the International Energy Agency's (IEA) Global Electric Vehicle Outlook 2020. The study also noted that while it is technically feasible to recover lithium, cobalt, nickel, and copper from lithium-ion batteries, only cobalt and nickel – the most valuable ones – are commonly recovered, and they only represent a small proportion of the supply for manufacturing. Metals recovered from other end markets are often recycled into the same products and are unlikely to be used for lithium-ion batteries, except for copper. Overall, lithium-ion batteries at the end-of-life are likely to become the main source of secondary metals for lithium-ion batteries. As such, economic and policy incentives are needed to boost the recovery of elements from lithium-ion batteries.

Bioenergy

Bioenergy is a flexible energy source that can be made from different feedstocks for different purposes. For example, solid bioenergy made from biomass (e.g. wood residues and agricultural waste) can be used as a fuel source; biogases, produced when bacteria anaerobically digest organic waste, can be combusted for power and heating homes; and liquid biofuels can be used in cars, planes and ships (IEA, 2022c). Bioenergy is likely to play a role in powering heavy goods vehicles, planes and ships, as no other liquid fuel alternative is currently available (Correa et al., 2017).

In Australia, where high-quality solar, wind and hydro resources are abundant, bioenergy is seen as having a role to play in sectors where emissions are difficult to abate (ENEA Australia & Deloitte Financial Advisory, 2021). Australia has significant bioenergy potential considering the scale of forestry and agricultural resources. Key areas identified for potential bioenergy intakes in Australia include industrial heat generation (biogas and electricity), replacement of natural gas in the gas network, and liquid fuels (both jet fuels and road transport biofuels).

There are growing concerns about the food security and environmental impacts that could be triggered by the large-scale adoption of bioenergy. The use of food and feed crops as bioenergy feedstock has led to competition between energy and food crops, threatening food security outcomes in some parts of the world (Koizumi, 2015; Renzaho et al., 2017; Rosegrant & Msangi, 2014), where ‘energy crops’ have developed in areas of high biodiversity value (de Andrade Junior et al., 2021; Immerzeel et al., 2014).

Due to those concerns, recent bioenergy policies started focusing on the use of feedstock that would induce no or less land use change, such as agricultural and forestry residues and waste-based feedstock. This is the case in Europe and the USA (Baumber, 2017), but also in Australia, where the focus is now on using agricultural residue and lignocellulosic feedstocks (ENEA Australia & Deloitte Financial Advisory, 2021).

Depending on the feedstock used, the environmental impacts of bioenergy production will vary (Hijazi et al., 2016; Miyake, 2014). As such, it is necessary to describe each type of feedstock and the potential impacts associated with it. In the next section, we will present the main types of feedstock used for bioenergy production. We will then proceed to discuss their impacts on habitat, wildlife, water and soil, and present mitigation and conservation strategies that can be adopted.

Description of technology

According to the IEA, bioenergy is defined as:

“A source of energy from the organic material that makes up plants, known as biomass. Biomass contains carbon absorbed by plants through photosynthesis. When this biomass is used to produce energy, the carbon is released during combustion and simply returns to the atmosphere, making modern bioenergy a promising near zero-emission fuel”[11].

Bioenergy can be used as a source for fuel, gas, heat or power (IEA, 2022c). Bioenergy can be produced from different feedstocks, which can be broadly categorised as follows:

- **First generation feedstock–- food and feed crops**: This encompasses sugar rich (e.g., sugarcane), starch rich (e.g., maize) and oily crops (e.g. rapeseed).
- **Second generation feedstock–- non-food oil crops and lignocellulosic biomass crops**: This encompasses non-food oil crops, such as Jatropha, and herbaceous (e.g., miscanthus) or woody (e.g. eucalyptus) biomass crops.
- **Third generation feedstock–- microalgal cultivation systems:** Those systems use algae to produce bioenergy. However, they are currently in development and have not been implemented at scale yet.
- **Agricultural and forestry residues:** Agricultural residues are, for example, sugarcane bagasse, cereal straws and stover, nut shells etc. Forestry residues include forest thinning, branches, leaves, etc.
- **Organic waste from primary industry and urban streams:** animal manure and food processing by-products, along with organics from municipal solid waste and wastewater treatment plants.

These feedstocks can then be converted into fuel, heat, or power through a variety of conversion processes that are presented in the Table 3 below.

Table 1 Technologies, end products and end uses of bioenergy feedstock (based on Lee et al., 2019).

Technology/ method	Description of technology/method	End product	Description of end product	End use
Combustion	Biomass feedstock is combusted to produce energy	n/a	n/a	Electricity, heat
Pyrolysis	Biomass feedstock is heated at a temperature of ~400-500 °C, in the (near) absence of oxygen	Syngas	Combination of hydrogen and carbon monoxide, in various ratios.	Electricity, heat, conversion into biofuel or methane to be used as a replacement for natural gas
		Bio-oil	Liquid fuel	Electricity, heat, powering engines, turbines etc.
Gasification	Biomass feedstock is heated at a temperature of ~700 C with a regulated amount of oxygen.	Syngas	Presented above	Presented above
Liquefaction	Conversion of wet biomass into bio-oil at a temperature of ~200-400 and under high pressure	Bio-oil	Presented above	Presented above
Anaerobic digestion	Microorganisms, in the absence of oxygen, break down biomass feedstock.	Biogas	Renewable gaseous fuel	Electricity, heat, powering vehicles

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[11] IEA 2022, Bioenergy, International Energy Agency, <https://www.iea.org/reports/bioenergy>.

Alcoholic fermentation	Sugars from biomass feedstock (e.g. sugarcane, wheat, corn) is broken down to produce ethanol	Bioethanol	Liquid biofuel	Powering vehicles
Photobiological hydrogen production	Microorganisms and sunlight are mobilised to turn water (and biomass feedstock) into hydrogen	Biohydrogen	Type of biofuel	Electricity, heat, powering vehicles
Transesterification	Chemical reaction that transforms fats from oils into biodiesel	Biodiesel	Biodiesel is made from combining ethanol with animal fat, recycled cooking fat, or vegetable oil.	Powering vehicles
Microbial fuel cell	Bio-electrochemical device that uses microbes to convert organic substrates (e.g. algae) into electricity	n/a	n/a	Electricity

Impacts

Existing studies in Europe, where biogas and biofuels have been widely disseminated, have found that the overall environmental impacts from construction and the demolition of biogas plants and biorefineries are small in comparison to feedstock production from agriculture (Hijazi et al., 2016). As a result, we will centre our discussion on the impacts related to raw material sourcing, and to a lesser degree on the construction, operation, and decommissioning phases.

Raw material sourcing

First generation feedstock: Food & feed crops

In addition to ecosystem related impacts, bioenergy created with food and feed crops were identified to have supplementary environmental effects. The use of food and feed crops for bioenergy is known to trigger a large amount of direct and indirect land use changes, which have the potential to threaten food security in some parts of the world (Koizumi, 2015; Renzaho et al., 2017; Rosegrant & Msangi, 2014) as well as to increase carbon emissions (Fargione et al., 2008; Searchinger et al., 2008). Food security can be affected when demand for bioenergy lead to food and feed crops being converted into bioenergy crops, which can reduce the availability of food at the local scale and increase food prices (Gasparatos et al., 2018). In some circumstances, first generation food and feed crops can release an equal amount of (or sometimes more) carbon than conventional fossil fuels (Holland et al., 2015), which are due, among other things, to land-use change and the adoption of agricultural practices that require the use of fossil fuels (e.g., use of fertilisers) (Gasparatos et al., 2018). Logically, clearing ecosystems that act as carbon sinks (such as peatlands, forests) would have long payback periods. For example, it was estimated that it would take 423 years to capture the carbon emissions released when peatland rainforests were replaced by palm oil cultivation in Indonesia and 319 years to do the same for tropical rainforests cleared for soybean production for biofuel in Brazil (Fargione et al., 2008).

Regarding ecosystems, a range of impacts were observed on habitat, wildlife, water (quality and quantity) and soil. The main potential impacts of first-generation bioenergy crops on habitat and wildlife are habitat loss and reduction of species diversity (notably species of high conservation concern), due to direct and indirect land-use change (native ecosystems are replaced by intensive cropping systems, or food crops are converted into energy crops and native ecosystems are then cleared to make space for more food crops) (Correa et al., 2017; de Andrade Junior et al., 2021; Di Fulvio et al., 2019; Gasparatos et al., 2018; Immerzeel et al., 2014) This has been witnessed in numerous highly biodiverse developing countries, notably Brazil. In contrast, this has not been the case in developed countries, where first generation bioenergy crops are primarily cultivated on agricultural land (Gasparatos et al., 2018). In some circumstances – when bioenergy crops are planted on degraded land – bioenergy crops could lead to an increase in biodiversity values, as they may bring about more structurally and functionally complex ecosystems (Correa et al., 2017). Additionally, some bioenergy crops, when situated in proximity to large tract of forests, may be of use to wildlife, as a source of food for example. However, this would only be the case if wildlife is not hunted when in those areas (Correa et al., 2017).

Another impact of bioenergy crops on habitat and wildlife is that they create the conditions for the arrival of invasive species. Alternatively, some bioenergy crops have the potential to become themselves invasive species. This is notably the case of rapeseed (Correa et al., 2017).

Various impacts on water quality and quantity were also identified, which can all vary depending on the type of crops and agricultural practices adopted. The production of first-generation feedstock may require high fertiliser and agrochemical use, which can lead to the pollution of aquatic ecosystems, notably by increasing the concentration of nitrate (Dominguez-Faus et al., 2009; Gasparatos et al., 2018; Taniwaki et al., 2017). Regarding water quantity, the cultivation of first-generation feedstock can lead to the diversion of water from natural ecosystems and other human uses (Dominguez-Faus et al., 2009; Gasparatos et al., 2018). This is particularly true of crops that require irrigation, such as sugarcane for example.

Finally, first generation feedstocks are likely to have impacts on soil. Again, the impact will depend on the specific crop and agricultural practices adopted (Correa et al., 2017; Gasparatos et al., 2018). The cultivation of intensive monocultures, such as corn or sugarcane can lead to soil erosion, due to bare soil being exposed to the elements. Additionally, agricultural practices can have impacts (Gasparatos et al., 2018). For example, excessive use of fertilisers can pollute soils with heavy metals, while tillage may increase erosion and affect soil properties. Soil degradation can then have a deleterious effect on aquatic habitat and wildlife, through eutrophication, sedimentation, and changes in the properties (physical or chemicals) of aquatic ecosystems (Correa et al., 2017).

Second generation bioenergy crops: Non-food oil crops and lignocellulosic biomass crops

Controversies around the competition between first-generation feedstock and food production, led some countries, including Australia, to redirect their efforts to second-generation feedstock–- that is non-food oil crops and lignocellulosic biomass crops. The rationale appears to be that they can be placed on marginal land – that is land that are not productive and where farming would not be cost-effective, which could avoid negative effects on food production. However, this overlooks the fact that marginal land can provide a range of ecosystem services (Pulighe et al., 2019). Therefore, the development of second-generation feedstock, even on marginal land, can lead to negative impacts on ecosystems.

With regard to habitat and wildlife, several studies found that second-generation feedstocks appear to have less impacts on habitat and wildlife than first generation feedstocks (Immerzeel et al., 2014; Núñez-Regueiro et al., 2021; Tudge et al., 2021). However, the development of second-generation feedstock still involves the conversion of natural ecosystems, which leads to habitat loss (Gasparatos et al., 2018; Littlejohn et al., 2015) and a loss in species abundance and diversity. Tudge et al. (2021), synthesising the data from 116 sources, found that second-generation feedstocks were leading to a 19% reduction in species richness and 25% reduction in species abundance. Additionally, some lignocellulosic biomass crops, such as miscanthus and switchgrass have the potential to become invasive species (Gasparatos et al., 2018).

However, second-generation feedstocks–- particularly lignocellulosic biomass crops – also have the potential, in some circumstances, to positively impact habitat and wildlife. They can provide habitats for birds and insects, enhance connectivity between habitats and play the role of a buffer for areas that may have high conservation value, such as riparian areas (Gasparatos et al., 2018; Pulighe et al., 2019). It is important to remember that second-generation feedstocks are likely to play that positive role only if they do not displace native vegetation (Gasparatos et al., 2018)

The impacts of second-generation bioenergy crops on water quantity and quality are often discussed in comparison to first-generation bioenergy crops. Concerning water quantity, findings appear to diverge. Indeed, in some cases second-generation bioenergy crops are presented as having a similar water use efficiency as first-generation bioenergy crops but higher evapotranspiration, which could have negative impacts on water, particularly in dry areas (Holland et al., 2015). This is the case of miscanthus for example. In other cases, second-generation bioenergy crops can be seen as conserving more water than first-generation crops, because they do not necessarily require irrigation (Gasparatos et al., 2018). For example, rainfed jatropha would require less water than irrigated monocultures of sugarcane. It is also important to note that the impacts of second-generation feedstocks on water quantity will also depend on the hydrological situation of the area where they are located and the density of the plantation (Gasparatos et al., 2018). For example, a dense plantation of jatropha in a dryland area, which would normally be sparsely vegetated, would affect water quantity available for other uses in the area. Regarding water quality, the main advantage of second-generation bioenergy crops over first-generation is that they are likely to require less fertiliser and pesticide use, with a positive impact on water quality (Gasparatos et al., 2018; Holland et al., 2015).

Finally, when it comes to soil, some second-generation bioenergy crops are linked to potential or demonstrated soil related benefits, such as erosion control, enhanced soil structure and pH and improved water retention capacity and microbial presence in the soil (Gasparatos et al., 2018; Pulighe et al., 2019). While some of those benefits have been the subject of quantification – e.g., in an experimental farm in Italy, Miscanthus and giant reed were shown to have increased carbon accumulation in the soil–- (Pulighe et al., 2019), others do not – e.g., erosion control (Gasparatos et al., 2018). Additionally, second-generation bioenergy crops have been found to have the potential to improve soil on land contaminated with heavy metals or organic pollutants and avoiding leaching into groundwater (Pulighe et al., 2019).

Third generation bioenergy crops: Microalgal cultivation systems

A third generation of bioenergy crops is emerging: microalgal cultivation systems. Like for second-generation bioenergy crops, the impacts of the third generation are often analysed in comparison to the first-generation. Third generation energy crops are still in an incipient state and have not been deployed at a large scale. As such, it is not always easy to ascertain what their impacts will be. However, it is anticipated that overall, they are likely to have a lesser impact on ecosystems than first-generation bioenergy crops. A review of the literature on the biodiversity impacts of microalgal cultivation systems provided the following insights on the impacts of microalgal cultivation systems on land, soil and water and ecosystems (Correa et al., 2017):

- The microalgal cultivation systems require less land than first generation bioenergy crops, which means that they are likely to lead to a lower loss of habitat. Additionally, microalgal cultivation systems can be installed in marginal land, which do not compete directly with food production. This would lead to less competition for land and less indirect land-use change (bioenergy crops compete with food production crops, which then lead to clearing of native vegetation for food production). However, as mentioned in the previous section, marginal land can have high habitat value and be important to wildlife. The development of microalgal cultivation systems on marginal land would therefore not fully avoid impacts on habitat and wildlife. Additionally, if the growth medium used in the microalgal cultivation systems found its way to natural water ecosystems, microalgae could become invasive species. However, the likelihood of this happening could be limited if native microalgae are used and if the water used in the production system is recycled.
- Microalgal cultivation systems are likely to have less impacts on soil – notably soil erosion – than first-generation bioenergy crops. However, these systems require the construction of pounds, which could lead to soil erosion, compaction and altered soil properties. Such impacts could be limited if ponds are built in elevation, limiting soil disturbances.
- Finally, microalgal cultivation systems are likely to have less impacts on water quality and quantity than first-generation bioenergy crops, because they can use water from wastewater treatment systems or seawater. Secondly, pesticides do not need to be used in those systems, and while fertilisers are used, notably nitrates, ammonium and phosphate, run off can be controlled, which limits the likelihood of impacts on water ecosystems.

Agricultural and forestry residues for bioenergy

Increasingly, agricultural and forestry residues are being considered as feedstock for bioenergy. Residues can be defined as what is left once agricultural or forestry products have been harvested.

Agricultural residues

One of the perceived advantages of using residues is that they would not directly compete with food provision, which was one of the main concerns around first-generation bioenergy crops. However, crop residues play critical role inmaintaining and enhancing soil properties. As such, the removal of agricultural residue for bioenergy use must be managed carefully and sustainably. Indeed, the excessive removal of agricultural residue for bioenergy can reduce the productive capacity of the soil on agricultural land (Muth et al., 2013). Cherubin et al. (2018) describe how the harvesting of crop residues can impact soil. Firstly, harvesting crop residues can lead to a diminishing availability of nutrients in the soil. In the long term, this may lead to a need to use more synthetic fertilizers on the land. Secondly, it can also negatively affect soil structure, due to a decrease in carbon input in the soil and increased use of machinery in the field to collect and harvest residues. This can then lead to soil compaction, which, in turn, will make the soil less porous and able to store water, and hinder root penetration. Additionally, the absence of residue protecting the soil means that it will be more likely to be subject to soil erosion. Thirdly, agricultural residues can also play a role in maintaining and enhancing the soil biota and controlling the presence of pests and diseases in the soil.

Forestry residues

A review of the literature conducted by Ranius et al. (2018) provides insights on the impacts of the removal of stumps and slash on habitat, wildlife, water, and soil:

- Three types of impacts on habitat and biodiversity are hypothesised: i) loss of habitat for dead wood dependent species, ii) disturbance of the understorey vegetation, and iii) impacts on ground-living organisms. It appears that the removal of slash and stumps can negatively affect dead wood dependent species by leading to a reduction in population densities. The authors suggest that there most likely exists a threshold above which the removal of stumps and slash could trigger the disappearance of species in the areas harvested. However, they also mention that dead wood dependent species are also likely to use other dead wood categories. As a result, they explain that conserving native forests may sometimes be a more effective conservation strategy than avoiding the removal of forestry residues. Regarding the effects of slash and stump removal on understory vegetation and on ground-living organisms (not necessarily dead-wood dependent), studies found contradictory results (positive, negative, or neutral), which indicates that impacts may vary according to local conditions.
- Concerning impacts on soil and water, the removal of stump and slash can lead to nutrient depletion – notably nitrogen and phosphorus – however this does not appear to be always the case. Additionally, the removal of stump (but not of slash) generates soil disturbance, which is sometimes associated with higher level of nutrients (notably nitrogen) being found in runoff water than for stem-only harvest. The increased presence of nutrients in water ecosystems can, in turn, impact aquatic biodiversity. However, those impacts are highly variable and site specific. Finally, slash extraction has been associated with soil and water acidification and an increase in aluminium concentration.

While the removal of forestry residues can have negative impacts on ecosystems, there are circumstances where it can generate positive impacts on ecosystems. For example, an ecological restoration project in South Africa found that removing invasive species present on the site for bioenergy production would contribute to restoring the landscape, while offsetting the costs of the restoration project (Reid et al., 2020). Additionally, practices, such as forest thinning may reduce the risk of wildfires. As such, using the wood from thinning as bioenergy can lead to positive ecosystem outcomes (Reid et al., 2020).

Organic waste from primary industry and urban streams

Organic waste from primary industry and urban streams, which notably include animal manure food processing by-products, sewage sludge or domestic organic waste (e.g., food waste, garden waste), is increasingly being considered as a feedstock for bioenergy production, using anaerobic digestion. One reason that may explain the interest for organic waste is that they do not lead to direct large scale land use-change and do not directly compete with food production (Tufvesson et al., 2013). As such, they are also less likely to negatively impact ecosystems. Additionally, they may also reduce some of the negative impacts associated with some of this organic waste ending up in landfill, notably food waste. Indeed, leachate from landfill can contain toxic substances that can be released in water run-offs (Hafid et al., 2022).

However, it is important to understand how the use of organic waste for bioenergy production may indirectly create impacts by diverting some organic waste from their previous use. For example, studies by van Stappen et al. (2016) and Tufvesson et al. (2013) found that some of the organic waste that was used as feed in the past was now used as feedstock for bioenergy. As a result, additional agricultural land was required to produce feed for animals. The expansion of agricultural land could lead to negative impacts on habitat, wildlife, water, and soil. It is therefore essential not to use organic waste that is already having a function, notably as animal feed.

Additionally, concerns are also raised by some that the use of organic waste, specifically animal manure, can diminish the carbon input into the soil, as manure that would usually be used as agricultural input is being diverted to bioenergy production (Hoang et al., 2022). This loss in carbon input may be compensated by the use of residues from anaerobic digestion (i.e., digestate) as a fertiliser. However, uncertainties still surround the use of digestate on soil function and structure (Uddin et al., 2021).

Construction & installation

Construction of bioenergy plants can impact directly and indirectly on local biodiversity. Direct impacts can be caused by destruction and disturbance from human activities, such as native vegetation clearing, and habitat loss for specific flora and fauna species. Indirect impacts can occur during construction activities due to sedimentation and erosion, pollution, contaminated run-off (particularly as a result of leaks or spills from vehicle or equipment) and the introduction of weeds (Jemena & Sydney Water, 2021).

During construction, biogas generation from WWTPs also can impact surface and ground water quality via sediment or soil runoff, or accidental fuel or chemical spills from plants and equipment (Jemena & Sydney Water, 2021).

Operation

During operation, bioenergy plants have the potential to impact on surface and groundwater. Poor implementation, such as the safeguards that are in place to deal with hazardous events and the operation of these facilities, can lead to the contamination of groundwater and surface water supplies, as well as causing unwanted methane (CH4) emissions/leakage and chemical spills (Jemena & Sydney Water, 2021).

A study from Germany reported that biogas plants using agro-industry organic waste can release heavily contaminated stormwater from silage effluent in silo facilities in a storm event (Cramer et al., 2019). Silage effluent contains a large concentration of organic components (expressed in biochemical oxygen demand (BOD)), which remove oxygen in the watercourse to kill aquatic ecosystems. On a related and positive note, with proper implementation processes in place, biogas production at WWTPs can also reduce oxygen levels in wastewater, reducting eutrophication impacts on downstream waterways (Shao et al., 2021).

Additionally, there has been documentation of the impact of bioenergy on GHG emissions (Paolini et al., 2018), air contaminants, local noise and odour (e.g. from animal manure-produced gas) (Gittelson et al., 2021; Thrän et al., 2020).

Decommissioning

No information identified.

Mitigation and conservation strategies

The sourcing of raw material is the phase of bioenergy production that is likely to have the highest impacts. As such, our discussion of mitigation and conservation strategies will mainly focus on it, with a shorter discussion on construction and operation related impacts. Due to the variable nature of bioenergy production, this section is structured differently from the other mitigation and conservation strategies. It is firstly structured around the project phases, and within that, we discuss the four themes: habitat and wildlife protection and vegetation management, land surface, soil alteration and resource use, reuse and recycle. For the raw material sourcing phase, those themes are discussed separately for each type of feedstock.

Raw material sourcing

Based on our discussion of impacts, it appears that agricultural and forestry residues, waste-based feedstock and–- to a lesser degree–- second-generation bioenergy crops are preferred to first-generation bioenergy crops, as they are likely to have less impacts on food production (and food security), as well as ecosystems (habitat, wildlife, water, and soil). Additionally, third-generation bioenergy crops are emerging as a potentially less impacting practice. As such, we could argue that, as a general rule, it would be preferrable to prioritise the use of agricultural and forestry resides, waste-based feedstock and – to a lesser extent – second-generation bioenergy crops to first-generation bioenergy crops. However, we acknowledge that the use of a diversity of feedstock types may be necessary and that ways to mitigate impacts should be explored for each of them.

First-generation feedstock: Food & feed crops

Habitat and wildlife protection

To reduce impacts on habitat and wildlife, an integrated land-use approach can be used to identify areas where the development of bioenergy crops will have the least impact on habitat and wildlife. This approach was used by de Andrade Junior et al. (2021) in Brazil. Using geographical information on land-cover, above ground carbon stocks, near-threatened and threatened terrestrial vertebrate species, agricultural suitability, and proximity to road infrastructures (less than 5.5 km), they developed two scenarios for the development of first-generation bioenergy crops: a conservation-considered planning scenario and a conservation blind planning scenario, where agricultural expansion is prioritised. In the former, agricultural expansion occurs in areas that are suitable for agricultural use, are close to road infrastructure and have the lowest impact on biodiversity. In the latter, agricultural expansion occurs in a way that minimises costs and maximises profits. It was found that the conservation-considered planning scenario was dividing by two the number of species negatively impacted by the expansion first-generation bioenergy crops. However, the authors note that, even under this scenario, the impacts of bioenergy expansion on biodiversity remained high.

Resource use (reuse and recycle) & soil alteration

Strategies can be adopted to reduce the use of water and minimise impacts on soil (and habitat and wildlife), which are the prioritisation of crops that need less water and agrochemical input (Miyake, 2015), and the adoption of best land management practices production (Waterhouse et al., 2012). For example, soybean may be adopted instead of maize, as they require less fertilisers and pesticides. Some suggest that the adoption of less impacting production systems and best practice land management could be incentivised through payment for ecosystems services (PES) (Gasparatos et al., 2018). PES have been widely adopted in some parts of the world (e.g., Costa Rica), however their effectiveness in maintaining and enhancing ecosystems services is debated.

Second-generation bioenergy crops: Non-food oil crops and lignocellulosic biomass crops

Habitat and wildlife protection & soil alteration

Second-generation feedstocks, particularly lignocellulosic biomass crops, have the potential contribute to the restoration of ecosystems. They can have a positive impact on habitat and wildlife by contributing to the restoration of habitat, which can positively impact wildlife. Indeed, when they are planted in degraded landscapes or areas dominated by monocultures, lignocellulosic biomass crops can enhance the habitat value of the landscape (Gasparatos et al., 2018; Pulighe et al., 2019). They can also play a role in improving soil quality on contaminated land and controlling erosion (Gasparatos et al., 2018; Pulighe et al., 2019). As such, for second-generation bioenergy crops to have a positive impact, degraded or monocultural landscapes, contaminated land as well as land with erosion control issues should be prioritised.

Similarly, to the integrated land-use approach presented in the section above, assessments of the impacts of a transition to second generation bioenergy crops on ecosystems services can be conducted. This was done by Holland et al. (2015) in England, where they assess the impacts on ecosystems services (including water quality and availability and soil quality) of the transition of arable, semi-improved grassland or woodland to second-generation bioenergy crops using a threat matrix.

Third-generation bioenergy crops: Microalgal cultivation systems

Habitat and wildlife protection & land surface

While microalgal cultivation systems do not have a neutral impact on habitat and wildlife, they appear to constitute an opportunity to reduce habitat and wildlife impacts in comparison to first and even second-generation bioenergy crops because they require much less land to produce the same amount of bioenergy (Correa et al., 2017). Additionally, they are also less likely to pollute aquatic ecosystems as they do not require the use of pesticides and are able to control run off, meaning that nutrients from fertilisers are less likely to leak into the environment (Correa et al., 2017).

Resource use (reuse and recycle) & soil alteration

Regarding resource use (water) and soil alteration, microalgal cultivation systems can be designed in a way that reduces water and soil related impacts (Correa et al., 2017). They can notably use recycled wastewater, which means that they would not withdraw groundwater, and build elevated ponds, which would limit soil erosion.

Agricultural and forestry residues

Habitat and wildlife protection

The removal of forestry residues – notably stumps – has the potential to impact (dead wood dependent) species (Ranius et al., 2018). As a result, determining the threshold above which the removal of forestry residues will result in a reduction of population densities and potentially, a disappearance of the species in the area. Identifying this threshold would reduce the risk of having an irrevocable impact on those species at the local scale.

In some circumstances, the removal of forestry residues can contribute to the restoration of ecosystems. For example, thinning can be used to minimise fire risks and its impacts on habitat and wildlife. Similarly, invasive species can be used as bioenergy crops. Identifying cases where the removal of forestry residues (or plants) can play a positive role for habitat and wildlife would lead to this practice having a restorative role (Reid et al., 2020).

Soil alteration

Two strategies were identified to reduce the impacts of the removal of agricultural on soil (Cherubin et al., 2018). Firstly, impacts on soil can be minimised by only collecting the part of the residue that contains the smallest amount of nutrient. In the case of sugarcane, it would be the dry lower leaves for example. This would mean that the nutrient rich part of the plant would remain in the field. However, no information was provided on the feasibility and cost-effectiveness of such a practice. Secondly, best practice land management can be adopted to reduce the impacts of the removal of residues on the soil. This can include: no-tillage, crop rotation, use of annual or perennial cover crops, manure or other organic amendments.

Organic waste from primary industry and urban streams

Land surface

Organic waste from primary industry and urban streams has the potential to lead to indirect land-use change (and impacts on habitat, wildlife, water and soil) if organic waste that was used for animal feed is diverted to bioenergy production. As such, ensuring that organic waste that already has a function – as animal feed for example – is not used for bioenergy production would avoid or reduce these kinds of trade-offs.

Construction and installation (and operation)

Habitat and wildlife protection & soil alteration

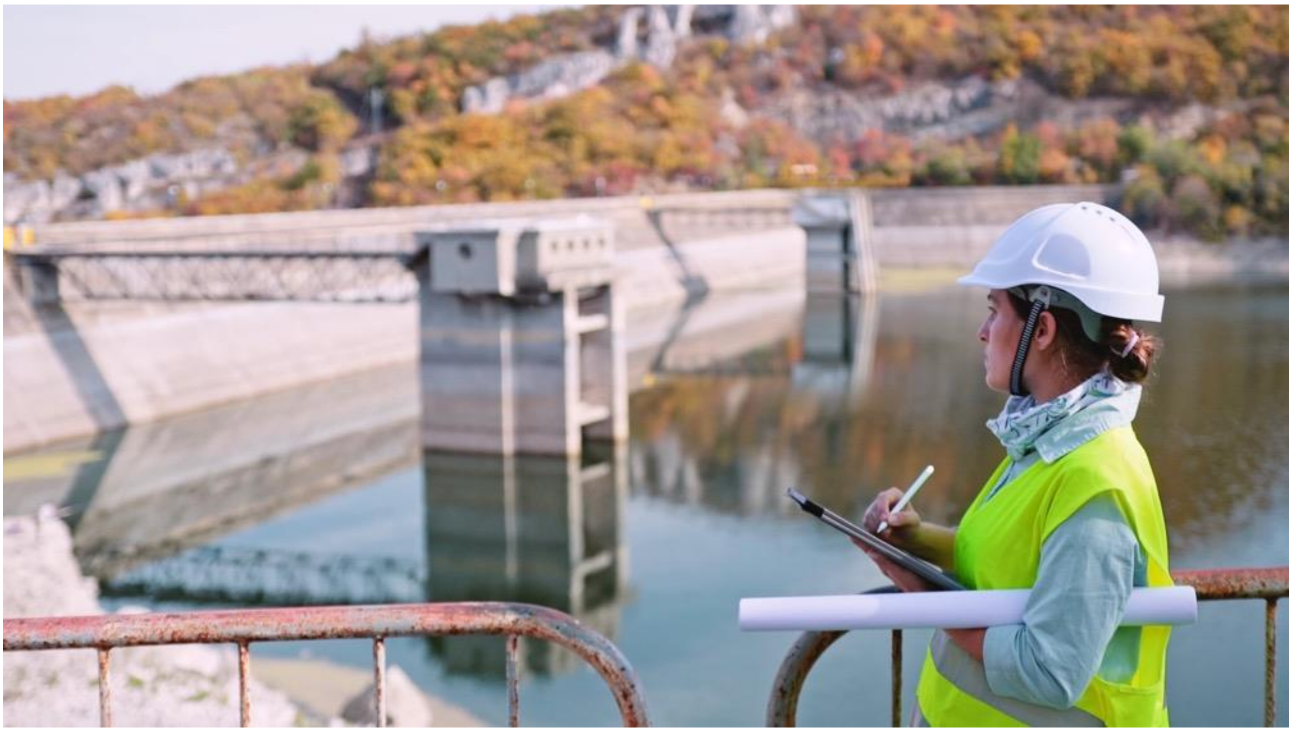
Bioenergy projects require careful planning and consideration of local flora and fauna. For instance, the planned biomethane proposal at Malabar WWTP in Sydney includes safeguards for construction and operation stages to minimise impacts to flora and fauna. Some of these safeguards include minimising vegetation clearance and disturbance; placing signage around the site to identify vegetation that is to be cleared and/or protected; protecting trees in accordance with government regulations; managing invasive plant species, like weeds; and, identifying native fauna when it is encountered on site and stopping work to allow it to move away (Jemena & Sydney Water, 2021).

From an operational perspective, to avoid the contamination of groundwater and surface water, plant operators need to put safeguards in place for the hazardous events, including an improved stormwater management on site. For example, the proposed biomethane project in Malabar WWTP, Sydney, includes environmental safeguards to minimise risks, especially for surface and groundwater quality. Some of these safeguards include storing potential contaminants on robust waterproof membranes, away from drainage lines; storing all chemicals and fuels in accordance with relevant Australian Standards and Safety Data Sheets; conducting equipment wash down within a designated washout area; and, monitoring the weather forecast to ensure soils and stockpiles are covered where practicable during rain events (Jemena & Sydney Water, 2021).

Decommissioning

No information identified.

Hydropower



Hydropower is one of the world's oldest forms of electricity generation and still contributes more to the global electricity supply than all other renewables combined - one sixth of all global electricity production in 2021, helping supply 1 billion people with clean electricity (Clean Energy Council, 2021; International Energy Agency, 2021). In recent years, however, hydropower's growth rate has been just one third of what is required to reach the International Energy Agency's *Net Zero Emissions by 2050 Scenario* and almost 40 per cent of the global hydropower fleet is aging to the point where major refurbishments will be necessary[12]. The International Energy Agency (2021) labelled Hydropower as the 'forgotten giant of low-carbon electricity'.

In Australia, there is 8.5 GW of hydropower assets currently in operation across the country (Clean Energy Council, 2021). Few hydropower projects have been developed in Australia without substantial government support, with only 2 projects with a capacity of 2.3 GW progressing to financial commitment since 2017. The major hydropower projects that are currently under construction in Australia are pumped hydro energy storage (PHES) projects, including Snowy 2.0 in NSW and Battery of the Nation in Tasmania (Clean Energy Council, 2021). PHES projects, expected to increase significantly in the future, vary significantly in terms of their size and design, which affects the extent of their impacts on biodiversity and ecosystems.

There are several concerns about hydropower's environmental impacts. These relate to the way that it alters the flow patterns of rivers and results in large changes to river landscapes and ecology; its impacts on freshwater ecosystems that are associated with damming, reservoir creation, and flow patterns; its potential effects on water quality and the release of biogenic GHG emissions[13]; and how it can cause the displacement of local communities who are forced to move from regions where the developments take place (UNEP, 2016), such as the enormous 22,500 MW Three Gorges Dam in China which displaced over a million people from their communities along the Yangtze River (Gan, 2020). One project in Australia that has generated a lot of concern recently is Snowy 2.0. for the impacts it will have on native fish populations and the pollution it will cause to freshwater systems (Harris & Lintermans, 2020).

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[12] Major refurbishment investments are required for hydropower plants when they reach between 45 and 60 years old to modernise them, improve performance, and increase their flexibility (International Energy Agency, 2021).

[13] The emissions that arise from the decomposition of organic matter (e.g., woodlands or aquatic vegetation) that was flooded during reservoir/dam construction, transferred by river runoff, or has grown in reservoirs/dams (e.g., algal production) (Scherer & Pfister, 2016).

There are also a significant set of measures that can be undertaken to refrain, reduce, restore and renew environmental impacts, including using brownfield sites for reservoirs, water flows management, establishing passages for fishes and revegetation.

Description of technologies

Hydropower uses the energy of moving water to generate electricity. Water flows, usually from a reservoir or dam, pass through a turbine which converts the water's motion into electrical energy. Depending on geographical constraints, the three main hydropower technologies include storage hydropower, run-of-river hydropower, and PHES[14].

Storage hydropower relies on large volumes of water that is stored in a reservoir using a dam system. Electricity is generated when water from the reservoir is released and passes through the turbine. Storage hydropower provides a continuous supply, a dispatchable resource that can be shut down and started up with limited delays according to the demands of the grid, and can store enough energy capacity to operate independently for weeks and even months (International Hydropower Association, n.d.).

Run-of-river hydropower channels the water from a river system through a canal or penstock to spin the turbine. This technology will have little or no storage capacity but has some operational flexibility, depending on daily fluctuations in electricity demand by controlling the water flow through a facility.

PHES systems cycle water from a lower reservoir to an upper reservoir through pipes and tunnels at different times depending on energy demand. During periods of surplus energy, when demand is low, water is pumped from the lower reservoir to the upper reservoir. When demand is high, the water is then released through a turbine to generate electricity. PHES projects vary significantly in scale, with projects like Snowy 2.0 lying on the larger end of the spectrum compared with some mini-pumped hydro systems, like the 1.5 megawatt PHES project under construction in Walpole, Western Australia (Mercer and Bennett, 2021).

Impacts

Construction and installation

During construction hydropower technologies can have a range of impacts on water, soil, habitat, and wildlife. Assessing these impacts can be complex because they largely depend on the specific project, technology, and environmental context. For instance, water quality impacts are more prominent in large-scale hydropower plants, with the negative effects of small-scale plants stabilising with time (Gasparatos et al., 2017; Valero, 2012). These differences should therefore be weighed when considering the environmental impacts of hydropower.

The construction of hydropower infrastructures has the potential to significantly alter water flow, nutrient cycles, and sediment loading, along with the movement of aquatic species (Gasparatos et al., 2017; UNEP, 2016; Van Den Berg et al., 2001; Zhang et al., 2022). Those alterations can lead to numerous and inter-connected impacts, which can sometimes be amplified by climate change. Some of the potential impacts of hydropower infrastructures are as follows:

- Large quantities of soil and rocks are moved during the construction process (UNEP, 2016), which can lead to soil destabilisation (Normyle & Pittock, 2019). Additionally, some rocks and soil may be dumped in water (Normyle & Pittock, 2019), which can lead to acid and asbestos pollution (Harris & Mcphail, 2006; Harris & Lintermans, 2020) and alter sedimentation, which will in turn affect wetlands (Normyle & Pittock, 2019). Additionally, it can lead to the introduction of exotic species (Normyle & Pittock, 2019).

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[14] Offshore hydropower is another technology that harnesses tidal currents or waves from the ocean to generate electricity (International Hydropower Association, n.d.). However, as it is less established and still relatively nascent compared with the other technologies, it is not a focus of this report.

- Changes in nutrient cycles and sediments loading can lead to eutrophication[15] (Gasparatos et al., 2017; Van Den Berg et al., 2001), notably in the reservoir, while sediments may be lacking downstream, which can deprive some species of habitat or spawning ground (UNEP, 2016).
- The combination of a drop in the velocity of water and the increased depth of the reservoir can lead to thermal stratification (UNEP, 2016), which means that the surface water, due to the action of the sun, becomes warmer and less dense than the deeper water, which is cooler, denser and receives less oxygen (Victorian Fisheries Authority, 2022).This has been shown to affect water quality in drinking water reservoirs (Qu et al., 2018).
- The use of gravel – which is relatively impervious – for road access can increase run-off during rainfall events, which can in turn worsen soil erosion and lead to the accumulation of contaminants in sedimentation areas (Van Den Berg et al., 2001).
- All the impacts described above are likely to impact fauna and flora. In addition, hydropowers infrastructures can flood large areas, fragment habitat and prevent the migration of fish – notably due to damming – sometimes leading to extinction or risk thereof (Gasparatos et al., 2017; UNEP, 2016; Van Den Berg et al., 2001; Zhang et al., 2022). Additionally, hydropower infrastructures can connect water bodies that were previously separated and lead to the introduction of invasive species, creating competition for habitat and food (Harris & Lintermans, 2020). See Box 18 below for examples of concerns around invasive species at Snowy 2.0. Furthermore, dams and reservoirs can prevent seasonal flooding events from happening, which reduces the flow of nutrients to flood plains. This reduction in nutrients impacts ecosystems and species that rely on regular flooding for important lifecycle processes to occur (Kunz et al., 2011). Inversely, dams and reservoirs can also create new habitats for some bird species by replacing wetland lost to agriculture, however with lower biodiversity values (Kumar et al., 2011; UNEP, 2016)

Box 18: Concerns around invasive species at Snowy 2.0.

In Australia, one concern with the Snowy 2.0 project is that highly adapted native species such as climbing galaxias, which can climb wet vertical surfaces, will threaten other native species, like the stocky galaxias that are unable to climb (Harris & Lintermans, 2020). There is also the risk of disease spreading from dominant and alien fish species to vulnerable native species. It is also feared that the invasive redfin perch, which are widespread throughout the cooler waters of NSW and Victoria, will spread a disease that kills will the endangered Macquarie perch, located below the Tantangara reservoir in the Kosciuszko National Park, NSW (Harris & Lintermans, 2020).

Operation

Water flow regime changes are one of the main operational impacts from hydropower and can have widespread effects on habitat and wildlife. Hydropeaking, for example, is a common practice with storage hydropower plants that can impact downstream alpine fish populations. Hydropeaking is the process whereby turbined water is suddenly released during periods of peak energy demand, causing artificial flow fluctuations downstream from the plant (Greimel et al., 2018; Person et al., 2014). These hydrological impacts can directly and indirectly affect riverine species and communities, such as fish, insects, invertebrates, and plants. For instance, it has been reported that species such as the brown trout have become less abundant in alpine rivers due to hydropeaking. The fluctuation in water requires the fish to invest a lot of energy to avoid being pushed downstream, and spawning areas are displaced or lost. This can reduce natural reproduction and the survival of young trout, causing a drop in population sizes (Greimel et al., 2018; Person et al., 2014).

Mitigation and Conservation Strategies

Habitat and wildlife protection

Planning

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[15] Eutrophication can be natural or caused by human activities. It occurs when a water source becomes overly enriched with nutrients and minerals such as phosphorus and/or nitrogen. This often leads to harmful algal blooms, dead zones and fish kills (US Department of Commerce, n.d.).

As with other renewable technologies, impacts from hydropower can often be mitigated by refraining from harmful planning and siting decisions. Many of the impacts from hydropower can be linked to storage and run-of-river hydropower plants that cause the flooding of ecosystems and drastically change water flow regimes (UNEP, 2016). Some PHES projects (e.g., off-river PHES), on the other hand, can be constructed in existing or artificial reservoirs, such as old mining sites ('brownfield sites'), which significantly reduces the adverse impacts on biodiversity from damming (Blakers et al., 2021). A recent example of this is the 250MW Kidston Pumped Storage Hydro Project in Far-North Queensland, which is being constructed on an old gold mine. The Kidston project is unique in that it is a hybrid project that combines a PHES system with solar and wind energy units. It is expected to be operational in early 2025 (Louloudis et al., 2022; Richards, 2022).

Construction and installation

Several design and construction measures have been developed to reduce the impacts of hydropower infrastructure on migratory fish species:

- Gateways, such as fish ladders, enable fish to access to upstream waterways in storage hydropower (Wollebæk et al., 2011). Upstream passage is also provided to fish species in run-of-river plants through natural bypass channels, rock ramps and engineered structures (Anderson et al., 2015; NSW Government Department of Primary Industries, n.d.).
- Downstream passes, such as spillways or screened surface bypass collectors, are normally highly engineered structures in storage hydropower. However, it is also possible for 'nature-like' bypass channels to prove functional as they mimic the structure of natural streams and are more economical compared with other fishway designs (Anderson et al., 2015; NSW Government Department of Primary Industries, n.d.). Run-of-river hydropower plants have also been constructed with passages to allow fish to pass through the turbine as they move downstream (Deng et al., 2010).

Hydropower management fields, including the management of instream flow, reservoirs, bedloads, and the structure of the power plant, can also reduce ecological impacts. This may involve constructing infrastructure like fish passages, using fish-friendly turbines, and the restoration of segments of the stream or river system (Hastik et al., 2015). In the case of hydropeaking, retention basins can be constructed that increase the minimal base flow, reduce flow fluctuation and amplitude rates, as well as incorporating drainage systems via side channels that can create a stabler flow and restore riverine ecosystems (Greimel et al., 2018). Artificial boulder-field creation can also restore habitats for endangered species (Schulz & Wilks, 2017).

Operation

In the case of run-of-river hydropower schemes, adjustments can be made to the environmental flow regime during operation to reduce impacts on riverine systems and habitats. This would include stipulating a minimum river flow requirement, as well as simulating seasonal floods events, to allow the sediments necessary to the lifecycle of various species, to be moved downstream species (Anderson et al., 2015). These adjustments would only have a small impact on power generation (UNEP, 2016).

'Flow splitting' is another measure that can reduce the impacts on water regimes and habitats. Run-of-river hydropower schemes involve 'abstracting' the river water to turn a turbine and generate electricity. Abstraction is a general term that refers to the process of physically taking and using water from any natural water source, including a river, lake, aquifer, stream or spring (Bureau of Meteorology, n.d.). When run-of-river plants are operating, the flow abstraction can be proportionally split between the flowing river channel and the water running through the hydropower plant. This promotes a more natural flow regime. Additionally, operation can be ceased during key stages of fish life cycles (Anderson et al., 2015).

To reduce the impacts of hydropeaking, several measures can be implemented, such as increasing the minimum base flow, and reducing flow fluctuation rates, amplitude and frequency (Greimel et al., 2018). To restore the habitats and wildlife impacted by hydropeaking, river and stream channels can tributaries can be reconnected, and the period that surfaces are permanently wetted can be increased (Greimel et al., 2018).

Soil alteration

Construction and installation

One approach that has been adopted in Australian alpine regions to mitigate the negative impacts of hydroelectric schemes on soil is to use native species to revegetate and restore the soil that was disturbed during the construction process. Prior to this, bare soil created by disturbances was stabilised by applying an exotic seed mix and fertiliser, with little regard to the invasive properties of these exotic species. As a result, there has been a considerable increase in the cover and number of native species (McDougall, 2001). The growth of locally dominant native species was implemented at sites within the Kosciuszko National Park that were affected by the construction of the original Snowy Scheme (MacPhee & Wilks, 2013). Additionally, the re-establishment of vegetation cover has been implemented to protect endemic fauna (Pickering et al., 2007).

Green Hydrogen

Currently, the bulk of hydrogen is produced using fossil fuels (IEA, 2022a). Green hydrogen is a ‘clean fuel’ because when it is consumed in a fuel cell it only releases water, and it is produced using renewable energy. Hydrogen could be an alternative energy source for domestic consumption and decarbonise Australia’s energy exports when converted to hydrogen derivatives such as ammonia. The World Energy Council has identified Australia as a “giant with potential to become a world key player” in the export of synthetic fuels (World Energy Council, 2018).

However, green hydrogen is a technology that is still in its infancy which means that existing projects are mostly small-scale and at the pilot stage (Moreno et al., 2020). As a result, literature on its impacts on water, soil, habitat, and wildlife is scarce. Nonetheless, there are several technical reports that provide insights on green hydrogen’s impacts on natural environments (Heinemann et al., 2021; Moreno et al., 2020), especially in the mining of metals for electrolysers and the large consumption of water in operation.

Hydrogen could drive large-scale demand for new renewable energy which add to the pressures of managing the environmental impacts of large-scale renewable energy covered already.

Description of technology

Green hydrogen has a wide range of applications: it can be used as a fuel source for transportation, an industrial chemical feedstock for products such as fertilizer and ammonia, it can blend with or replace natural gas to power homes and industry, store energy and generate electricity for mines and remote communities (DCCEEW, n.d.- a; Dincer, 2012).

Hydrogen is categorised using different colour codes based on the fuel sources (National Grid Group, n.d.):

- Grey hydrogen is made with fossil fuels, such as coal or natural gas.
- Blue hydrogen is also produced using fossil fuels, but the CO_2 emissions are sequestered using carbon capture, utilisation, and storage (Energy Education, n.d.). However, while blue hydrogen is considered a ‘low carbon’ option, greenhouse gas emissions from producing blue hydrogen can result from methane leakage from gas extraction and transport (Howarth & Jacobson, 2021).
- Green hydrogen is produced by splitting water (H_2O) into hydrogen (H_2) and oxygen (O_2) through a process called ‘electrolysis’ and powered by renewable energy sources (mainly wind and solar).

Impacts

Raw material sourcing, processing and manufacturing

One source of environmental impact arises from the raw material sourcing and mining activities undertaken to produce the electrolysers (nickel and zirconium) as well as the fuel cells used in vehicles powered by hydrogen (copper and platinum group metals (IEA, 2022b):

- Nickel is ideal for hydrogen electrolysers due to its high abundance and low costs (Angeles-Olvera et al., 2022), but producing nickel is an energy intensive process and generates large amounts of solid wastes, namely smelter slags and leaching residues, which can contaminate soil, and surface- and ground-water if they are handled improperly (Bartzas et al., 2021). On Obi Island, Indonesia, near the country's largest nickel mine, drinking water has become too dangerous to drink for local communities because it is highly contaminated by a carcinogenic chemical called hexavalent chromium (Firdaus & Levitt, 2022).
- The environmental impacts of zirconium have not been studied in great detail, but if it seeps into and contaminates soil it has been reported to negatively impact soil-plant systems (Shahid et al., 2013), and microorganisms such as algae if it contaminates freshwater systems (Doose et al., 2019).
- Copper mines have a particularly bad track record for toxic impacts. Copper contaminates soil and accumulates in plants and animals (Lenntech, n.d.). If copper sulphide enters waterways, it can contaminate drinking water aquifers, cause public health problems, kill fish and other wildlife, and destroy habitats (Earthworks, n.d.).
- Platinum group metals ore grades are relatively low, meaning that the majority of ore becomes waste rock and tailings, which can impact waterways from tailings dam failures, the disposal of tailings in riverine or marine ecosystems, and from ongoing acid drainage (Mudd, 2012; Glaister & Mudd, 2010).

Construction and installation

In addition to the environmental impacts from renewable energy used to power hydrogen, the construction and installation of the green hydrogen facility and the pipelines to transport the hydrogen may have impacts on wildlife and habitat (Moreno et al., 2020).

Operation

The process of electrolysis requires high-quality fresh water as an input, mainly for cooling purposes (Heinemann et al., 2021). Approximately 9 litres of water are required to produce 1 kilogram of hydrogen (Bergman & Johnstone, 2021). Besides the impacts on water availability, there could be flow-on impacts on habitat and wildlife in arid, water scarce areas (Heinemann et al., 2021). Transporting hydrogen could have environmental impacts if leaks occur during transportation and chemicals such as ammonia are released (Heinemann et al., 2021).

Mitigation and Conservation Strategies

Resource use, reuse and recycle

Operation

At the operation phase, two strategies can be adopted to reduce the use of fresh water:

- Desalination plants could be used to provide seawater instead of freshwater (Bergman & Johnstone, 2021). Desalination comes with potentially negative environmental impacts, notably the release of brine into marine ecosystems (Doyle, 2019; Heinemann et al., 2021). While the brine produced from desalination can have a detrimental impact on ecosystems, there is a circular economy opportunity to capture the brine from the desalination and use it to extract valuable minerals, like lithium (Sharkh et al., 2022). To date, desalination 'concentrate mining' has not developed on a commercial scale due to the relative costs, but the process is becoming more economical due to advances in seawater brine mining technologies (Sharkh et al., 2022). There have been some technological developments investigating the capabilities of electrolysers to hydrolyse low-grade and saline water directly (Tong et al., 2020), bypassing the desalination process, but they are still early-stage and the technology is not yet commercially viable (Bergman & Johnstone, 2021).

- Recycled water from WWTPs could be used during operation (Freund et al., 2020), which is cheaper than fresh or desalinated water and will be less impacted by drought (Bergman & Johnstone, 2021). Pilot projects for using purified water from WWTPs to create hydrogen are being trialled by water utilities in NSW and Victoria (Barwon Water, 2022; Harris, 2021; Water Research Australia, 2021). Notably, Viva Energy announced its ambitious project to develop a New Energies Service Station in Geelong, Victoria, with construction expected to start in 2024. This will be Australia's first commercial hydrogen refuelling station that is available for public use. It will use recycled water from Barwon Water's Northern Water Plant to facilitate the commercial deployment of green hydrogen for use in fuel cells electric vehicles (Viva Energy Australia, 2022).
- Other avenues include using renewable biogas alternatives as fuel sources with lower environmental impact than green hydrogen across its lifecycle. For example, Jemena and Sydney Water are currently developing a demonstration project to upgrade biogas from the Malabar WWTP to biomethane for injection into the Jemena gas distribution network (Jemena, n.d.).

See Box 19 below for an example of the use of bio-methane (a by-product of waste-water treatment) as feedstock for hydrogen and graphite production.

Decommission and disposal

There has not been a lot of information published about the decommissioning and disposal of green hydrogen infrastructure. However, there are some established and novel end of life technologies and strategies that can be used to recycle hydrogen fuel cells and other hydrogen products. These include hydrometallurgical, pyro-hydrometallurgical, and hydrothermal treatments, transient dissolution, the acid process, selective electrochemical dissolution, and the alcohol solvent process (IRENA, 2020; Valente et al., 2019). These techniques can be used to recover the platinum in platinum group metals (IRENA, 2020), refraining from and reducing the need to mine new raw materials.

Box 19: Hazer Hydrogen Commercial Demonstration Plant

The Hazer Hydrogen Commercial Demonstration Plant at Woodman Water Resource Recovery Facility (WRRF) in Munster, Western Australia, converts bio-methane generated at the WRRF into green hydrogen and graphite (ARENA, 2019; Jazbec et al., 2020). Green hydrogen can be used for industrial application and transport fuel, while graphite can be used in a range of manufacturing applications, including energy storage (Hazer Group, 2022). The Hazer Plant addresses the refrain and reduce steps of the MCH.

In January 2024, the plant produced its first hydrogen and graphite, and should have the capacity to produce 100 tonnes H_2 and 380 tonnes graphite per year (CSIRO, 2024).

Innovation

When processing or decomposing organic waste into biogas, CO_2 is generated. The Hazer technology uses methane, a by-product of the wastewater treatment, as feedstock to produce hydrogen (H_2) and graphite (carbon) (Jazbec et al., 2020). The carbon, instead of being released as CO_2 into the atmosphere, is captured into solid graphitic carbon materials which acts as a carbon sink. The reaction is conducted using a fluidised bed reactor at 900°C, over an iron ore catalyst (Hazer Group, 2022; Jazbec et al., 2020).

Applications

-The H_2 produced is fuel grade and can be used for industrial use, notably to produce ammonia, and as transport fuel (Hazer Group, 2022). A stationary hydrogen fuel cell generation system will allow the plant to generate renewable energy for self-consumption (CSIRO, 2024).

-The graphite can have carbon black, activated carbo and battery anode applications (Jazbec et al., 2020)

Benefits

In addition to generating green hydrogen, the Hazer technology produces graphite. Graphite is one of the primary minerals necessary for battery performance, longevity, and energy density (IEA, 2022b), with 96% of anodes used in lithium-ion batteries containing graphite (natural or synthetic) (Pell et al, 2021). The World Bank projects that by 2050 - under a 2-degree scenario - the demand for graphite for energy technologies is likely to have increased by 500% compared to 2018, corresponding to 68 million tonnes of graphite between 2018 and 2050 (Hund et al., 2020). Along with the other direct and indirect impacts of mining such as habitat loss, water pollution etc, the purification of battery-grade anode products involves the use of reagents that can have negative impacts on human health and the environment (Pell et al., 2021).

The graphite from the Hazer process replaces the need to mine for natural graphite or to use harsh chemicals used for the creation of synthetic graphite (Hazer Group, 2022).

Appendix II – Bomen solar farm

Drivers for Change

Investor interest:

The decision to site the Bomen Solar Farm on an industrial zoned area was a happy coincidence, given the infrastructural needs of the project for developers. A key driver for supporting the decision to develop a site zoned industrial, was from the investor Westpac. Westpac was interested in signing a long-term contract (Power Purchase Agreement) for the electricity generated from the farm to fulfil their April 2019 pledge to source 100% of its electricity from renewable sources by 2025 (Foster, 2019). The fact that it is on industrial land and can be removed at end of life with minimal damage was an added attraction.

Local government support:

Wagga Wagga council has set a corporate Net Zero Emissions target by 2040 (City of Wagga Wagga, 2022). As a result, the Council supported the project as it would contribute toward that target.

Catalyst & Success Factors

Reduced administrative burden:

A key advantage of a brownfield-to-brightfield approach to solar farms is that the burden of biodiversity assessment for the environmental impact assessment is slightly reduced. The NSW Department of Planning and Environment had already assessed the industrial park site from a biodiversity perspective, and although some large trees had to be removed for the development, they had already been offset. This simplified the administrative process.

Working with neighbours:

One of the conditions of the agreement with Westpac was the exploration of multiuse options for the site. Agri-solar options are increasingly seen as a win-win for project developers and the local community. The Bomen Solar Farm project has invited local initiatives for sheep grazing and bee keeping for a honey farm. The sheep grazing allows the neighbouring farmers to feed their livestock, while reducing the cost of slashing grass for fire safety for the solar developers.

Managing Challenges

Visual impact & biodiversity:

One of the main challenges was the public’s objection to the development, which mainly related to the visibility of the solar farm as it was perceived as unesthetic. As a result, the visual impacts have been reduced and the distance to the nearest residential area has been maximised. The project developers undertook landscaping around the solar farm and put in vegetative screens. Additionally, the local council agreed to an initiative to plant 50,000 trees in the local area to improve biodiversity.

Contamination risk:

Another challenge was the risk of contamination. The project was to be developed on an industrial site, which had a history of wool manufacturing. This raised the issue of assessing the risks posed to the local environment as well as the crew working on site. A preliminary assessment of the land found no contaminated land within the project site and the project was able to proceed without further delay.

Appendix III – Better Energy

Drivers for Change

Land use competition:

Solar parks are increasingly becoming large-scale projects, which occupy significant amounts of land. In Northern Europe, where BE predominantly operates, available land is scarce and there is competition for its use. BE recognised the need to develop projects that integrate a diversity of uses, including biodiversity protection and enhancement.

Addressing the climate and biodiversity crises:

At a global level, humankind faces the climate and energy crisis as well as the biodiversity crisis. Developing solar projects that produce green electricity while providing positive biodiversity outcomes became, for BE, a way to contribute to addressing these two crises simultaneously.

Social license to operate:

Developing solar projects that also provide positive biodiversity outcomes gives BE its social license to operate with local authorities and communities. Indeed, local authorities appear to be more likely to support solar projects that can demonstrate that they have thought about the interactions between the project and the natural environment. Similarly, local communities will more readily support projects that will increase the number of natural spaces in their local areas and will provide them with recreational opportunities.

Catalysts & Success Factors

Using expert knowledge:

Ecology is a complex field and designing projects that enhance biodiversity requires specific competencies. As a result, it is necessary to reach out for external support, notably ecologists and biologists, when designing a project. In the case of their recent Blangslev project, BE partnered with biologists and local biodiversity experts to assess the entire site and the surrounding landscape to deep dive into the possibilities, options, and challenges that the site represented in terms of biodiversity.

Community engagement:

Engaging with community in the early phases of the project is also essential to ensuring its success. The community may have insights on the local biodiversity that may not otherwise be available in the scientific literature. As such, engaging in a dialogue early in the project and drawing on local knowledge and expertise can inform the design process, while also garnering support for the project.

Building on learnings from previous projects:

While each project is unique and requires a distinct set of activities to be implemented on site to enhance biodiversity, building on learnings from past projects can help improve the process for the next project, both in terms of community engagement and design for biodiversity outcomes.

Managing Challenges

Degraded land:

BE solar projects are often developed on agricultural land that have been fertilised for many years. As such, little biodiversity remains on the land. Bringing back a broader diversity of species can sometimes be challenging. Some processes, like the removal of the nutrient rich topsoil, may help in achieving this. However, it is a costly process that may not always be feasible.

Community conflict:

Members of the local communities may have different views on the types of nature and recreational activities they want to have in their local area. For example, if parts of the site are open to the broader public for recreational purposes, this may be perceived positively the general community who will now have access to nature areas. However, this may be perceived negatively by individuals who live adjacent to the site who will experience an influx of visitors in proximity to their houses. In these situations, BE has to initiate a dialogue between community members in order to reach an agreement on the kind of outcomes they want for their area.

Profit margins:

The costs of integrating biodiversity into the solar projects is included in the overall costs of the project. As such, the possibility of conducting activities related to biodiversity depends on the profit margin of the project, which is determined by a variety of technical factors, such as the distance to the local transformer station, the time necessary to connect to the grid, the size of the site etc.

Opportunities

Larger areas for biodiversity on solar sites:

Opportunities to enhance biodiversity outcomes on solar sites may lie in allocating larger pieces of land to biodiversity within a project. For example, the Blangslev project allowed for the development of micro-habitats distributed across the site. Currently, BE is developing a project where a larger proportion of the land (one third) will be dedicated to biodiversity conservation and enhancement. While this may not be possible on every project, it is one of BE's priority to look for further opportunities to develop projects that have larger areas of land designated as biodiversity areas.

Multifunctional land-use:

One of BE's drivers of change was the lack of available land, and the need to use the land for multiple purposes. While this is already a guiding principle of BE's action plan, continuing to develop ways in which solar projects can be used for multiple purposes – biodiversity, agriculture, recreation, wetland protection – remains a priority.

Appendix IV – The Nature Conservancy

Drivers for Change

Rapid growth in solar:

The main driver for the involvement of the North Carolina Chapter of the TNC was the rapid development of solar facilities that started around 2018. Two agencies – the US Fish and Wildlife Services and the North Carolina Wildlife Resources Commission – who are involved in different capacities in the permitting process, were uncertain about how to advise and comment on those solar projects. They brought together different stakeholders, including the North Carolina Chapter of the TNC, to engage with the industry on the question of wildlife and habitat conservation on solar projects.

Risk & impact management:

From an industry perspective, the drivers appear to be two-fold. The first one is a genuine desire from some industry players to improve sites or lessen their impact and ensure they do not harm wildlife and habitat unnecessarily. The second one relates to a desire to avoid environmental conflicts during the county approval process, which can lead to projects being cancelled. If conservation values are not considered in the project but are identified by the community during the county approval process, this may lead to applications being dismissed. As such, considering wildlife and habitat in the initial stages of the process may increase the support it receives from the community.

Catalysts & Success Factors

Working with developers:

One challenge, which is a success factor when it is overcome, is the development of positive relationships between solar developers and the North Carolina Chapter of TNC. A second success factor is to present solar developers with options that will mitigate impacts on wildlife and habitat while not requiring large amounts of time and financial investment. For example, the wildlife-friendly fencing does not cost more than a chain link fence but is likely to facilitate the movement of some mammals through the facility. Another example is to keep settling ponds in place and let them become part of the landscape.

Managing Challenges

Two different types of challenges were identified: i) challenges faced by the North Carolina Chapter of TNC to encourage the uptake of wildlife and habitat friendly practices by solar developers, and ii) challenges faced by solar developers to implement those practices.

Encouraging uptake:

The uptake of these practices is voluntary. As a result, one challenge is to find ways to scale up and disseminate those practices to reach more solar developers. This is combined with the need to raise awareness of the issues relating to wildlife and solar installations. This was achieved in the western regions of the US where ungulates (animals with hooves) cover long distance in their migration routes but is harder to achieve in North Carolina where the migration of ‘iconic’ mammals does not tend to occur.

Developer engagement:

Another challenge (which is now a success factor) was to develop positive relationships with developers to collaborate on those kinds of projects. The implementation of wildlife and habitat friendly practices may be limited in several ways. Firstly, it may sometimes be complex to find a site that meets all the legal and technical requirements (i.e. a site that can be developed, can be leased or bought, is flat, is near transmission etc). In those situations, avoiding areas that are of importance for wildlife or habitat may be seen as an additional constraint. Secondly, implementing wildlife and habitat friendly practices may be costlier and require additional management.

Opportunities

Several opportunities were identified to facilitate the adoption, and to enhance the effectiveness of wildlife and habitat friendly practices on solar developments.

Rating solar facilities:

Solar facilities that implement wildlife and habitat friendly practices could be rewarded by being rated as more conservation friendly than facilities that do not implement those practices. This could then, in turn, make them more competitive on the market.

Conducting research on wildlife and habitat friendly practices:

Further research needs to be conducted to develop a full quantitative picture of the impacts of current wildlife friendly practices on wildlife and improve them. Research could provide insights on animals who adapt well to those facilities and those who do not. It could also provide insights on the types of measures that are most effective.

Landscape scale:

As solar facilities develop across the landscape, it is increasingly necessary to look at how they interact with the broader area, and what measures can be implemented to limit landscape fragmentation and enable the movement of species across the land. This could then inform the siting of facilities in a way that avoids or reduces landscape fragmentation.

Appendix V – Lightrock Power

Drivers for change

Addressing the ecological crisis:

The initial driver for this endeavour was a personal desire from the founders to develop projects that contribute to solving both the climate and the ecological crisis.

Social licence:

The second driver is related to social license to operate. Local communities are consulted on solar projects before a planning permit is issued. As solar projects are sometimes considered by communities as profit-making projects, developing projects that show a genuine interest in protecting and promoting the local biodiversity can be perceived more favourably by the community.

Catalysts & Success Factors

Three main factors appear to be decisive in the success of projects:

Collecting ecological data early in the process:

LP collects ecological data early in the project through a suite of surveys. This data informs the design of the site and enables LP to confidently develop a set of measures for the protection and enhancement of biodiversity on site.

Collaborating with individuals and organisations who have expert ecological knowledge:

LP collaborates with several environmental organisations who provide valuable insights on measures that can be taken to protect wildlife and habitat. The companies with which LP collaborates to construct and operate solar farms also partner with ecologists and academics in the UK who can monitor the ecology of solar farms over the long term. The availability of this existing ‘ecosystem’ of experts was considered as particularly important.

Having time to develop projects:

Conducting initial surveys to establish a baseline of the ecology of the site is an essential step of the process. Conducting those surveys is time consuming: collecting the baseline data may take at least a year, because surveys need to be conducted at specific times of the year due to seasonal variations. In addition, when many species are identified on a site, developing adequate protection measures may require additional time. As such, having a long(er) timeframe is required to develop than business as usual projects

The following point may not have been presented as factors of success per se, but is worth mentioning:

Environmental designations present in the UK, such as Green Belt, Natural Beauty or Special Scientific interest, means that most of LP’s projects are conducted on degraded agricultural land, which increases the likelihood of the projects bringing positive biodiversity outcomes, as opposed to projects developed in biodiversity rich areas.

Managing Challenges

Perceptions around financial viability:

Due to the additional steps that are needed to design and implement them, these projects can be perceived as having a higher cost. Additionally, designing projects with biodiversity in mind may sometimes require a reduction in the amount of energy produced on a site. LP is looking into ways to combat the perception that they incur higher costs. Indeed, if managed well, they may require reduced management (e.g. using pulse grazing may be cheaper than hiring contractors to spray), which may be commercially beneficial.

Extended timeframe:

As mentioned above, allowing time to collect ecological data is a factor of success. However, it can also be perceived as a challenge or a difficulty as it is slowing down the design phase of the project. That being said, most permitting authorities in the U.K will now not allow projects to go ahead until such surveys have been completed and mitigation measures factored into the design.

Opportunities

Several opportunities were identified to encourage the uptake of such practices by solar developers, and to improve their ecological effectiveness:

Accreditation:

LP is looking into the possibility of getting their solar farms accredited as ‘Fair to Nature’. Fair to Nature is a program run by the Royal Society for the Protection of Birds (RSPB) that accredits farmers who manage their farm responsibly. LP believes that having this type of accreditation for their business would create additional value insofar as they can sell their electricity for, and appeal to, ethically motivated companies.

Landscape scale:

Developing solar projects that protect biodiversity may also present an opportunity to become part of a broader network of areas providing habitat for wildlife. In one of its projects, LP was involved with stakeholders working on landscape scale conservation, which encouraged them to think about their project as a ‘node in a network’ rather than as an ‘island’. Considering opportunities for solar projects to contribute to broader landscape conservation are likely to enhance the role they play in the protection of habitat and wildlife.

Appendix VI – IRMA

Drivers for change

IRMA was founded in 2006, when Tiffany & Co., reached out to Earthworks (a non-profit organisation focusing on advocating against the impacts of mining pollution on communities and the environment) to discuss how the company could assess which mines around the world were operating responsibly. Tiffany showed interest in ensuring that they responsibly source their material, however it became clear that there was no clear definition of responsible mining. The idea was formed to create a standard for mining that would be similar in nature to the standard created by the Forest Stewardship Council for forestry.

Catalysts and success factors

Multi-stakeholder governance

One of the distinctive characteristics of IRMA is its multistakeholder governance model. To develop the standard, IRMA brought together six stakeholder groups holding equal authority in shaping the standard and overseeing IRMA as an organisation: mining companies, companies which use mined materials in their products, finance (banks and investors), mining-impacted communities, labour organisations and non-profit organisations (environmental and social). Those six groups worked together to identify the different topics that needed to be addressed in the standard and the detail of the requirements for each of them. In IRMA's system of equal governance, if the two representatives from one stakeholder groups both disagree with a decision being made, they can vote 'no'. The entire board then revisits the decision to decide on a different path on which all stakeholders can agree. This means that the final standard, the assessment process, and other important elements of the IRMA system are a reflection of the consensus reached between those six groups.

A detailed standard

The standard provides a set of detailed requirements that flesh out what responsible mining looks like. This is important both from a mining company perspective and an auditing perspective. Mining companies can use the standard as a 'guidebook' to what responsible practice looks like at the site level. For mines undergoing a third-party audit, it allows for a more rigorous evaluation than other mining standards, as it provides specific and detailed information when deciding on whether a mine site meets a standard. Additionally, the auditor needs to score each requirement and provide a rationale for their score, which encourages them to justify their scoring. This process minimises the likelihood of auditors making unsubstantiated decisions.

A transparent auditing process

The auditing process for IRMA aims to be transparent. As mentioned earlier in the description of the initiative, once a mine agrees to go through an audit, IRMA will make that information public through its newsletter and also reach out proactively to stakeholders to invite them to reach out to auditors. The aim is to provide anyone who wants to be interviewed during the audit process to be heard. Once the audit is finalised, the report is also made available publicly so that anyone can download it and use it. Community members may use it for advocacy purposes, while purchasing companies may use it to get a better understanding of how their supply chain is performing.

Incentivising mine sites to improve practices

At its core, IRMA is about driving more responsible practices in the mining sector. The audit process itself is an important part of that vision, as it provides both transparency into current practice and a motivation for change, given the unprecedented transparency of the audit reports. Many mines improve their practices during the audit process, based on their self-assessment and preliminary feedback from the auditors. Once the audit is complete, the public report may be used by other stakeholders to encourage the mine site to further improve.

Managing challenges

Uptake by mines

The main challenge encountered by IRMA is to have sufficient participating mines using the standard to enable a sector wide shift toward responsible mining practices. Mining companies may be reluctant to participate because may already undertake several audits and may not want to allocate resources (e.g. senior staff member time) to an additional audit. In addition, the IRMA audit requires a degree of transparency some mines may not be willing to accept.

‘It really is a seller’s market’

Purchasing companies are increasingly aware of the importance of sourcing their materials responsibly. However, sellers (mining companies) have the upper hand in the market as the demand is high. Consequently, purchasing companies may be unable to push mining companies to participate in IRMA, as they may simply decide to sell their minerals and metals to purchasing companies that do not expect them to do so.

Opportunities

Transforming the energy and mining sector together

A potential opportunity is for the renewable energy sector, which requires high quantities of minerals and metals, to drive a change toward responsible mining practices that will not contribute to exacerbate pressures put on the environment. Early signs of this shift are visible with EV companies becoming members of IRMA, as EV companies buy large volumes of metals and are able to push mining companies toward better practices. This is not yet visible in the renewable energy sector, but there are opportunities for this sector to play a role.

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