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THOMAS REVIEW

Impacts of the renewable energy transition on global plant diversity: A review

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Societal Impact Statement

People and nature need a renewable energy transition to help address the growing, and catastrophic, effects of climate change. A sustainable energy transition involves rigorously examining the potential impacts on nature – including plant life – and creating pathways for impact mitigation that strike a clear balance between energy production and biodiversity conservation. Given the critical roles that plants play in ecosystems, culture, wellbeing and prosperity, including for Indigenous people, their protection must be recognised, upheld and enhanced in the energy transition. This review seeks to chart a course for policymakers, proponents and practitioners to consider plants when planning, designing and implementing renewable energy infrastructure and projects.

Summary

A global scale renewable energy transition is now underway, bringing opportunities and challenges for nature, including plant life. Plants form the basis of terrestrial ecosystems and provision of essential ecosystem services; their protection and stewardship must be ensured during the renewable energy transition. Here, we provide a synthesis of the potential impacts of the energy transition on plants. We combine knowledge from research literature in plant ecology, plant biology, sustainability, conservation, spatial planning and social justice with that from policy documents, working papers and environmental assessments for existing renewable developments. The DPSIR method (Drivers, Pressures, State, Impacts, Responses) is used to organise the synthesis, including an examination of the utility of project life cycle assessment for anticipating impacts to plants. Where impacts may negatively affect plants or people, specific calls to action are offered. These include the need to tackle 'plant blindness' (i.e., the tendency to overlook, or undervalue plants, compared to animals) in the life

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cycle of renewable projects – from approval to decommissioning – and the need for Indigenous ownership and benefit sharing. Solutions which can accommodate and enhance plant biodiversity in conjunction with renewable energy projects, including closed-loop or circular renewable design within the landscape, are discussed. Multiple global strategies call for the biodiversity and climate crises to be addressed in tandem (e.g., the Paris Accord, Global Biodiversity Framework, UN Sustainable Development Goals), underscoring the need for a nature-based transition to renewable energy. Plant life must be recognised, valued and secured alongside wider biodiversity to achieve a sustainable future for Earth.

KEYWORDS
biomass energy, geothermal, green energy, hydroelectric power, low carbon technology, nature-based solutions, utility-scale solar, wind energy

1 | INTRODUCTION

Human society is operating well beyond the safe operating space that nature can support (Rockström et al., 2009), and whole-of-system actions to prevent damage and restore ecosystems are needed to safeguard the processes that support all life on Earth (Dinerstein et al., 2020). The continued loss and degradation of biodiversity combined with the consequences of Earth's rapidly changing climate are twin crises with systemic impacts that must be cohesively addressed (Pettorelli et al., 2021). Many strategies have emerged to halt and reverse these two pressures, including protected area commitments (e.g., Kunming-Montreal Global Biodiversity Framework: Target 3 – 30 × 30 [WWF & IUCN WCPA, 2023]), improving natural resource use practices (e.g., Sustainable Development Goals [see Mishra et al., 2024]) and enhancing degraded ecosystems through ecological restoration (e.g., United Nations Decade on Ecological Restoration [Nelson et al., 2024]). The incubation and adoption of these big-picture strategies around the world provides evidence of people's capacity to work collectively to implement positive environmental change.

Decarbonisation (i.e., the process of eliminating or removing carbon dioxide and other greenhouse gas emissions from the atmosphere, see glossary [Table 1] for further definitions) is a grand challenge for humankind (Geels et al., 2017), essential for addressing both climate change and the associated loss of biodiversity. To meet emissions' targets, technologies which generate energy must rapidly transition to become both renewable and sustainable (UNFCCC, 2015). To do so, transformational change is needed to replace fossil fuel-based energy production with power generated from renewable resources such as wind, solar, geothermal, water (hydropower, and marine or tidal) and other low emissions technologies (see Table 1 for definitions).

The renewable energy transition is moving rapidly, but unevenly, across the world following the endorsement and implementation of low-carbon energy production strategies (Ganivet, 2020) backed by the United Nations Framework Convention on Climate Change (UNFCCC) Paris agreement (UNFCCC, 2015). While the transition to low-carbon energy systems is undoubtedly a critical step toward mitigating the adverse impacts of climate change—including those on biodiversity and ecosystems—the implementation of renewable technologies may inadvertently place new or increasing demands on the natural environment (Pettorelli et al., 2021; Smith et al., 2022).

1.1 | Benefits of the renewable transition for plant biodiversity

The climate mitigation effects of a global transition to renewable energy are clear and offer important benefits for nature through lowering CO_2 emissions and, in turn, slowing the overall rate of global warming across climate systems (Smith et al., 2022). Reducing fossil fuel use and emissions is predicted to benefit biodiversity, particularly plants, by reducing the severity of climate-driven extreme events and minimising direct (Butt et al., 2013) and indirect habitat loss such as that linked to altered temperature and precipitation patterns (Pörtner et al., 2021), thereby helping to preserve the ecological conditions necessary for species persistence. Although some level of climate change is already locked into the earth system by existing emissions (Fankauser et al., 2022), slowing or altering the pace of climate change may help maintain the integrity of native plant communities in the face of more proximal drivers of loss such as land conversion and direct exploitation (Jaureguiberry et al., 2022).

It remains unclear if, or by how much, the benefits of reducing fossil fuel use (e.g., emissions reductions, avoided land use change) may be counterbalanced by the environmental impacts associated with a transition to renewable energy (Rehbein et al., 2020). Environmental impacts of renewables are not uniform: many technologies differ in their spatial scale, ecological footprint and material demands (e.g., for mining and infrastructure). Moreover, the development of renewable energy projects varies across global biomes (Figure 1), influenced by differences in technology type, resource availability and landscape suitability. As the global community strives to meet

TABLE 1 Glossary of terms.

Term	Definition
Biodiversity	The variety and variability of life forms, including the diversity of species, ecosystems and genetic differences within species.
Biofouling	The colonisation of artificial habitat from submerged infrastructure by aquatic plants, animals and other organisms.
Biomass Energy	Energy produced from organic materials like wood, agricultural residues and energy crops (e.g., corn, sugarcane, soy). Includes biofuels (e.g., ethanol, biodiesel) and biopower (electricity from combustion or digestion).
Circular Economy	An economic system aimed at eliminating waste and promoting the continual use of resources through principles of reuse, repair, recycling and regeneration.
Complementarity	In spatial conservation planning, the principle of selecting conservation areas in a way that maximises biodiversity coverage by adding new, unprotected species or ecosystems with each additional area selected.
Country-based Endemic	A species of plant, animal or other organism that is found naturally only in a specific country, and nowhere else in the world.
CSP (Concentrated Solar Power)	A solar power technology that uses mirrors or lenses to concentrate sunlight onto a small area, typically a receiver, where it is converted into heat to drive a turbine and generate electricity.
Dam Retrofitting	Modifying and upgrading existing dams to improve their functionality, safety or efficiency, often incorporating environmental enhancements.
DPSIR Framework	A conceptual model used to understand the relationships between human activities and the environment. Using DPSIR helps analyse environmental issues (based on Drivers, Pressures, State, Impacts and Responses) and guide policy by identifying causes, effects and potential solutions.
Ecological Footprint	The impact of an action or actor on the environment, expressed as the amount of land required to sustain their use of natural resources. Specifically, the footprint of a renewable project that results from all stages of its development from exploration, resource acquisition, execution, construction, operation and decommissioning.
Ecosystem Services	The benefits humans receive from ecosystems, including provisioning, regulating, supporting and cultural services.
Energy transition	The process of shifting from fossil fuels to renewable energy sources to reduce greenhouse gas emissions and limit climate change.
Geothermal Energy	Renewable energy derived from the Earth's internal heat, typically harnessed by tapping into reservoirs of steam or hot water to produce electricity or provide direct heating.
Hydroelectric Power	Electricity generated by converting the kinetic energy of flowing or falling water into mechanical energy using turbines. Includes dams, run-of-river systems and pumped-storage plants.
Integrated Vegetation Management	A strategic approach to managing plant communities that combines ecological, mechanical, chemical and cultural methods to achieve specific land use goals—such as maintaining utility corridors or conserving habitats—while minimising environmental impact.
Life Cycle	In the context of renewable energy transition, life cycle refers to the series of stages a renewable energy technology or project goes through, from initial development and production to its use, maintenance and eventual decommissioning or recycling.
Life Cycle Assessment (LCA)	A methodology for assessing the environmental impacts of products or services throughout their entire life cycle, from raw material extraction to disposal.
Like-for-like Offsetting	Compensating for biodiversity loss by restoring, enhancing or protecting habitats of the same type and ecological value as those impacted, ensuring the offset maintains comparable species, functions and ecosystem services.
Low Carbon Technologies	Technologies designed to produce energy, goods or services with minimal greenhouse gas emissions, contributing to climate change mitigation.
Narrow-range Endemic	A species which only occurs across a restricted area and therefore may be subject to a higher risk of decline and extinction if subject to clearing and other threats.
Nature-based Solutions	Approaches that use natural processes and ecosystems to address environmental challenges, such as climate change mitigation or disaster risk reduction.
Plant Species Richness	A count of the number of plant species occurring in a given location, such as a site, protected area, country or continent.
Protected Areas	Geographically defined spaces where human activities are limited to conserve biodiversity, ecosystems and cultural heritage.
PV (Photovoltaic)	A technology that directly converts sunlight into electricity using semiconductor materials, such as silicon, in solar panels or cells.
Stacked Energy Scapes	The integration of multiple renewable energy sources (such as solar, wind and hydro) into a single landscape to optimise energy generation and minimise environmental impact (Harlan & Baka, 2024).

(Continues)

TABLE 1 (Continued)

Term	Definition
Tidal/Marine Energy	Energy captured from the motion of ocean tides and waves. Tidal energy relies on the predictable rise and fall of tides, while wave energy harnesses surface motion from wind-driven waves.
Utility-Scale Solar	Large-scale solar power systems designed to generate electricity for distribution through a utility grid. Uses photovoltaic (PV) panels or concentrated solar power (CSP) technologies over extensive land areas.
Value Chain	A value chain refers to the full range of activities that a company or organisation undertakes to create a product or service, deliver it to the customer and maintain a competitive edge. It encompasses all the processes involved in designing, producing, marketing, delivering and supporting a product or service.
Wind Energy	Energy harnessed from the kinetic power of wind using turbines to generate electricity. Wind farms can be located onshore or offshore.

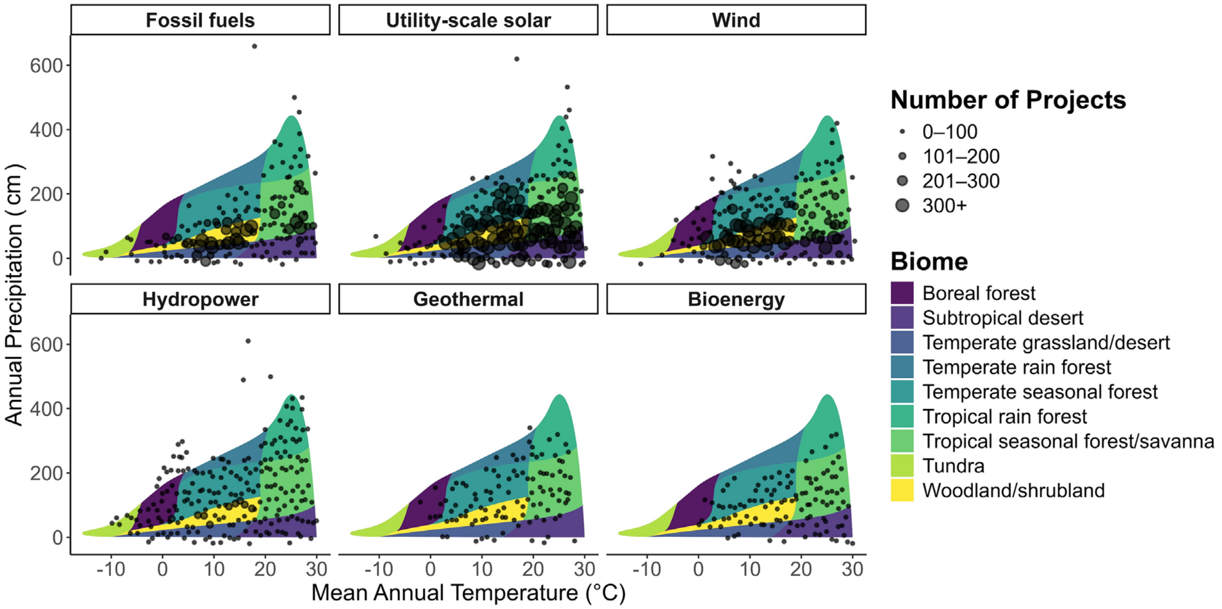


FIGURE 1 Distribution of existing fossil fuel and renewable energy projects (black circles) across global biomes. Project locations are overlain on a Whittaker biome diagram, and each point represents the mean annual temperature (°C) and precipitation (cm) occupied by the project. Circle size indicates the number of projects at a location. Energy project data are from the Global Integrated Power Tracker (GIPT) by Global Energy Monitor (accessed May 2025) and biomes from Ștefan and Levin (2018).

ambitious decarbonisation targets, critical evaluation of biodiversity impacts of the renewable energy transition is needed—particularly for plant life for which impacts remain understudied.

1.2 | Why do we need to consider plant diversity in the renewable energy transition?

Despite the foundational role plants play in ecosystems and the provision of their ecosystem services (see Table 1), such as sequestering carbon and cycling nutrients (Heinrich et al., 2023), individual efforts to understand how global plant diversity may be impacted by renewables (e.g., Alfaro-Saiz et al., 2023; Ji et al., 2023; Lannuzel et al., 2022; Nordberg et al., 2021; Qin et al., 2022; Tang et al., 2017; Urziceanu et al., 2021; Wade et al., 2023) is yet to be synthesised. Much research to date has focused on the intersection of migration routes and home range impacts for highly mobile animal species, such as bords, bats and fish, with renewable technology infrastructure (Jager et al., 2021). Despite the importance of this research, policymakers and scientists require a broader knowledge base to anticipate and prevent potential negative consequences of the energy transition on nature.

Because most plants are sessile organisms, they may be vulnerable to impacts at various points across the renewable energy transition life cycle (see Table 1), including from extractive land uses required to supply critical minerals to build infrastructure (Sonter et al., 2020), land clearing and habitat conversion for infrastructure installation and maintenance (Rehbein et al., 2020). End-of-life management of renewable technology infrastructure may also pose issues where inappropriate disposal pathways for new materials expose plants to pollution through contamination of water and soil (Kwak et al., 2020; Nazir et al., 2019) or where lands cleared for renewable projects require restoration (Hernandez et al., 2015). However, renewable energy development may also yield positive outcomes for plant communities, and broader biodiversity, particularly where low-impact siting facilitates habitat restoration or conservation, or where infrastructure operation creates a supportive microenvironment for plant establishment and growth (Harlan & Baka, 2024; Santangeli et al., 2016; Smith et al., 2022). Importantly, many places targeted for renewable technology expansion are located on Indigenous homelands where plants underpin significant human connections to landscapes (Kennedy et al., 2023). In these regions, where the global visibility of impacts may be lower, unsustainable practices may become entrenched with little oversight in the absence of strong planning, governance and monitoring.

As international agendas for halting the biodiversity crisis and reducing emissions collide, policy makers, regulators, proponents, Indigenous communities and conservationists are facing difficult choices addressing the demands of pledges to halt and reverse human impacts on the biosphere (Pettorelli et al., 2021). The nexus between climate change, biodiversity and society is beginning to be addressed in policy and regulation in the transition towards more sustainable energy production (Pascual et al., 2022); however, there remains an urgent need for integrated strategies which consider the risks and opportunities for global plant conservation and enhancement within this transition. Indeed, analytical tools and data do exist to optimise land use decision making and explore renewable technology impacts (e.g., TNC, 2022; Whitehead et al., 2017), yet we lack a clear framework that sets out the drivers, pressures, impacts and responses associated with this transition on plants.

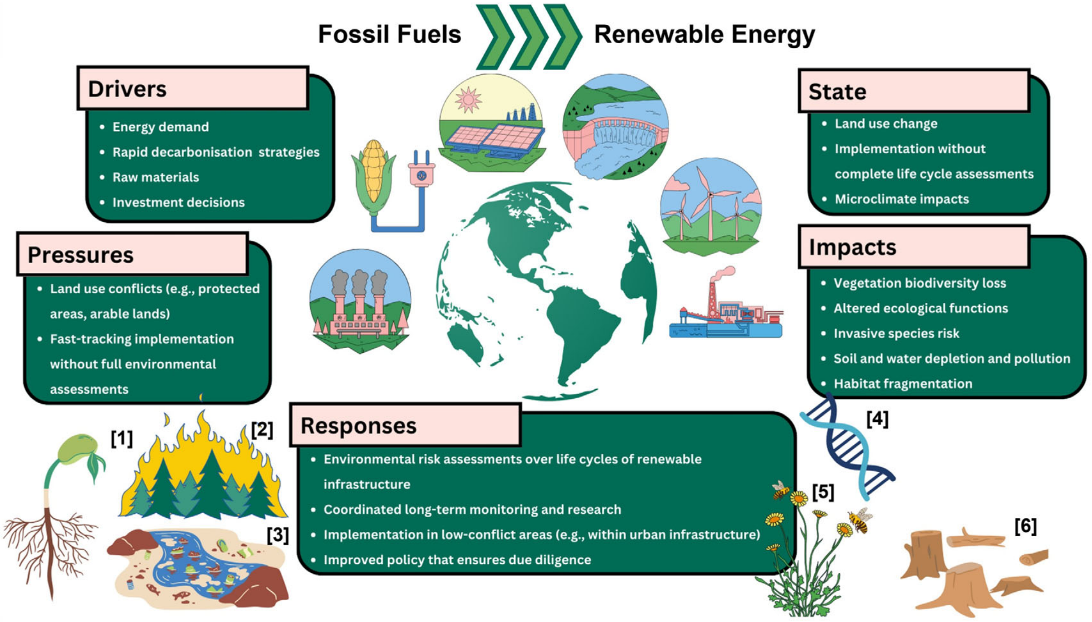
In this review, we provide an overview of global plant diversity and establish a causal framework for how plant species, communities and vegetation may be exposed to renewable technology development and implementation using the DPSIR model (drivers, pressures, state, impact, response) (Smeets & Weterings, 1999) (Figure 2). When applied to the renewable energy transition and its effects on global plant diversity, the DPSIR framework identifies the key factors that influence the relationships between renewable energy development, society and the natural world. Drawing on these findings, we provide a suite of solutions and policy options aimed at mitigating the potential impacts of the energy transition on plant diversity and provide calls to action that seek to maximise the co-benefits for biodiversity as we transition to renewables across the world.

2 | GLOBAL PLANT DIVERSITY: AN OVERVIEW

More than 350,000 plant species have been described from across the world's terrestrial, marine and freshwater ecosystems (Antonelli et al., 2023). Although plant life occurs on all continents, including Antarctica, and in every ocean, plant species richness (see Table 1) is unevenly distributed across the world. Richness is generally highest in tropical and subtropical regions, but also notably high in regions with Mediterranean climates and on islands (when considered on a per area basis; Gallagher et al., 2023). Most countries also have a unique complement of plant species which occur nowhere else on Earth. These country-based endemic species (see Table 1) make up > 60% of global plant species richness (Gallagher et al., 2023) and should be the primary target of national regulations that seek to curb the potential impacts of renewable technologies on biodiversity. Renewable energy projects are similarly widespread across the world, but geographically highly variable in their distribution, which includes countries with a high percentage of endemic plant species (Figure 3; Table 2).

Biodiversity portals and citizen science platforms, such as the Global Biodiversity Information Facility (GBIF; https://www.gbif.org/), Plants of the Word Online (https://powo.science.kew.org/) and iNaturalist (https://www.inaturalist.org/) provide readily accessible occurrence record information for plant species worldwide, though important gaps in global plant knowledge still persist. Many plant species are known from only a handful of locations across their range, making it difficult to distinguish narrow-range endemic plants (see Table 1) from those which are poorly collected, or have limited survey coverage throughout their range (Ondo et al., 2024). This has implications for the regulation of potential renewable energy impacts because the risk of plant diversity loss increases when an entire species' range is affected, making the need to avoid impacts on narrow-range endemics paramount. For example, in some cases, plant species may be locally adapted to sites with specific soil mineral composition, such as those including rare earth or ‘critical’ minerals like nickel, which are highly sought-after to support renewable technology infrastructure (Calderon et al., 2024; Meindl et al., 2014). Further, more than 15% of plant species are estimated to remain unknown to science creating an additional risk that species will be lost to extinction before they can be described and included in adaptation and mitigation strategies (Ondo et al., 2024). Several small island countries containing high proportions of known endemic plant species, and likely gaps in collection – such as The Philippines and Borneo – contain high numbers of renewable energy facilities (Figure 3; Table 2) with pressure growing to expand these (Erdiwansyah et al., 2019). However, to comprehensively evaluate the true impact of these developments on plant species, projects must account for their specific ecological footprint, as well as its specific effects on local biodiversity and data may be limited.

Plant species are already under threat across the world from the direct, indirect and compounding effects of land clearing, urbanisation, disease, invasive species and climate change, including the specific effects of changed fire and drought regimes (Antonelli et al., 2023). Recent estimates place 45% of known plant species at risk of extinction in the coming decades because of these threats (Bachman et al., 2024), though more work is required to refine and test modelled estimates against evidence from the field. If even a fraction of this predicted loss is realised, the diversity of remaining plant life will be significantly diminished, impacting plant evolutionary history and the biotic interactions it provides, which underpin cross-kingdom biodiversity and ecosystem function. Additional pressures on global plant diversity may result if the renewable energy transition proceeds without due recognition of the importance of avoiding and mitigating impacts. While existing environmental regulatory frameworks may provide the foundations for managing such impacts, new and



	Definition	Key Question
Drivers	The economic, social, and political forces that underpin the transition from fossil fuels towards renewable energy.	What are the underlying factors or motivations driving the need for renewable energy?
Pressures	The effects imposed on global plant diversity from driving forces related to the renewables' transition.	What pressures resulting from the transition to renewable energy are asserted?
State	The modified condition of ecological systems resulting from pressures driven by the renewable energy transition.	How is the current state of plant diversity affected by these pressures?
Impacts	How changes to ecosystem states may affect plant species and communities, and vegetation integrity.	How might the modifications in ecosystem states due to renewable energy projects impact plant species, communities, and overall vegetation health?
Responses	Actions which can be taken to mitigate negative impacts or enhance positive outcomes for plant diversity impacted by renewable energy projects.	How can we respond to mitigate negative impacts or enhance positive outcomes for plants from renewable energy development?

FIGURE 2 The DPSIR framework (Drivers, Pressures, State, Impact, Response) provides a structured approach to reviewing human-environment interactions. Here, we define the key linkages between the renewable energy transition and plant diversity. Graphic icons depict potential state changes and impacts on plants across the renewable energy life cycle including [1] impacts on plant regeneration, [2] increased fire risk, [3] exposure to pollutants, [4] changes to pollination and gene flow, [5] altered species interactions and [6] habitat fragmentation and loss.

emerging intersections of resource use and plant species may have to be considered to minimise and manage impacts; understanding the locations of species and renewable energy projects at appropriate scales will be integral to achieving this.

3 | ASSESSING THE INTERSECTION BETWEEN PLANT DIVERSITY AND RENEWABLE TECHNOLOGY USING THE DPSIR FRAMEWORK (DRIVERS, PRESSURES, STATE, IMPACTS, RESPONSES)

DPSIR is a causal framework intended to systematically structure complex systems and challenges, highlighting the interconnectedness of society with the environment (Smeets & Weterings, 1999) (Figure 2). It is used to synthesise research across diverse disciplines (e.g., social, environmental, economic, political) to support sustainable decision making and 'fit-for-purpose' policy development (Carnohan et al., 2023). Despite its broad use, DPSIR can have some limitations, including the fluidity of category boundaries, limited inclusion of local contexts and oversimplification of complex elements. In this review, we address these limitations by incorporating diverse perspectives from the literature, evaluating studies across various contexts (different ecosystems and implementation pathways) and scales (from local to global), organising our analysis by separation of different renewable energy types, and, where possible - proposing adaptations. To assess each element of DPSIR, we gathered literature related to renewable technology and plant diversity using the search terms: ("renewable energy" OR "low carbon technologies" OR "clean energy" OR "renewable technologies" OR "solar energy" OR "wind energy" OR "geothermal energy" OR "biomass" OR "biofuel" OR "hydropower" OR "tidal energy" OR "marine energy" OR "renewable resources") AND ("plant diversity" OR "flora"

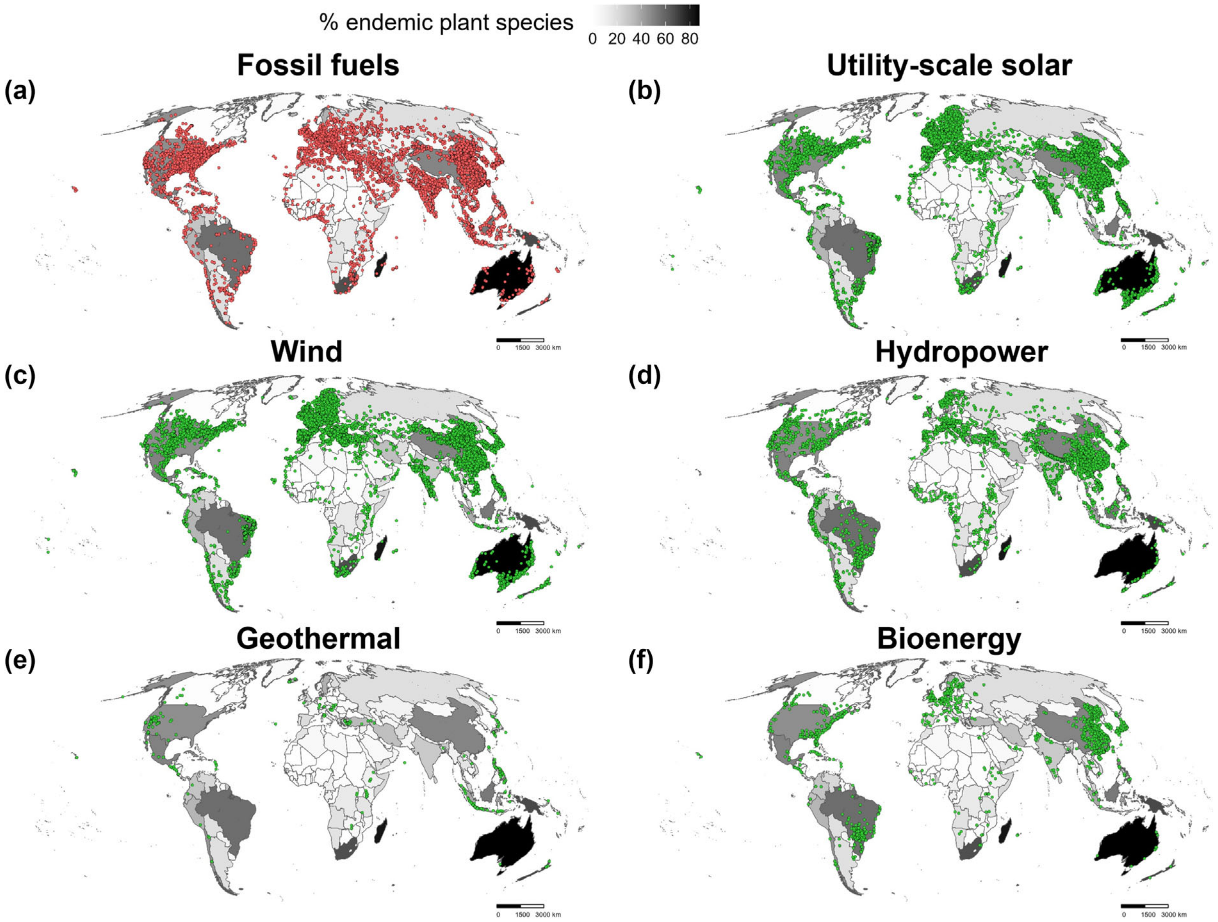


FIGURE 3 Percentage of endemic plant species in countries and regions of the world relative to existing fossil fuel energy projects (a; red points) and existing renewable energy projects (b-f; green points). The percentage of endemic species was sourced from Gallagher et al., 2023 and is based on the World Checklist of Vascular Plants (Govaerts et al., 2021). Data on renewable technology projects was sourced from the Global Integrated Power Tracker (GIPT; https://globalenergymonitor.org/projects/global-integrated-power-tracker/; accessed May 2025), which provides a continually-updated catalogue of the geolocations of power stations and facilities worldwide (GIPT Global Energy Monitor, 2025).

OR "threatened plants" OR "vegetation" OR "biodiversity" OR "plant recruitment" OR "pollination" OR "environmental impacts" OR "microclimate"OR "disturbance effects" OR "pollution" OR "germination" OR "clearing") AND ("mitigation" OR "policy" OR "consequences" OR "solutions"). Studies were cross-checked to ensure inclusion of key, foundational and recent studies relevant to each renewable energy type and biodiversity impact. Given the broad scope of this review, and existing knowledge gaps on new renewable technologies, we have not set out to comprehensively develop all elements of the DPSIR framework. Rather, we use DPSIR as a tool to organise and synthesise the literature, highlighting areas for further research and capacity building to benefit global plant diversity as society shifts towards renewable energy sources.

3.1 | *Drivers* of the renewable energy transition impacts on plants

Meeting global energy demands while mitigating the impacts of greenhouse gas emissions on the environment are two significant drivers of renewable expansion, resulting in gradual, but significant, policy changes and increasingly rapid infrastructure development (Pascual et al., 2022). When projects are thoughtfully integrated with existing biodiversity and nature protection frameworks, the transition to renewable energy presents opportunities to drive positive change in the way vegetation is managed (Gasparatos et al., 2017; Pettorelli et al., 2021). Public and private interest in transitioning to net-zero are driving investment in research and development in renewable energy technology and deployment (Loiseau et al., 2016). However, conservation objectives may be deprioritised in contexts where renewable energy investments are pursued primarily through the lens of technological efficiency, economic viability or infrastructure durability (San Cristóbal, 2011). In many cases, the need for countries to transition to renewable technologies may also be driven by geopolitical instabilities that threaten current supply chains for energy production, such as pipelines and shipping channels, or on isolated small island nations (Leal Filho et al., 2022).

Support for projects that disregard or downplay environmental consequences can drive the unsustainable implementation and expansion of renewables. For example, many countries' governments

TABLE 2 The top 10 ranked countries or regions by percentage of endemic plant species and their count of existing renewable energy facilities. The percentage of endemic species was sourced from Gallagher et al., 2023 and is based on the World Checklist of Vascular Plants (Govaerts et al., 2021). Data on renewable technology projects was sourced from the Global Integrated Power Tracker (GIPT; https://globalenergymonitor.org/projects/global-integrated-power-tracker/), which provides a continually-updated catalogue of the geolocations of power stations and facilities worldwide (GIPT Global Energy Monitor, 2025). Data was filtered to include all power stations for each renewable type that are either operating, decommissioned, planned or in progress from May 2024 (newly announced developments without permits or government approval were excluded).

		Renewable energy facilities (count)					
Country or region	Endemic plant species (% total flora)	Solar	Wind	Hydropower	Geothermal	Bioenergy	Total
Australia and territories	88	392	312	40	1	11	756
Madagascar	82	4	1	4	0	0	9
New Zealand and territories	69	45	36	21	25	2	129
New Guinea (Papua New Guinea and West Papua)	68	0	0	6	0	0	6
South Africa	67	110	66	7	0	0	183
Brazil	56	3,018	1,611	161	0	265	5,055
Borneo	53	11	5	19	0	0	35
Philippines	52	320	121	55	59	10	565
Mexico	50	409	127	26	25	8	595
China	49	13,246	7,936	908	0	729	22,819

(e.g., the United States, Germany, China) have provided support towards increasing the expansion of small-scale hydroelectric power plants backed by the assumption that these small plants will result in fewer adverse ecological impacts compared to large hydropower schemes; in reality, however, this assumption is not supported by current evidence (Couto & Olden, 2018; Lange et al., 2019). Empirical evidence in the Brazilian Amazon basin suggests that the proliferation of small hydropower plants is having substantial cumulative, negative and wide-reaching impacts on aquatic systems and their adjacent ecosystems and plant diversity (Freitas et al., 2022). Further, some countries (e.g., India, Switzerland) use the expected energy capacity of a dam to delineate the degree of pre-assessment required, permitting some small-scale hydropower projects to commence without comprehensive environmental impact assessments (Lange et al., 2019). Additionally, demands for raw materials (e.g., critical minerals and strategic materials such as lithium, cobalt, nickel and other rare earth elements), necessary for component parts and batteries in renewable technologies, will drive the expansion of new mining efforts, which could have serious consequences for plant species and natural areas if poorly regulated (Carr-Wilson et al., 2024; Lannuzel et al., 2022; Parker et al., 2024; Sonter et al., 2020).

Many jurisdictions in Australia are developing specific planning provisions that seek to 'streamline' environmental approvals with the goal of increasing the rate of renewable energy project approvals (e.g., https://www.herbertsmithfreehills.com/notes/environmentaustralia/2024-posts/nsw-renewable-energy-planning-framework-commences-with-immediate-effect). While this is generally motivated by the desire to transition rapidly toward low carbon emission energy generation, it has the potential to reduce the rigour of environmental impact assessment, that can take time to ensure that cryptic and low detectability species are properly surveyed and monitored at impact locations. On the other hand, incentives for biodiversity-friendly renewable energy siting (e.g., existing cleared or degraded agricultural land) which are designed to enhance local biodiversity through restoration in accordance with existing nature conservation policies (e.g., EU Restoration Law) offer avenues for policy to drive positive outcomes for plants in the renewable energy transition (The Nature Conservancy (TNC) & SolarPower Europe, 2024).

3.2 | *Pressures* on plant species and vegetation communities

While the transition towards renewable sources of energy aims to reduce fossil fuel usage and thereby mitigate climate change, the rapid development of new infrastructure necessary to support this change may conflict with areas of intact vegetation. Several low emissions' energy technologies, such as solar, hydropower and wind-based approaches, require substantial areas of land, which can place pressure on native vegetation (IPBES, 2019). When renewable energy projects are situated in areas that are incompatible with existing infrastructure for power generation and transmission, changes in existing land uses will be needed, likely requiring the removal of many plants and their habitats (Oakleaf et al., 2019). For example, the development of infrastructure access tracks and transmission lines to transfer energy from where it is harnessed to where it is needed will place pressure on local environments and vegetation irrespective of renewable technology type (Diffendorfer et al., 2019).

Land requirements for new renewable project sites will depend on where effective energy can be harnessed to achieve the highest profit margin within a regulatory framework. To maximise energy capture, renewable energy infrastructure is often located in areas with specific characteristics suited to each energy type, leading to varying pressures on local biomes and vegetation (Figure 1). For example, energy generation projects are more cost-effective when built nearby existing transmission infrastructure and close to energy consumers. In Australia, population density is greatest along the eastern seaboard between the Great Dividing Range and the coast. Energy generation developments may therefore systematically impact coastal zones and escarpment forest ecosystems. Similarly, wind farms may be more efficient when situated on exposed topographies such as ridgelines, where wind speeds are higher and more consistent and energy generation can be maximised relative to infrastructure costs (Diffendorfer et al., 2019). Given these regions are generally unsuitable for many other land uses (e.g., agriculture, urban development), they may provide relatively high-quality habitat for plant species, free from threats such as clearing or nutrient addition. These high elevation locations may also provide refugia for species in the face of a changing climate as plants migrate upslope to track conditions for growth and reproduction (Anderson & Wadgymar, 2020). Indeed, many of these 'residual' areas could be placed under increased pressure from renewable technology projects which are rolled out in the absence of effective regulation and scrutiny.

Harnessing hydropower is highly reliant on riverine regions with sufficient water flow, placing concentrated pressure on aquatic ecosystems and their associated and adjacent riparian flora, and geothermal power must be harnessed within regions of high geothermal activity (e.g., the United States, Turkey, Indonesia, Philippines) (He et al., 2024; Rehbein et al., 2020). Both aquatic environments and geothermally active regions often support fragile and biologically unique plant assemblages, and broader diversity (e.g., lichens, insects, fish) (Mammoth-Pacific & Paulus, 2009; Pavlik & Enberg, 2001; Winemiller et al., 2016). Solar facilities are best placed in places of high solar radiation and flat terrain, while tidal energy requires infrastructure development in coastal regions. Meanwhile, some forms of biomass energy production (see Table 1) require large areas of arable land to support high energy crop outputs, placing pressure on both native vegetation and food security (Behrman et al., 2015; Potrč et al., 2021). Regulatory processes will sometimes require specific consideration of the potential impact of a renewable project on highly productive arable land. For instance, some Australian states require an assessment that considers impacts on arable land, including through community consultation and mapping. In some instances, lands integral to cultivation or grazing can be integrated into circular systems approaches, such as agrisolar (Al Mamun et al., 2022; see section **3.4 Responses to potential impacts on plant diversity from the energy transition** for more details).

The total amount of land required to produce the same amount of energy differs between renewable energy technologies, resulting in varying scales of land use impacts. For example, evidence suggests that ground-mounted solar and biomass farms require a greater total area of land compared with existing fossil fuel energy systems to produce the same amount of energy, meaning that transitioning to these technologies may require effective land use planning to minimise pressures on native vegetation and food security (Potrč et al., 2021; Ritchie, 2022). By contrast, wind energy requires minimal vegetation clearance per turbine, potentially supporting landscape-scale conservation relative to other energy generation approaches; however, the broad spatial distribution of turbines may have significant cumulative ecological impacts (Ritchie, 2022) and access tracks to transport large infrastructure components can fragment landscapes (Diffendorfer et al., 2019). Harnessing power from rivers can place concentrated pressures on riverine ecosystems and communities, as seen in cases like the development of the Three Gorges Dam in China, which affected an area of approximately 58,000 km^2 and required the relocation of millions of people (Abbasi & Abbasi, 2000; Wu et al., 2004). Equally, small-scale hydro development results in the spread of impacts across multiple river catchments, often requiring more land to produce the same amount of power as its larger counterparts (Lange et al., 2019; Ritchie, 2022). In some instances, high land use technologies such as solar arrays can be integrated with biodiversity conservation and restoration projects (see section **4.5 Future Perspectives**).

These complexities reinforce the need for holistic, site-specific, integrated planning of renewable energy projects that consider the diversity of values, impacts, constraints and opportunities relevant to any given region. For instance, Integrated Vegetation Management tactics (see Table 1) along energy transmission corridors can enhance native plant diversity by encouraging a mix of herbaceous species and shrubs, thereby supporting high-quality habitat for vegetation-dependent fauna such as bats and bees (Campbell et al., 2024; Russell et al., 2018). By contrast, poor planning can place uneven strain on diverse plant assemblages such as those found in closed desert basins where rare earth minerals—essential mining constituents for certain technologies—tend to accumulate over time (Parker et al., 2024).

Importantly, the transition towards renewable energy could place pressure on plant conservation efforts in protected areas. Rehbein et al. (2020) observed that 17.4% of large-scale renewable facilities globally operate within important conservation areas, and an increase to 19% is projected by 2028. Additionally, Ng et al. (2020) reported that 71% of global geothermal energy projects were found to operate within 10 km of one or more protected or Key Biodiversity Areas, including in the Philippines, where more than half of all plant species are endemic (52%; Table 2; Gallagher et al., 2023). Pressure to rapidly expand renewable energy could jeopardise native plants are they are often neglected in the planning of life cycle assessments (LCA's; see Table 1) for renewable technologies (Levenda et al., 2021; Rahman et al., 2022). Further, many places targeted for renewable infrastructure expansion or resource extraction to support the transition to renewables are located on Indigenous homelands, potentially placing tension on cultural connections to important plant species as industry expands infrastructure to meet energy demands (Kennedy et al., 2023; Owen et al., 2023). Accounting for the environmental impacts of a product, process or service across all life-cycle stages from development to end-use will be essential to guide a sustainable energy transition (Caetano et al., 2024).

3.3 | *States* and *impacts* on plant species and vegetation communities

Outlining the known and potential state changes and impacts the renewable energy transition may impose on global plant diversity can help direct fit-for-purpose responses for project proponents and regulators who set limits on the scope, permissible impacts and life-cycle requirements of projects. Each renewable energy type creates a unique ecological footprint (see Table 1) with impacts that can either directly or indirectly influence plant diversity and vegetation (Table 3). The scale (local, regional, global), and feasibility to mitigate within the bounds of current known ecological responses will also vary considerably across and within renewable types. Note that we recognise that the literature may underreport positive biodiversity impacts of renewable energy development, potentially due to limited research attention or publication bias. Accordingly, we highlight examples and scenarios that illustrate potential synergies between renewable energy and biodiversity to draw attention to these win-win scenarios.

3.3.1 | Utility-scale solar

The installation and operation of utility-scale solar (see Table 1) infrastructure can result in both direct and indirect impacts on native plant diversity. Sometimes large areas of land and soil must be cleared and graded to produce level ground for panel installation (Hernandez et al., 2014), in conjunction with direct removal of vegetation through ongoing blading, mowing or herbicide application, to prevent panel shading and mitigate fire risks (McCall et al., 2023; Turney & Fthenakis, 2011; Vaverková et al., 2022; Wade et al., 2023). Fire risk is a particular concern for utility-scale solar facilities due to their installation of high-voltage infrastructure in areas of high solar radiation, which are typically fire-prone (Vaverková et al., 2022). Long-term implications for plant communities could stem from these repeated disturbances if vegetation is consistently mowed before plants reach reproductive maturity, resulting in seedbank depletion and reproductive inhibition (Hábenczyus et al., 2024), or off-target effects from herbicide addition reducing important functions such as plant growth or plant-pollinator relationships (Russo et al., 2020).

The disturbance caused when installing solar panels can also create niche space for opportunistic alien plant species to colonise before native vegetation can recover (Karban et al., 2024). Native- to invasive-dominated transitions are also possible via changes to fire regimes resulting from accidental ignitions, which may favour pyrophilic species (Karban et al., 2024). Equally, some species may be lost to a site over time if continued disturbances inhibit long-term genetic diversity, reproduction and recruitment (Wade et al., 2023). Within solar energy scapes, indirect effects have also been observed such as altered microclimates, hydrology and soil respiration rates resulting from shading by solar panels (Armstrong et al., 2016; Barron-Gafford et al., 2016; Wu et al., 2024). Following changes to a site's local microclimate, vegetation state changes could be possible due to loss or recruitment of new plant species under or around solar infrastructure that are adapted to these altered conditions, resulting in novel communities.

Agrivoltaics—the co-location of agriculture, such as shade-tolerant crops or livestock, beneath solar panels—can reduce land-use pressures and support ecosystem services like water cycling, indirectly benefiting plant diversity (Al Mamun et al., 2022). Ecovoltaics, or ecologically informed design of solar PV arrays, has been proposed as an extension of agrivoltaics with even higher potential benefits for plant diversity (Sturchio & Knapp, 2023), though it remains to be seen how broadly ecovoltaic approaches will be adopted on an industrial scale. Some impacts associated with utility-scale solar development may have nuanced effects on plant diversity. For instance, microclimate changes from solar infrastructure, can impose favourable conditions for plants and foster the delivery of important ecosystem services (Graham et al., 2021; Liu et al., 2019; Nordberg et al., 2021; Semeraro et al., 2022; Wynne-Sison et al., 2023). In cropland or pasture settings, solar panels add structural complexity, shading and shelter that can provide microenvironmental and habitat diversity, in turn supporting greater plant biodiversity compared to control sites such as arable fields (Montag et al., 2016). Shading and precipitation captured by panels can also promote increased soil water retention, in turn leading to increased biomass and species richness of adjacent vegetation, particularly in water-limited ecosystems (Liu et al., 2019).

3.3.2 | Wind

Some poorly-sited wind farms have demonstrated direct negative impacts on threatened endemic plant communities resulting from land clearing and soil disturbances required to support infrastructure development (e.g., invasive species colonisation, loss of endemic or rare taxa) (Keehn & Feldman, 2018; Urziceanu et al., 2021). Aside from impacting marine vegetation occurring where they are sited (e.g., mangroves, seagrass meadows, kelp forests), offshore wind farms may also pose impacts to coastal plant communities, given their requirements for transmitting power onto land (Taormina et al., 2018). On land, the need for access tracks and roads to transport infrastructure and parts may result in further clearing impacts (Dhar, Naeth, Jennings, & El-Din, 2020). Additionally, increased soil erosion, contamination and sedimentation have been observed on wind farms (Nazir et al., 2020), suggesting that the vegetation which co-exists with these new infrastructures may be operating in alternative states.

While the ecological footprint of wind turbines may require lower rates of land clearing or disturbance for project siting compared to other renewable energy types, indirect effects of wind farm operation on land have also been reported. Wind farm infrastructure has the potential to indirectly influence plant-insect interactions as turbine operation may result in the mortality of pollinators and other invertebrates (Weschler & Tronstad, 2024). Further, altered microclimates beneath wind infrastructure have led to indirect impacts on plant community composition at some sites, with endangered peat bogs

TABLE 3 Summary of potential direct and indirect impacts on plant species, communities and vegetation from renewable energy types (utility scale solar, wind, hydropower, geothermal, biomass, marine or tidal and all types), their potential impact type and potential responses to help drive more sustainable futures for global plant diversity during the renewable energy transition. See glossary (Table 1) for explanation of renewable types and other key terms.

Renewable Type	State/Impact	Impact type	Potential impact on vegetation	Potential responses	References
All types (Utility-scale solar, wind, hydropower, geothermal, biomass, marine or tidal)	Land use change for infrastructure installation, including access roads and transmission lines	Direct	Habitat loss, fragmentation of plant populations, reduced local and regional plant diversity and function; erosion of protected area provisions in areas that conflict with infrastructure placement; loss of arable land for cultivation, placing additional pressure on the retention of native plant species and vegetation and on food security	**See section 3.4 Response** for details of the following: • Upholding the mitigation hierarchy (i.e., avoid, mitigate, remediate, offset) • Using ecological restoration and remediation • Translocating populations and creating/using ex-situ collections • Using spatial planning to site renewable projects • Undertaking weed risk and soil health assessments • Investing in new research and partnerships	Cavelius et al., 2023; Dai et al., 2015; Guerin, 2017; Hernandez et al., 2015; Keehn & Feldman, 2018; Nazir et al., 2019; Thompson et al., 1984; Urziceanu et al., 2021
	Significant increase in mining to support new infrastructure and energy storage	Direct	Habitat loss and degraded habitat quality from mining for raw materials to support renewable expansion	**See section 3.4**	Oakleaf et al., 2019; Parker et al., 2024; Sonter et al., 2020
	Changes to invasive species risk	Indirect	Increased weed invasion risk through disturbances associated with installing, operating and maintaining infrastructure	**See section 3.4**	Barney & DiTomaso, 2008; Karban et al., 2024; Rahman et al., 2022
	Reduction in soil quality	Indirect	Soil compaction, contamination, sedimentation, erosion and altered biotic and abiotic constituents are possible following infrastructure development and site maintenance, which can influence the viability of future vegetation	**See section 3.4**	Das et al., 2016; Dhar, Naeth, Jennings, & El-Din, 2020; Dhar, Naeth, Jennings, & Gamal El-Din, 2020; Tomczyk et al., 2022
	Modified plant–animal interactions	Indirect	Changes to pollinator visitation rates; changes to seed dispersal through alterations in animal visitation and movement	**See section 3.4**	Graham et al., 2021; Semeraro et al., 2022; Walston et al., 2024
Utility-scale solar	Altered microclimate beneath solar panels	Indirect	Localised modification of hydrology, temperature, solar radiation (shade), humidity and soil respiration beneath solar panels and around infrastructure, which affect plant growth, recruitment and survival	Avoid panel siting in areas that conflict with native vegetation, and rare or threatened plants, especially those whose geographic range may be small; explore opportunities for panel siting within existing agricultural landscapes (e.g., agrivoltaics) as microclimates have been shown to be suitable for crop species; assess potential microclimate impacts of panel installation on native vegetation and mitigate where possible by modifying	Armstrong et al., 2016; Barron-Gafford et al., 2016; Choi et al., 2023; Wu et al., 2024; Wynne-Sison et al., 2023

(Continues)

TABLE 3 (Continued)

Renewable Type	State/Impact	Impact type	Potential impact on vegetation	Potential responses	References
				panel height and angle placement	
	Infrastructure maintenance	Direct	Vegetation frequently mowed, bladed or sprayed with herbicide beneath solar panels; high demand for new water use for washing panels to their maintain efficiency, and potential for ground or surface water depletion; plant growth and productivity inhibited; species may be lost over time if continued disturbance inhibits recruitment; exacerbated impacts on narrow-range endemic plant species	Avoid sites that will require vegetation clearing. Use grazing (e.g., sheep, native animals) designed to mimic natural disturbance regimes to manage groundcover vegetation beneath solar panels; where maintenance of infrastructure is unavoidable, opt to mow over blading or herbicide. If vegetation removal is required, plant slower growing high biodiversity native species in lieu of commonly planted and often non-native, counterparts (e.g. non-native grass species) to stabilise soil and reduce stormwater runoff while enhancing biodiversity; monitor local vegetation disturbance and recruitment and align maintenance schedules with natural growth or reproduction cycles	Turney & Fthenakis, 2011; Nordberg et al., 2021; McCall et al., 2023
Wind (terrestrial and offshore)	Altered microclimate around infrastructure	Indirect	Localised changes to microclimate such as turbulence, wake-effect and temperature can result in vegetation changes (e.g., vegetation drying, increased drought sensitivity); in marine environments, changes to currents and eddy creation, may affect plant growth and dispersal	Avoid wind farm construction in high biodiversity, or climate-sensitive vegetation types on- or offshore; minimise impacts on localised vegetation using active management to maintain ecosystem functions (e.g., irrigation to minimise vegetation drying)	Aksoy et al., 2023; Fraga et al., 2008; Tang et al., 2017; Qin et al., 2022
	Vegetation transitions	Direct + Indirect	Changes to vegetation structure, diversity and productivity over time following microclimate changes resulting from infrastructure installation and operation	Continue long-term monitoring to understand the full scope of impacts on vegetation, employ mitigation measures for species that may be at high risk of loss or change	Aksoy et al., 2023; Dai et al., 2015; Liu et al., 2020; Ji et al., 2023
	Fragmentation due to access tracks, road developments or transmission lines	Direct	Clearing of vegetation to provide for transport of large components (e.g., turbine blades) or new transmission lines, including those from offshore wind facilities; dust creation and settling on plant leaves and stems, affecting photosynthesis; note these impacts include for offshore wind where transmission lines come on land	Plan and execute expansions on existing tracks and roads to minimise new disturbance; Consider transportation impacts in assessment processes for new projects	Diffendorfer et al., 2019
Hydropower	Flow alteration and reservoir creation	Direct	Flooding of habitats, resulting in reductions geographic range of some species and reduced	Avoid hydropower sites in regions that will have high biodiversity impacts; minimise	de Resende et al., 2019; He et al., 2024; Jager et al., 2015;

TABLE 3 (Continued)

Renewable Type	State/Impact	Impact type	Potential impact on vegetation	Potential responses	References
			diversity and abundance; increased risk of algal blooms; increased risk of downstream vegetation mortality related to increased flows; increased incidence of hypoxic events that deprive plants of oxygen reducing growth and increasing mortality; decomposition of affected plants in flooded regions contributing to increased CH_4 and CO_2 emissions	impacts by moderating flows that mimic natural disturbance regimes; implement reservoir operation strategies to reduce algal blooms; monitor GHG emissions and reduce operations in response to high levels; ensure restoration and offsetting to account for any residual impacts that are unavoidable	Li et al., 2012; Rahman et al., 2022; Song, 2023
	Modified river connectivity	Direct	Increased fragmentation of riparian and wetland species due to limitations on the dispersal of some species reliant on connected flows or animal migrations to disperse seeds; reduced gene flow between plant populations	Avoid further development of hydropower in regions that will increase riverine disconnection; use restoration and assisted migration to mitigate negative impacts on flow-dependent species and seeds	Parolin et al., 2013; Jones et al., 2020; Schöngart et al., 2021
	Alteration to natural water flow and sediment transport	Direct	Maintenance creating flushes of increased sedimentation and nutrient deposition affecting up and downstream vegetation; reduced benthic algae and macrophyte species diversity; changes to seedbank dynamics and germination related to inundation, sediment mixing and turbulence	Use sediment capture and bypass technologies to minimise negative impacts of dam maintenance on riparian ecosystem health; monitor, via soil cores, the soil-based seedbanks overtime to detect changes in composition and respond through environmental plantings of species which show decreased abundances	Asaeda & Rashid, 2012; He et al., 2024; Tomczyk et al., 2019
Geothermal	Surface disturbances from drilling access points	Direct	Habitat loss (e.g., around wells and associated infrastructure), fragmentation, soil erosion, changed abiotic conditions for plant growth. Fluid extraction at plant can cause permanent loss of geothermal active hotspots in other parts of a region, threatening plants adapted to these specific habitats	Engage with geothermal experts prior to construction to understand the scale of potential impacts for large geothermal systems; avoid development in geothermal regions with highly sensitive flora; implement directional drilling of several wells at a single site to concentrate geothermal power source reducing the total area of land affected; engage in site remediation following closure of geothermal sources to facilitate ecosystem recovery	Ármannsson & Kristmannsdóttir, 1992; Barrick, 2007; Ng et al., 2020
	Modifications to groundwater dynamics	Indirect	Large quantities of water required to cool geothermal plants can deplete resources available for groundwater-dependent plants such as deep-rooted trees	Create or transition to closed-loop geothermal methods to reduce competing use of groundwater, particularly for tree and shrub species with deeper root systems	Abbasi & Abbasi, 2000; Axtmann, 1975; Bošnjaković et al., 2019; Ng et al., 2020
	Pollution	Indirect	Wastewater pollutants can enter habitats, altering abiotic conditions for plant growth,	Isolate the energy system from the subsurface water by transitioning to closed-loop	Axtmann, 1975; Bacci et al., 2000; Bayer et al., 2013

(Continues)

TABLE 3 (Continued)

Renewable Type	State/Impact	Impact type	Potential impact on vegetation	Potential responses	References
			reproduction and survival; transitions in vegetation composition over time	geothermal methods; regulate the need for remediation to protect affected waterways, including fines to avoid impacts	
Biomass	Risk of introducing new invasive species	Indirect	Species used in biomass cropping may become naturalised or invasive, increasing competition with native plant species or changing fire regimes	Conduct comprehensive weed risk assessments to identify low invasion risk biofuel species; explore the use of high diversity native grasses as alternative biofuel sources with co-benefits to biodiversity, or waste-based biofuel sources	Barney & DiTomaso, 2008; Raghu et al., 2006; Tilman et al., 2006
	Soil depletion and water use	Indirect	Soil erosion and/or nutrient augmentation or composition change, leading to altered abiotic conditions for native plant species growth; reductions in biodiversity at higher trophic levels due to intensive farming and increased homogeneity of vegetation (monocultural cropping) leading to changed pollination and dispersal dynamics	Implement sustainable agricultural practices into biofuel farming (e.g., low fertiliser and chemical inputs, enhance on-farm diversity with native species plantings, crop rotation, agroforestry); select biofuel species that are more sustainable to grow (high land/water use efficiency, low nutrient demands, low pesticide inputs)	Dauber et al., 2010; Tudge et al., 2021
Marine or tidal	Habitat displacement and artificial habitat creation from infrastructure development	Direct	Biofouling by species, affecting macrophytes such as seagrass and algae; changes in tidal vegetation communities and shifting dynamics (e.g. competition, facilitation)	Increasing our understanding of the ecological functionality of marine habitats created by renewable infrastructure, improved risk assessments of coastal habitat impact prior to marine energy developments	Bonar et al., 2015; Macleod et al., 2016
	Changes to water salinity and oxygen levels	Indirect	Altered abiotic conditions changing settings for plant growth, reproduction and survival; increases in halophytic species and shifting competitive dynamics; increased risk of hypoxia	Implement continuous monitoring of salinity and oxygen levels and be rapidly responsive to fluctuations beyond the limits to plant growth; increase hydro-environmental research to better understand and predict the biotic and abiotic impacts of emerging marine renewable technologies	Kadiri et al., 2012; Rahman et al., 2022
	Alteration of tidal and wave dynamics	Indirect	Changes in tidal displacement, sedimentation and turbidity resulting in changes in the dynamics of coastal plant communities	Identify plant species and ecosystem types that are susceptible to changes in hydrodynamic conditions, understand local and large-scale impacts of tidal energy developments on vegetation	Hooper & Austen, 2013; Shields et al., 2011

becoming increasingly colonised by invasive species and transitioning toward wet-meadow ecosystems (Fraga et al., 2008). Despite these observed changes to plant communities (Ji et al., 2023; Liu et al., 2020), the short timescales of many studies may not capture the full impacts of operational wind farm infrastructure on vegetation. For example, a 16-year study on wind farm impacts on vegetation in Turkey observed significant changes in herbaceous vegetation cover beneath operational turbines, yet detectable differences for longerlived perennial species may require longer timescales to emerge (Aksoy et al., 2023).

Well-sited and responsibly managed wind farms can offer tangible biodiversity benefits. In agricultural landscapes, wind infrastructure can create microhabitats that enhance plant and pollinator diversity, supporting vegetation communities comparable to that of nearby seminatural grasslands (Pustkowiak et al., 2018). In extreme environments, such as the Gobi Desert, wind turbines modify local microclimates in ways that improve vegetation cover and biomass (Xu et al., 2019). Despite their large size, the low-intensity footprint of wind farms relative to other energy generation approaches may present specific conservation opportunities. For example, the Kaheawa Wind Power Project in Hawaii integrated a habitat conservation plan alongside infrastructure development to restore and manage native plant communities and protect the endangered bird and mammal species throughout the project's life cycle (Kaheawa Wind Power, 2017). Similarly, the submerged structures installed for offshore wind developments can serve as artificial reefs and habitat for marine species (Kamermans et al., 2018).

3.3.3 | Hydropower

Hydroelectric power presently accounts for 50% of the total power generated across all renewable technologies, with far-reaching impacts across many biomes globally (IEA, 2023). For example, important regions for floristic diversity such as the Brazilian Cerrado (Ferreira et al., 2022), or sensitive landscapes like the flora of Iceland's alpine tundra (Thórhallsdóttir, 1993) have been significantly affected by hydropower development. Hydroelectric power systems impact ecosystems across all stages of a project's life cycle, as dam construction, operation and maintenance lead to direct landscape changes (e.g. flooding, erosion, water diversion) that can significantly impact vegetation both up- and downstream of the diversion (Botelho et al., 2017). The development of hydropower infrastructure often requires significant land clearing, or flow alteration, creating reservoirs that flood out large regional areas, resulting in changes to vegetation diversity, structure and function (He et al., 2024). For example, impacts following the construction of the Three Gorges River hydroelectric dam in China resulted in significant shifts in plant community composition, including the loss of threatened riverbank-dependent vascular species, and increases in non-vascular aquatic species, resulting in distinct novel vegetation assemblages relative to the pre-dam community (Yang et al., 2012).

Equally, the decomposition of vegetation following post-construction flooding can contribute to increased greenhouse gas emissions, which could indirectly impact global vegetation (Deemer et al., 2016). Disturbances in river connectivity resulting from hydro infrastructure development affect plant movement and can either transport or inhibit the movement of invasive weeds to connected waterways (Rahman et al., 2022; Yang et al., 2012). Such disturbances in connectivity can further limit the dispersal of native plant seeds, including fish-assisted dispersal, with follow-on impacts on the condition of downstream vegetation (Jones et al., 2020; Parolin et al., 2013; Schöngart et al., 2021). Maintenance of many hydropower stations require releasing large volumes of water, a novel disturbance which can trigger mortality of downstream vegetation (de Resende et al., 2019).

While hydropower is a high-output energy source often associated with significant impacts on biodiversity, in some cases, dams may act as a dispersal barrier restricting the spread of invasive species, offering positive downstream benefits (Anderson et al., 2020). Equally, careful design and management can reduce the environmental impacts of hydropower facilities. For instance, the controlled maintenance of ecologically representative flow regimes from dams can be managed to support downstream plant diversity (Xu et al., 2020). Equally, emerging technologies like Natel Energy's FishSafe™ (https://www.natelenergy.com/turbines) turbines enable small-scale power generation without the need for flooding large basins and their vegetation, allowing safe passageways for migratory fish.

3.3.4 | Geothermal

Geothermal energy constitutes approximately 0.5% of renewable generation capacity globally and generally has a low land-use footprint relative to other energy technologies (IRENA & IGA, 2023). However, impacts on plants across all stages of a projects life cycle are possible, and will differ based on the type of facility, local environment and affected ecosystem's characteristics (Ng et al., 2020). Some geothermal power plants emit greenhouse gasses and other pollutants, such as mercury, boron and arsenic, which can directly influence nearby vegetation or contribute indirectly to the large-scale emissions driving climate change (Bayer et al., 2013; Dhar, Naeth, Jennings, & Gamal El-Din, 2020; Rahman et al., 2022). For example, vegetation uptake of hydrogen sulphide and mercury was observed from emissions at a geothermal plant in Italy (Bacci et al., 2000). Generally, the concentrations of pollutants in vegetation decrease with increasing distance from active power plants (Dhar, Naeth, Jennings, & Gamal El-Din, 2020). However, wastewater from active power plants can contain pollutants such as boron with off-target impacts on landscapes beyond the boundaries of geothermal plant project sites (Koç, 2011). Vegetation clearing to drill holes or develop infrastructure such as roads or transmission lines can have localised impacts on native vegetation (Ármannsson & Kristmannsdóttir, 1992; Dhar, Naeth, Jennings, & Gamal El-Din, 2020; Ng et al., 2020). Equally, thermal discharge from geothermal power generation can directly influence nearby vegetation and ecosystems (e.g., germination and persistence), with potential adverse impacts on specialist and often rare plants that inhabit thermophilic ecosystems (Mammoth-Pacific & Paulus, 2009; Pavlik & Enberg, 2001).

Importantly, the impacts of geothermal energy types can be localised or have far-reaching indirect effects. The extraction of geothermal fluids at a plant may indirectly cause permanent losses of geothermal active hotspots in other parts of a region (Barrick, 2007). Reports of biogeochemical state changes such as altered groundwater temperatures, microbial community composition shifts and contamination have been observed from geothermal energy projects (Griebler et al., 2016).

Careful planning, implementation of mitigation measures and ongoing management can be used to minimise impacts and benefit the diverse and endemic vegetation assemblages that typically inhabit geothermal regions (Beadel et al., 2018). While complete avoidance of ecological disturbance may not always be feasible due to the siting constraints for infrastructure, prioritising the avoidance of sensitive areas—combined with efforts to minimise operational impacts such as closed-loop designs (Bošnjaković et al., 2019) can significantly reduce environmental impacts. For example, the Tu Deh-Kah Geothermal project in Canada (https://tudehkah.com/) repurposed a depleted oil well to avoid additional land clearing, while employing low-impact, closed-loop systems alongside habitat restoration to enable sustainable and biodiversity-friendly geothermal energy extraction.

3.3.5 | Biomass

Biomass energy is one of the oldest forms of renewable energy, spanning from simple methods of burning wood to cook and heat to modern technologies such as plant and waste-based biofuels and gases that can power vehicles and produce electricity. Evaluating the impacts of biomass energy on native vegetation is difficult as there are many types of biomass energy, all with different value chains (see Table 1) and in varying stages of production (Cavelius et al., 2023). However, most of the current biomass energy production (~90%) uses food crops (e.g., corn, wheat, sugarcane, soybean, palm), and has similar impacts on native vegetation as most large-scale agricultural practices (IEA, 2023; Tudge et al., 2021). Importantly, the expansion and intensification of agriculture to cultivate biomass crops drives further loss of plant species and their habitats and contributes to significant degradation of soils and water use, reducing the ecological health of nearby ecosystems (IEA, 2020; Elshout et al., 2019; Tudge et al., 2021). Soybean and palm-based biofuel production has grown considerably across important biodiversity hotspots with unique vegetation (e.g., Wallacea, Atlantic Forest and Madagascar), placing further threats on these already threatened landscapes (Koh & Ghazoul, 2008).

Colonisation into natural ecosystems is another possible indirect risk to native plants from biofuel crop production, as many targeted crops share similar life history traits with established invasive weeds (Barney & DiTomaso, 2008; Raghu et al., 2006). A 2015 study conducted weed risk assessments for 17 commercial bioenergy crops, finding that 94% (16 cultivars) of the evaluated species have a high probability of becoming invasive in the United States (Smith et al., 2015). Further, experimental introductions conducted by Barney et al. (2012) found that two of the leading bioenergy crops in the United States (switchgrass and giant miscanthus) can develop self-sustaining populations in riparian ecosystems in California, suggesting that colonisation into native ecosystems is possible. Australian *Acacia* species have also become highly invasive across the world, including in Africa, where they are used extensively for biomass production (Reza et al., 2019).

Despite the above trade-offs, plant-derived renewable energy sources offer significant promise for a sustainable energy transition (Grace et al., 2020). The benefits largely depend on how, where and what species are grown or parts sourced for fuel production. For instance, biomass systems using native or perennial plant species can enhance plant diversity by providing habitat, improving soil health and increasing carbon capture (Grace et al., 2020; McGrath et al., 2017; Tilman et al., 2006). Equally, utilising post-agricultural plant waste for biomass can foster improved agricultural sustainability by aligning waste management with energy production (Whalen et al., 2017). Biomass derived from invasive species also presents a valuable opportunity to synergise fuel production alongside ecosystem management (Grace et al., 2020; Nackley et al., 2013; Van Meerbeek et al., 2015). Finally, emerging technologies using algae-based biofuels also provide a sustainable alternative, requiring less land, water and nutrients compared to traditional crops (Borowitzka & Moheimani, 2013; Grace et al., 2020).

3.3.6 | Marine or tidal

Marine energy systems are designed to extract and convert hydrokinetic energy from tides, oceanic currents and waves as well as thermal or salinity gradients. Evaluating the impacts of these renewable systems is difficult due to the complex and dynamic interactions that occur in oceanic environments, coupled with the infancy of many of these technologies (Bonar et al., 2015). Martínez et al. (2021) found that studies evaluating the environmental impacts of marine energy extraction are limited (8–17% of total publications on marine renewables) and demonstrate a 10–23-year time lag between the publication of environmental impacts relative to the development of these technologies. Of this limited pool of knowledge, hydrokinetic energy systems can cause physical disturbances to marine and coastal ecosystems during development, operation and decommissioning of power plants (Gill, 2005), which can directly or indirectly impact vegetation through modifications to habitat area and structure, water dynamics and sediment transport (Bonar et al., 2015). The development of barrages to support tidal energy generation can directly remove estuary habitats, affecting important vegetation such as benthic microalgae. Importantly, these impacts can occur directly within the infrastructure footprint or also have far-reaching impacts (estimated up to 10 km away from a plant) which could affect primary producers across regional tidal ecosystems (Shields et al., 2011).

Tidal energy plants have also been found to modify water salinity and dissolved oxygen levels, posing a threat to the persistence of native aquatic plants, which are sensitive to these state changes (Kadiri et al., 2012). For instance, during seabed surveys prior to the construction of the MeyGen tidal energy project in northern Scotland, observations were made of rare seaweed (macroalgae) species that may be impacted by hydrological alterations from tidal energy infrastructure (Moore, 2009; Shields et al., 2011).

Marine energy systems, however, can provide benefits to biodiversity by creating additional habitats on submerged infrastructure. These artificial reef-like structures can support the development of macroalgal communities such as seagrasses and kelps. In many instances, these artificial habitats have demonstrated biodiversity improvements (Inger et al., 2009); however, careful monitoring is required to ensure these structures do not become colonised by invasive species (Inger et al., 2009; Nall et al., 2017). Moreover, marine and tidal energy sites can function as de facto marine protected areas due to restrictions on fishing and boating activities in their vicinity (Thurstan et al., 2018).

3.4 | *Responses* to potential impacts on plant diversity from the energy transition

The energy transition must be carefully planned with sound and equitable responses to reduce negative outcomes for climate, nature and people.

To guide the planning and implementation of a plant-positive renewable energy transition, integrated, cross-sectoral and participatory planning approaches are required as siloed environmental plans are seldom effectively adopted (Gutierrez et al., 2024). Achieving community and local buy-in to a plan requires genuinely engaged planning processes that start with clear articulation of local and stakeholder aspirations (Opdam et al., 2008; WWF & IUCN WCPA, 2023). A clear articulation of outcomes sought by stakeholders allows policy analysts to identify constraints and opportunities, including identifying zones in the landscape that are available and not available for energy development. In practice, no-go zones could be areas of high biodiversity, cultural or agricultural value. Key systematic planning principles such as complementarity (Leathwick et al., 2010; see Table 1) help ensure that environments and ecosystems are not disproportionately impacted in a way that leads to loss of species and ecosystems. At all stages of planning, the mitigation hierarchy (see Table 1) (avoid, mitigate, remediate, offset; Arlidge et al., 2018) must be upheld (see Table 5) (Cavanagh & Benjaminsen, 2014; Moilanen & Laitila, 2016). Fundamental to this, should be a global commitment to avoid actions that support renewable expansion within regions containing intact native vegetation, using planning tools such as spatial prioritisation to balance the needs of biodiversity and infrastructure (Butschek et al., 2023). For example, planning that favours siting solar developments within existing urban or agricultural landscapes (Nordberg et al., 2021) or retrofitting operational dams (see Table 1) to harness hydroelectric power can avoid additional expansion of renewables on land where native vegetation is still predominantly intact (Choi & Song, 2016; Hernandez et al., 2015). Similarly, the concept of ‘stacked energy scapes’ (see Table 1) is emerging to expand renewable development within existing operational energy footprints (land, infrastructure), to reduce environmental impacts and provide opportunities to communities that are reliant on energy economies (Harlan & Baka, 2024).

Where impacts cannot be avoided, they should be minimised through careful response strategies that comprehensively monitor risks and intervene to mitigate harm. For instance, it is possible to prioritise the co-existence of native vegetation alongside unavoidable new developments (Smith et al., 2022), assuming that appropriate environmental assessments have been conducted. Additionally, renewable projects modified to minimise negative impacts, such as by directional drilling of several geothermal wells at a single site, can reduce land impacts while concentrating power extraction (Bošnjaković et al., 2019; Ng et al., 2020). Equally, sustainable agricultural practices can be incorporated into biomass generation techniques by selecting biofuel species that are more sustainable to grow (e.g., low invasion risk, low land use requirements, low pesticide inputs), help utilise otherwise wasted agricultural material (e.g., 2nd-4th generation biofuels), or include species that provide co-benefits to biodiversity (e.g., diverse native grasslands) (Correa et al., 2017; Tilman et al., 2006). Spatial planning can also be used to optimise the placement of renewable technologies to avoid risks to food security where the infrastructure associated with renewable projects is sited on arable lands (Zhuang et al., 2022). For instance, repurposing existing industrial and disturbed spaces for solar development or shifting from utility-scale solar infrastructure toward increased adoption of microgrids within the built environment offer further opportunities to enhance the sustainability of solar energy deployment with minimal environmental impacts.

Translocation, ex situ conservation methods (e.g., seed banking, assurance colonies) and ecological restoration and revegetation must also be used to respond to and remediate impacts of renewable technology to plant species. However, we caution that these have a high risk of failure and can involve considerable expense (Doyle et al., 2023), especially when other ecological restoration is also required (Brancalion et al., 2019). Ex situ conservation measures can offer some recourse to preventing further losses to plant genetic diversity (Walters & Pence, 2021) but require significant investment and planning to ensure that new populations are established in appropriate locations and monitored to track progress in establishment. Where renewable energy projects are appropriately located on brownfield sites such as former industrial land, restoration and revegetation in tandem with renewable infrastructure development could benefit plant diversity, though such projects typically require considerable investment over a long timeframe to succeed (Brancalion et al., 2019; Sturchio & Knapp, 2023).

Importantly, we caution that compensating for project impacts through offsetting should only be considered as a last resort after all other measures within the mitigation hierarchy have been pursued. When offsetting is used, it is essential that proponents seek to use ‘like-for-like’ (see Table 1) offsets. Previous use of offsetting has failed to effectively address the impacts of projects on species diversity and ecosystem functions, resulting in a net loss for biodiversity (Cavanagh & Benjaminsen, 2014; Moilanen & Laitila, 2016).

Potential impacts can also be identified through systematic approaches to estimating risk, such as using formal Weed Risk Assessment (WRA) protocols or soil health monitoring procedures. WRA's have been used to assess the likelihood of invasion from new biofuel crop species prior to their importation (Smith et al., 2013). Similarly, soil health monitoring methods (e.g., pathogen/toxicity testing, sediment forecasting) can be used when planning new developments to identify risk factors for important plant–soil interactions and design solutions to minimise or mitigate these risks (Hernandez-Soriano, 2014; Dhar, Naeth, Jennings, & El-Din, 2020; Tomczyk et al., 2022).

Integration of the mitigation hierarchy alongside cross-disciplinary collaboration will be vital to balance the imperatives of biodiversity conservation with the goals of the renewable energy transition, with a number of leading examples already underway (Table 4). Partnerships which seek to address knowledge gaps around the circular processes in renewable infrastructure, such as recycling of raw components to limit requirements for extractive land use, can be co-designed with plant scientists to reduce impacts from mining on plant diversity. Similarly, working with social scientists to understand motivations of land holders for protecting plant species on private lands could provide important insights around ways to offset, covenant or otherwise protect plant species in renewable energy development. Working directly with industry partners, such as energy companies, or with Indigenous groups (see section 4.4 **Facilitating Indigenous ownership and benefit sharing in renewable energy projects**) to address research needs emerging from their projects may also help to create a bottom-up approach to preventing impacts on plant species.

4 | CALLS TO ACTION

To achieve the transformational change required to support a sustainable energy transition amid the global biodiversity crisis, actions must

TABLE 4 Example life cycle assessment (LCA; see glossary (Table 1)) of the potential impacts to plant diversity across all stages of renewable energy projects (see Caetano et al., 2024 for an explanation of LCA). The matrix displays theoretical renewable projects, detailing level of impact from each energy type against different project stages i.e., Exploration & Assessment; Project Design; Execution, Construction & Commissioning, including energy storage; Operation; Reclamation, Closure & Decommissioning. Each cell of the matrix is coloured according to the potential level of impact (yellow = minimal; orange = moderate; red = high).

Renewable Energy Type	Exploration & Assessment	Project Design	Execution, Construction & Commissioning	Operation	Reclamation, Closure & Decommissioning
Utility-scale solar	**Minimal**: Land assessment involves minor disruption	**Minimal**: Placement planning might marginally disturb vegetation	**High**: Where there is significant clearing for panels and ground preparation in large areas, and little adherence to landscape-sensitive designs	**Moderate:** Panels shade vegetation and alter plant community dynamics, panel maintenance may require frequent vegetation clearing	**Moderate:** Land restoration may be challenging depending on disturbance levels
Wind	**Minimal**: Land surveys and site evaluation may cause negligible vegetation impact	**Minimal**: Design plans avoid significant vegetation loss	**Moderate**: Clearing for turbine bases, access roads and cables	**Moderate**: Permanent structures have limited footprint	**Minimal**: Some vegetation restoration; minimal lasting changes
Hydropower	**Minimal**: Hydrological and ecological assessments may disturb riparian vegetation	**Moderate**: Design affects waterway ecosystems and vegetation upstream	**High**: Flooding land for reservoirs removes vegetation permanently	**High**: Altered hydrological regime affects vegetation, reservoir management (e.g., flushing sediments) can disrupt newly established communities	**High**: Decommissioning may not fully restore flooded or altered areas, immediate post-decommissioning flooding can cause severe community disruptions
Geothermal	**Moderate**: Drilling and site testing may disturb vegetation locally	**Minimal**: Design impacts depend on plant size and land requirements.	**Moderate**: Clearing for wells, pipelines and power plant construction.	**Minimal**: Limited impact during operation; small footprint	**Minimal**: Decommissioning involves restoration in some areas of the infrastructure footprint
Biomass	**Moderate**: Site evaluation may require soil sampling and vegetation clearance in areas considered for crop production	**Moderate**: Crop selection and land-use planning can significantly influence vegetation conversion and habitat loss	**High**: Large-scale land clearing and tilling for monoculture biofuel crops (e.g., corn, sugarcane, soy) lead to significant vegetation removal	**High**: Continuous planting, harvesting and use of agrochemicals prevent natural vegetation recovery and can degrade nearby ecosystems	**Moderate**: Land recovery may be limited by the intensity of land use change resulting from biomass cultivation
Marine or tidal	**Minimal**: Coastal surveys may disturb sensitive vegetation (e.g., seagrass, dunes)	**Moderate**: Design choices impact shoreline vegetation	**High**: Installation of turbines and associated infrastructure disturbs coastal habitats	**Minimal**: Operation does not require further vegetation disturbance	**Moderate**: Removal of structures may still impact sensitive coastal zones

TABLE 5 Leading examples of biodiversity-forward renewable energy projects for each technology type, benchmarked against the mitigation hierarchy (avoid, minimise, restore, offset). Where specific actions have been reported, they are described directly. In cases where project documentation does not yet include full information—particularly for restoration and offset stages—boxes are marked as 'Not yet reported' with text in italics indicating actions that could be implemented based on best practices or inferred intent, to highlight potential pathways.

Renewable	Example	Location	Avoid	Minimise	Restore	Offset	Source
Utility-scale solar	The Nature Conservancy's Mining the Sun Initiative	Various U.S. Locations	Repurposes former mining sites, avoiding new land conversion and ecosystem disturbance	**Not yet reported** *Best practices can be implemented to minimize further land clearing and biodiversity impacts*	**Not yet reported** *Actions to restore ecological functions to degraded sites could be implemented alongside operations*	**Not yet reported** *Minimal offsetting should be required if all other levels of the mitigation hierarchy are applied*	https//www.nature.org/en-us/what-we-do/our-priorities/tackle-climate-change/climate-change-stories/mining-the-sun-solar-energy-former-mine-sites/
Wind	Kaheawa Wind Power Project	Maui, Hawaii, USA	Located on degraded (pasture habitat), overlapping with endangered species ranges within conservation lands	Implements turbine shutdowns during peak bat activity and conducts regular monitoring under a habitat conservation plan to assess impacts on nearby conservation areas	Large-scale native plant restoration and habitat improvements through predator control and translocation are implemented.	**Not yet reported** *Limited offsetting should be required if outcomes from the project have minimal residual impacts*	https//www.kaheawawind.com/
Hydropower	Natel Energy's FishSafe™ Turbines	Various U.S. Locations	Retrofit design avoids new dams, minimising flooding and disruption to river ecosystems	Novel turbine technology minimises ecological impacts by improving river connectivity while generating power	**Not yet reported** *When combined alongside river restoration techniques, degraded waterways can be restored while generating reliable renewable energy*	**Not yet reported** *Limited compensation may be required given the low-impact retrofit design, but full outcomes are not yet documented*	https//www.natelenergy.com/turbines
Geothermal	Tu Deh-Kah Geothermal	British Columbia, Canada	Repurposes a depleted oil/gas well (Clarke Lake) into a geothermal facility, avoiding siting impacts	Attempts to minimise external impacts by using low-temperature geothermal resources, and harnessing waste heat for other energy applications (e.g., homes, agriculture)	**Not yet reported** *Limited ecosystem restoration reported at Clarke Lake so far in the project*	**Not yet reported** *The project is still in development; no clear evidence of formal offsetting measures at this stage*	https//tudehkah.com/
Marine or tidal	MeyGen	Pentland Firth, Scotland	The site was selected following a rigorous environmental review in the Pentland Firth, fully avoiding environmental impacts remains challenging, but efforts to implement low-	Careful turbine designs to minimise noise, use of biodegradable hydraulic fluids and reducing material discharge to minimise environmental impact; commitment to minimise	Focuses on rigorous environmental monitoring, and commitments to restore habitats to their original condition where possible	Commitment to offset residual impacts outlined in environmental review	https//saerenewables.com/tidal-stream/meygen/

(Continues)

TABLE 5 (Continued)

Renewable	Example	Location	Avoid	Minimise	Restore	Offset	Source
			impact siting were prioritised	disturbances across project life-cycle			
Biomass	Licella	Australia	Uses non-food biomass residues (e.g., sugarcane trash, wheat straw), reducing land conversion and food production competition	Hydrothermal Liquefaction process uses lower energy, reducing emissions and indirect impacts of these on biodiversity	**Not yet reported** *Restoration practices have not yet been reported*	**Not yet reported** *Offsetting of production-related emissions is suggested but not yet documented in detail*	https//www.licella.com/

shift from project-level responses to embrace system-wide shifts that prioritise the conservation of species, including global plant diversity. Biodiversity, climate change and energy production are intertwined within a complex social, economic, political and environmental system, and a just renewable energy transition should strive to provide complementary opportunities across all these sectors (Carley & Konisky, 2020; Gasparatos et al., 2017; Jager et al., 2021). Here, we outline four key areas for action that centre strategies for stronger plant conservation to the renewable energy transition.

4.1 | Recognising and addressing 'plant-blindness' in the energy transition

Conservation currently operates under a disparity in funding and attention between plants and animals, with animals benefiting from people's stronger preference for, better recall of and easier visual detection of animals (Balding & Williams, 2016). The tendency to overlook, or undervalue plants, compared to animals – dubbed "plant blindness" (Wandersee & Schussler, 1999) – risks becoming entrenched in assessment and mitigation approaches to the energy transition. Currently, most discussion on potential biodiversity impacts centres on potential interactions between renewables and animal species, primarily birds and mammals (Jager et al., 2021). However, survey work for large-scale renewable projects is turning up plant species which are entirely new to science (e.g., two plant taxa were collected and named for the first time as part of the Asian Renewable Energy Hub in northwestern Western Australia; Biota Environmental Services, 2017). Several actions are needed to address the omission of impacts on plants, including filling persistent data gaps on where plants are found and what the impacts to them are. We must also ensure regulators consider plants equally alongside animals, and that there is public pressure on governments to ensure a comprehensive approach to assessing the risks posed by all stages of renewable projects (see Table 3) on plant species and vegetation communities.

Awareness of impacts on plants can be supported by ensuring that conservation assessments are comprehensive and up to date. Undertaking, or updating, conservation assessments such as those on the IUCN Red List to clearly outline any risk of decline and ensure accurate extinction risk levels are assigned may be required. Systematic programs of assessment, such as the Global Tree Assessment (Cannon et al., 2023), provide a useful template for achieving this goal. Broadly, strong conservation assessments rely on increasing the completeness of occurrence data for plant species globally, and new efforts to make collections in 'dark-spots' (Antonelli et al., 2025; Lannuzel et al., 2022; Ondo et al., 2024) and aggregate resources into fit-for-purpose databases (e.g., Global Tree Search (Beech et al., 2017) are needed. The emerging use of citizen and community scientists to assist in conservation assessment (Gallagher et al., 2024) and our ability to apply machine learning approaches (Bachman et al., 2024) can also assist in assessing impacts.

4.2 | Ensuring national and international coordination, co-operation and integrated planning to avoid, mitigate and remediate impacts

Plant diversity is unevenly distributed across the world, and some notable areas of high endemism (e.g., the Philippines, Australia; see Table 2 and Figure 3) are also being targeted for renewable energy expansion. The consequences of the environmental burdens which may be associated with this expansion can be addressed through the development, or adherence to, international treaties and targets which recognise the multi-national nature of benefit sharing from the resulting reductions in emissions. For instance, the United Nations (UN) Clean Development Mechanism, previously allowed countries with an emission-reduction or limitation commitment under the Kyoto Protocol to implement an emission-reduction project in developing countries. Some of these provisions remain in the Paris Agreement and can be leveraged to apply sustainability standards to the rollout of projects in plant diversity hotspots. Several of the UN Sustainable Development Goals (SDGs), particularly SDG7: Affordable and Clean Energy, connect the energy transition to biodiversity, indirectly calling for sustainable approaches and consideration of the goals embedded with SDG15: Life on Land.

Importantly, relying on governments or corporations to engage in voluntary action alone is likely insufficient for driving a sustainability-focused energy transition. Incentivising the adoption of low-impact renewable solutions and circular economies (see Table 1) may promote greater uptake of sustainable practices by reducing resource extraction, minimising waste and fostering systems that balance renewable energy growth with environmental stewardship, including for plant species. Notwithstanding, improved policy and regulation will be required to minimise negative impacts and maximise benefits for global plant diversity. Policies should also consider the integration of biodiversity and climate targets to co-create sustainable solutions for nature, climate and people (Pettorelli et al., 2021; Pörtner et al., 2022). Equally, enforcing mandatory implementation and reporting of robust environmental impact assessments throughout renewable life cycles will help foster transparency and accountability for nature.

4.3 | Facilitating Indigenous ownership and benefit sharing in renewable projects

Plants are integral to Indigenous people, underpinning many aspects of cultural, social and spiritual practice including in their role as medicine, food, tools and in shaping identity by defining traditional narratives, ceremony, totems or moieties (Balick & Cox, 2020). In turn, Indigenous people often play a pivotal role in protecting plant species, including those at direct risk of extinction, through cultural practices which return appropriate disturbance regimes to landscapes, such as cultural burning or 'goodfire' or right-way fire (Fletcher et al., 2021; Long et al., 2021; Ruscalleda-Alvarez et al., 2023), or through species stewardship (Goolmeer & van Leeuwen, 2023; Ogwu & Osawaru, 2022). A shift to clean energy practices may also mirror the ethos of Indigenous stewardship, which typically centres respect for the environment (McLeod et al., 2024). Further, rights to the conservation and protection of the environment are embedded in the UN Declaration on the Rights of Indigenous Peoples and appear alongside the right to "the productive capacity of lands, territories and resources". Additionally, the Nagoya Protocol (Teran, 2016) embedded within the Convention on Biological Diversity enshrines access to plant (and animals) genetic resources and the fair and equitable sharing of benefits with Indigenous and local communities arising from their utilisation. The Nagoya Protocol is a legal framework that respects the value of traditional knowledge associated with plant genetic resources (Buck & Hamilton, 2011).

Many areas of notable plant diversity being targeted for renewable technology expansion are situated on the homelands of Indigenous people (e.g., hydropower across Canada and the Amazon basin (Athayde et al., 2019; Stefanelli et al., 2019), solar arid Australia (Fish & Nehme, 2024), solar and wind in regional Australia – Western Green Energy Hub (WGEH Pty Ltd, 2024), Asian Renewable Energy Hub (Biota Environmental Services, 2017) and proposals for lithium mining in Oregon (Bartholomew, 2024)). Ownership of renewable projects and/or the equitable sharing of benefits from their operations offer new opportunities for Indigenous people, with significant potential co-benefits for plant protection and conservation. For instance, renewable energy projects offer pathways to deliver equitable environmental and vegetation management on homelands, to promote and value cultural stewardship of culturally significant plant species, and to contribute to self-determination goals, such as employment and financial sovereignty in the identification, monitoring and management of affected plant species (Grosse & Mark, 2023; Hoicka et al., 2021; Stefanelli et al., 2019). Further, the integration of Indigenous knowledge of plant species – their occurrence, ecology and demography – throughout the life cycle of renewable energy projects can help prevent and/or alleviate impacts, particularly for projects situated in remote locations where scientific knowledge of species may be limited or non-existent (Fish & Nehme, 2024; Lannuzel et al., 2022). Traditional knowledge must, however, be given with consent, through partnerships which are collaborative and co-designed, and preferably in projects which are co-owned, to ensure equity, limit the misappropriation of Indigenous knowledge and prevent exploitation (Feron et al., 2016).

4.4 | Communicating effectively and combating misinformation

It is essential to raise awareness about the importance of assessing potential impacts to plant diversity from the renewable energy transition to promote transparency and accountability. Combating misinformation and misinterpretation of the impacts of renewables' on biodiversity, particularly plants, requires clear and balanced messaging. Communicating both the benefits and risks through scientific and public media will be vital to drive evidence-based decision-making. Alongside the need for clear communication sits the requirement for transparent assessment and monitoring of impacts through the life-cycle of projects, including into the decommissioning phase (see Table 4). To achieve this, we return to the actions needed to address plant-blindness, in particular investing appropriate data systems which capture where plants are and what the known and likely impacts are to them. Having such data systems in place enables transparent, evidence-driven regulatory decisions about how to meet multiple (at times competing) imperatives for our limited land resources including biodiversity conservation, food production and energy delivery. Without adequate and appropriate data on impacts our ability to create a strong evidentiary standard from which we can inform future policy options and improve outcomes for project proponents, neighbouring communities and for nature will be limited.

4.5 | Future Perspectives

The evidence synthesised in this review indicates that a transition to renewable energy must recognise and respond to the risks posed to plant diversity. However, the transition also presents opportunities which, when managed effectively, may enhance plant biodiversity. It is evident that the renewable energy transition poses grand challenges to plant biodiversity, yet also offers a number of potential new approaches and opportunities for plant conservation, underscoring the need for integrative approaches that balance energy development with ecological sustainability.

AUTHOR CONTRIBUTIONS

RVG proposed the review; RVG, SEA, VMA conceptualised the content and approach; RVG and SEA wrote the initial draft, with editing and review contributions from all authors.

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CONFLICT OF INTEREST STATEMENT

Ruby Stephens postdoctoral position is funded by Iberdrola Australia. Claire Hewitt is an employee of Environmental Resources Management Australia, who engage with the renewables industry. All other authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data and code used to generate Table 1, Figure 1 and Figure 3 is now available at https://osf.io/a5f3e/ from the following DOI: 10.17605/OSF.IO/A5F3E.

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