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PERSPECTIVE

Towards a standardized protocol to assess natural capital and ecosystem services in solar parks

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Abstract

1. Natural capital and ecosystem services have emerged as fundamental concepts of ecosystem management strategies in the past two decades, particularly within major international land assessment frameworks, including the UN's Millennium Ecosystem Assessment and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services' Global Assessment Report.
2. Despite the recent development of several analytical methods and models to quantify changes in natural capital and ecosystem services resulting from land use change, incorporating them into the land planning process can be challenging from a practical point of view without guidance on standard methods.
3. In an attempt to decarbonize energy supply systems to meet internationally agreed targets on climate change, solar energy production, in the form of ground-mounted solar parks, is emerging as one of the dominant forms of temporary land use for renewable energies globally.
4. We propose 19 directly measurable indicators associated with 16 ecosystem services within three major stocks of natural capital (biodiversity, soil and water) that are most likely to be impacted by the development of solar parks. Indicators are supported by well-established methods that have been widely used in pure and applied land use research within terrestrial ecosystems. Moreover, they can be implemented flexibly according to interest or land management objectives.
5. Whilst not intended as a precise recipe for how to assess the effects of solar park development on hosting ecosystems, the protocol will guide the solar energy industry and all actors involved, be they researchers, practitioners, ecological consultancies or statutory bodies, to implement a standardized approach to evaluate temporal and spatial changes in natural capital and ecosystem services resulting

from solar park development and operation, with the ultimate aim of generating comparable and reproducible data on ecosystem impact assessment across the solar energy sector.

KEYWORDS
biodiversity, carbon cycle, land management, nutrient cycling, pollination, soil quality, solar energy, water quality

1 | INTRODUCTION

Incorporating natural capital (NC) and ecosystem service (ES) assessments into land use decision-making requires systematic monitoring of ecosystems, which can be a major methodological and financial challenge without appropriate unified approaches (Mace et al., 2015). The rising global demand on land for food, energy, housing and industry to sustain increasing population growth is running parallel with an ever more urgent need to preserve the Earth's ecosystems to mitigate climate change and deliver the goods and services needed for human well-being (Lambin & Meyfroidt, 2011; Sharmina et al., 2016; Stehfest et al., 2019). These concomitant pressures on land are dictating the need for scientific evidence and reliable data to inform decisions (Turner et al., 2007). The use of NC and ES (Box 1) assessment frameworks has emerged as one of the main practices to assess the impacts of land use change on the environment under the whole ecosystems approach to sustainable development (Daily, 1997; MEA, 2005). As a result, there has been an increased effort over the past two decades to develop NC-ES science (Costanza et al., 1997; Daily & Matson, 2008; Guerry et al., 2015; Kareiva et al., 2011; Perrings et al., 2010; Smith et al., 2017) to offer tools and analytical methods to assess the impact of environmental change on the ability of ecosystems to provide resources to society (Bateman et al., 2013; Robinson et al., 2013). There is an urgent need to synthesize the different approaches to identify and link NC components to the continuous delivery of key ES and provide land managers with accessible decision support tools. Two main drivers amplify the need for these tools: (1) rapidly changing policy scenarios in response to climate and ecological emergency declarations made by national governments across the world (Ripple et al., 2020) and (2) the emergence of financial incentives to land owners and managers for enhancing ES at the local (To et al., 2012), national (Department for Environment Food & Rural Affairs, 2020; Liu et al., 2008) and global (Wara, 2007) scales.

Land use change for renewable energy infrastructure has rapidly accelerated in response to decarbonization targets (Dale et al., 2011; Konadu et al., 2015; Trainor et al., 2016). Solar photovoltaics (PV), in particular, are one of the fastest growing sources of renewable energies across the world given their decreasing cost and flexible deployment (IRENA, 2019). Solar parks (SPs) are predicted to cover up to 5% of total land in certain countries by 2050 to accommodate rising PV capacities worldwide (van de Ven et al., 2021). SPs often span large areas and are estimated to take approximately 1.6–2.4 ha of land for every 1 MW installed capacity (Solar Energy UK, personal communication; Taylor et al., 2019). Usually built on former agricultural land, grasslands, pasturelands or within deserts, several potential environmental costs have been linked to SPs (De Marco et al., 2014; Hastik et al., 2015; Hernandez, Easter, et al., 2014; Randle-Boggis et al., 2020; Taylor et al., 2019; Tsoutsos et al., 2005).

Guidance on land management practices that can sustain or enhance NC and ES within SPs has been published (BRE, 2014; Randle-Boggis et al., 2020; Solar Energy UK, 2022), but there have been limited quantifications of the impacts of SPs on hosting ecosystems (e.g. Armstrong et al., 2016). Risks and opportunities to enhancing the environmental sustainability of SPs depend on a

BOX 1 DEFINING NATURAL CAPITAL AND ECOSYSTEM SERVICES

Natural capital refers to the stocks of biotic and abiotic (living and non-living) components of ecosystems that interact to provide goods and services beneficial to human societies (Costanza & Daly, 1992; Guerry et al., 2015). Biodiversity comprises the living component of NC and is a good indicator of the habitat conditions provided by the abiotic components of NC, including soil, water and air, where plants and animals can perform their roles and contribute to the overall functioning of ecosystems.

Ecosystem services flow from NC stocks to sustain human life and activities and can be evaluated through qualitative or quantitative measures, as well as in monetary terms (Costanza et al., 1997, 2011). ES comprise different types of services, including *provisioning* services (**P**) such as food, fibre and fresh water; *regulating* services (**R**) that influence climate and weather events; *supporting* services (**S**) that contribute to nutrient cycling, plant productivity and soil formation; and *cultural* services (**C**) that provide recreational, educational and spiritual benefits to human societies (MEA, 2005). The rate of delivery of ES is highly dependent on the degree of human modification of ecosystems (Vitousek et al., 1997), with land use change currently listed as one of the main drivers responsible for affecting the long-term sustainability of ES provision (IPBES, 2019).

multitude of factors (Hastik et al., 2015; Moore-O'Leary et al., 2017; Tsoutsos et al., 2005), including siting (Cameron et al., 2012; Hernandez et al., 2015; Hoffacker et al., 2017; Stoms et al., 2013), size (Hernandez, Hoffacker, et al., 2014), planning and methods of site preparation (Grodsky & Hernandez, 2020) and construction (Hernandez et al., 2019), as well as local climate and land management practices adopted after construction (Armstrong et al., 2014). Therefore, it is becoming increasingly important to use standardized approaches to quantify the impacts of SPs across diverse climates and land use types and under different land management practices. The need for such assessments is heightened by the increasing emphasis on payment for ES and the need to prioritize multiple aspects of NC simultaneously (e.g. Department for Environment Food & Rural Affairs, 2020; Liu et al., 2008).

This paper aims to outline a standardized assessment protocol to assess the stocks of NC and fluxes of ES in SPs. The protocol has been designed to offer a unified approach to the measurement of natural assets within SPs, as well as to provide a cost-effective, rapid, repeatable and easy-to-use methodology that allows for the collection of large datasets comparable across SPs operating under different local environmental conditions and management practices. The paper is organized as follows: Section 2 discusses some of the potential risks and opportunities that SP development offers for NC stocks and ES provision; Section 3 introduces the protocol and its rationale (i.e. indicators, sampling regime, analysis and reporting, implications); and Section 4 offers some concluding remarks.

2 | EFFECTS OF SOLAR PARKS ON NATURAL CAPITAL AND ECOSYSTEM SERVICES

The construction and operation of SPs can simultaneously affect various NC stocks and influence the delivery of different ES. Effects can be negative or positive depending on local conditions (e.g. climate, ecosystem, land management and construction practices), the time-scale of measurements and the complex interconnected nature of NC and ES (Armstrong et al., 2014). Despite several studies offering some insight into the effects of SPs on hosting ecosystems, there is insufficient knowledge to date to show consensus across different climates and regions.

2.1 | Potential negative effects

A large portion of SP development occurs in dry climates, where sensitive ecosystems tend to show long recovery periods following disturbance (Lovich & Bainbridge, 1999; Lovich & Ennen, 2011). During construction, land clearance can result in habitat loss and wildlife mortality (Guerin, 2017; McCoshum & Geber, 2020; Turney & Fthenakis, 2011), with potential implications for species' genetic connectivity (Dutcher et al., 2020). An increase in fugitive dust, soil compaction and water use can affect air, soil and water quality (Grippo et al., 2015; Guerin, 2017; Rudman et al., 2017), while outbreaks of soil-borne pathogens can have implications for human health and disease regulation (Colson et al., 2017). SP construction can also alter the aesthetic and ecological value of the land to affect human well-being (Torres-Sibille et al., 2009) and impact religious and cultural services for resident indigenous peoples (Grodsky & Hernandez, 2020; Mulvaney, 2017). After construction, the operation of SPs in dry climates can result in reduced albedo (Broadbent et al., 2019; Yang et al., 2017) and an increase in day- and night-time temperatures (Barron-Gafford et al., 2016; Wu et al., 2020), with implications for climate regulation in often heat-stressed desert environments. Moreover, declines in photosynthetically active radiation under PV panels (Barron-Gafford et al., 2019; Liu et al., 2019; Tanner et al., 2020) can modify plant community composition (Tanner et al., 2014) and promote invasive species (Tanner et al., 2020). Bird species richness and density can also be impacted by changes in the distribution and abundance of resources for nesting and feeding (Visser et al., 2019).

Less evidence is available on the negative impacts of SP construction and operation in temperate climates, but similar themes of damage to regulating (Wilken et al., 2015) and cultural (Roddis et al., 2020) services have emerged. During construction, the disruption of soil aggregates and native vegetation through the installation of PV arrays and associated equipment (e.g. underground power cables) and the building of access roads can expose topsoil to erosion (Hernandez, Easter, et al., 2014; Turney & Fthenakis, 2011) and affect soil ecological functions, including climate regulation via soil carbon storage (Choi et al., 2020). During operation, the presence of PV arrays can alter the microclimate and exacerbate seasonal changes in gas fluxes between soil and the atmosphere (Armstrong et al., 2016). These could result in changes to photosynthetic rates and plant biomass under PV panels (Armstrong et al., 2016), as well as changes to species diversity (Hassanpour Adeh et al., 2018) and delays to crop maturity in agrivoltaic systems (i.e. land co-developed for solar PV power and agriculture; Elamri et al., 2018). In addition, PV panels can reflect horizontally polarized light to affect aquatic invertebrates that can mistake large areas of PV arrays for open water bodies and lay their eggs on PV panels, reducing their reproductive success (Horváth et al., 2010) and potentially impacting the wider food web by reducing food availability for bird populations (RSPB, 2014).

There is little available evidence on the negative impacts of SPs in continental climates. However, there could be disruption to several ES due to SP development, including agricultural and forestry products, land carbon sequestration, protection against natural hazards, habitat quality, landscape aesthetic and recreational values (Grilli et al., 2016). For instance, alterations to microclimate due to increased soil temperatures under PV panels can affect food provision in agrivoltaic systems (Cho et al., 2020).

Finally, there is evidence that landscape features and local socio-economic attributes can influence the location of SPs, which can result in their uneven distribution across regions and intensify local negative impacts due to their spatial clustering. For instance, SPs in Great Britain are more likely to be given planning consent if located on relatively level terrain or near similar existing developments, in close proximity to protected areas or on non- (or low grade) agricultural land, as well as in areas with relatively high levels of social deprivation (Roddis et al., 2018). These results suggest that it is easier to develop SPs in rural and semi-rural areas of limited agricultural use and low socio-economic status, and that aesthetic landscape features are particularly important for siting SPs, though mostly due to perceived visual impact by local communities rather than concerns around biodiversity and the value of natural habitats (Roddis et al., 2018).

2.2 | Potential positive effects

SPs have great potential to deliver positive environmental outcomes given their relatively small infrastructure footprint compared to that of fossil fuel energy plants (Solar Energy UK, 2019). There is significant scope to enhance energy production sustainability through land management actions (Moore-O'Leary et al., 2017) and techno-ecological synergy solutions (Hernandez et al., 2019).

In dry climates, opportunities exist to benefit NC and ES during the construction phase by adopting conservation measures. For example, installing permeable fencing and creating movement corridors and artificial dens can provide valuable habitat for listed mammal species (Phillips & Cypher, 2015). The use of low-impact, techno-ecological designs can favour rare plants, provide solar-powered drip irrigation and rainwater harvest to benefit agricultural production (Moore-O'Leary et al., 2017) and improve food security in desert regions (Burney et al., 2010). Construction management practices informed by local hydrological and ecological inventories can protect ephemeral stream channels to preserve riparian habitats for desert wildlife (Grippo et al., 2015) and provide nesting or foraging opportunities for bird species (Rudman et al., 2017). During operation, PV panels can mitigate high soil temperatures (Barron-Gafford et al., 2019; Tanner et al., 2020; Wu et al., 2020) and reduce soil evaporation (Liu et al., 2019). In hot arid regions, these changes can result in increased soil moisture and lead to greater diversity of wild plants (Tanner et al., 2020) and higher rates of seed bank survival (Hernandez et al., 2020), as well as enhance crop water use efficiency and total fruit production in agrivoltaic systems (Barron-Gafford et al., 2019). Similarly, the heterogenous microclimatic conditions normally present at SPs can provide refuge for various arthropod (Suuronen et al., 2017) and bird (Visser et al., 2019) species.

In temperate climates, positive impacts associated with SP operation include ES integration into PV design through the creation of green infrastructures. For instance, the establishment of wetland habitats alongside PV installations can enhance water quality regulation through wastewater recycling, provide habitat for wildlife and materials for biofuel and mitigate air temperature through the cooling effect of vegetation (Semeraro et al., 2020). Similarly, SPs that encourage biodiversity by promoting native annual and perennial forbs and grasses could provide a range of ES benefits, including carbon sequestration, flood regulation, crop pest predation and pollination (Gazdag & Parker, 2019; Moore-O'Leary et al., 2017). Indeed, establishing pollinator-friendly habitats (e.g. native flowering vegetation) may help restore local pollination services and have cascading beneficial effects on species diversity and agricultural production (Blaydes et al., 2021; Walston et al., 2018). In urban areas, PV panels with integrated vegetation have the potential to support arthropod abundance and diversity, including detritivores and parasitoids, both of which are important for urban ecosystem functioning and services (Armstrong et al., 2021). Some positive impacts of SPs in temperate climates can be linked to agrivoltaic systems, since they can provide shade to livestock (Maia et al., 2020), increase crop productivity (Hassanpour Adeh et al., 2018; Marrou et al., 2013; Sekiyama & Nagashima, 2019) and crop water use efficiency through reduced heat stress and increased soil moisture (Elamri et al., 2018; Hassanpour Adeh et al., 2018). The notion of multipurpose land use on SPs, through continued agricultural activity or agri-environmental measures, can support biodiversity and ES to yield economic and ecological benefits (BRE, 2014).

In continental climates, it has been argued that SPs can positively impact air quality and water supply through microclimate regulation depending on management practices (Grilli et al., 2016). Current evidence from agrivoltaic systems points to an increase in crop economic value compared to conventional agriculture by minimizing crop yield losses through cultivation of shade-tolerant crops (Dinesh & Pearce, 2016). Additionally, shade provided by PV panels may improve the welfare of dairy cows through heat stress reduction (Sharpe et al., 2021), whilst opportunities exist to reduce pest and disease burden on livestock and humans through the creation of PV panel traps, which exploit both the electricity generated and horizontally polarized light of PV panels to attract horseflies that exhibit positive polarotaxis (Blahó et al., 2012).

3 | DEVELOPMENT OF A STANDARDIZED ASSESSMENT PROTOCOL

To promote its uptake and effective inclusion into site management decisions, and to provide evidence for regulatory requirements, an NC-ES protocol needs to be time- and cost-effective, realizable by ecological consultants, flexible to implement, supported by robust evidence and oriented towards industry needs. Therefore, we grounded the protocol in existing wide-ranging decision-making frameworks for NC valuation (e.g. Natural Capital Coalition, 2016) and in recent major reports outlining the most urgent land use pressures on the NC stocks of biodiversity, soil and water underpinning climate and hydrological regulation and sustainable food production (FAO et al., 2020; IPBES, 2019; IPCC, 2019; Steffen et al., 2015). In addition, we drew on established understanding of implementing environmental impact assessment frameworks based on the valuation of ecosystem processes and services (e.g. Grizzetti et al., 2016; Haines-Young & Potschin, 2018; Mace et al., 2011; Meyer et al., 2015; Pulleman et al., 2012; Robinson et al., 2013) and on academic and industry stakeholder expertise, including recently published industry guidelines (Solar Energy UK, 2022), to link measurable environmental indicators to ES associated with NC stocks. From this, we identified potential methodologies suitable to industry needs and adopted a practitioner-informed hierarchy to classify them into methods that provide *key data* for the primary assessment of ES and do not require analytical instrumentation, as well as methods that provide *additional data* for more in-depth investigations of ES but that may require research-grade facilities and/or specialist skills, and tend to be more costly and time-consuming than *key data* methods (see methods classification in Table 1 and see Figure 1 for environmental indicators classified by time and financial costs). These data are supported by *auxiliary data* that will provide essential site information (e.g. land management practices, former land use) to help contextualize the results (Table 1). The methods chosen are well established and known to provide direct measures of the environmental indicators shown in Table 1 and have been extensively tested in the field by researchers and scientific organizations devoted to practical solutions for assessing long-term environmental change. In addition, the protocol (illustrated in Figure 2) offers the flexibility to employ methods comparable to national databases where available (e.g. habitat classification to estimate biodiversity net gain/loss; see Table 1) and to choose methods most suitable to fulfil local land management plans and objectives since they can be implemented in conjunction or separately. This approach allows for rigorous comparisons between sites and to larger environmental monitoring programmes, increases the protocol uptake and ultimately enables SP land managers to adopt a holistic approach to the management of hosting ecosystems.

3.1 | Indicators

The key NC stocks of biodiversity, soil and water were included in the protocol (Table 1), with a focus on biodiversity and soil assets given that these are the most likely to be affected by land use change for SPs (Armstrong et al., 2014, 2016; Randle-Boggis et al., 2020). Moreover, the complex interactions between soil and biodiversity drive the functioning of terrestrial ecosystems and the delivery of numerous ES (Bardgett & Wardle, 2010), making them foundational stocks to include in an NC-ES assessment protocol for SPs. For the purposes of routine implementation of the protocol by field practitioners, we equate biodiversity to species richness (although the methods also produce estimates of percentage cover for plants and abundance for birds) that can be directly measured in the field through simple species counts, visual cover estimates or transect walking (see methods in Table 1). The use of species richness measures to quantify taxonomic diversity presents limitations and miss some important aspects of biodiversity change related to species identity, dominance and rarity (Hillebrand et al., 2018). However, this simple approach, commonly used in multinational conservation efforts (e.g. Europe's Natura 2000 [https://ec.europa.eu/environment/nature/natura2000/index_en.htm]), should facilitate field data collection by industry and field practitioners on 1-day field visits and make results comparable across sites and regions, given the variety of methods available to quantify alternative measures of biodiversity (e.g. functional, phylogenetic). Nevertheless, the measures of species richness proposed here can be supplemented with a diversity index measure (e.g. Shannon's diversity index) to simultaneously account for the number and evenness (i.e. the distribution of individuals among species) of the species recorded. Shannon's diversity index has been found to perform well when detecting effects of land use intensity on species diversity and can be used in situations where rare and abundant species are expected to be equally important (Morris et al., 2014).

We adopted a holistic approach and identified potential effects caused by SPs on 16 ES comprising provisioning (four ES), regulating (six), supporting (four) and cultural (two) services (Mace et al., 2011) that could be linked to the three NC stocks through 19 measurable environmental indicators (Table 1). It is worth noting that the protocol is not meant to be an exhaustive list of methods and indicators. We have based our choices on the experiences of researchers and practitioners surveying SPs together with our own knowledge of the needs of the solar energy industry, while considering time requirements and cost commitments of the methods selected. Alternative survey methods focusing on fauna not included in Table 1 (e.g. reptiles, bats, moths) will likely be site- and/or country-specific and could be implemented according to local land management plans, whereas the ones included in Table 1 are likely more universally applicable and closely related to ES delivery.

3.2 | Sampling regime

Adoption of the protocol by SP operators and land managers will enable replicate sampling and provide standardized and comparable measurements across a wide range of SPs built on different types of former land use and under different management regimes. We suggest stratified replicate random sampling (three to five replicates) under PV arrays, between rows of PV arrays, in areas of enhanced biodiversity if applicable (e.g. field margins, areas actively managed for biodiversity) and in control areas that represent previous land use to provide baseline values and enable differences caused by land use change and management practices to be established. If possible, a larger number of sampling plots (15+) should be established per site when surveying biodiversity to ensure most of the species present are captured; the minimum number recommended above recognizes time constraints on SP operators and field practitioners. In addition, samples taken pre-SP construction could provide baseline values within the developed land. If possible, the proposed methods should be implemented in regular yearly intervals (Table 1) to determine temporal trends after land use change, preferably at the same time of year to make the data comparable across time.

TABLE 1 Environmental indicators and methods for the standardized assessment of natural capital (NC) and ecosystem services (ES) in solar parks (SPs). Indicators can be directly measured and linked to the delivery of several ES. The references listed in the last column should provide detailed description to allow for the replication of the proposed methods (fourth column), which are directly linked to the indicators (second column) and their most important associated ES (3rd column). Bold letters in brackets after each ES indicate a provisioning (**P**), regulating (**R**), supporting (**S**) or cultural (**C**) service. Survey methods have been classified into those that provide *key data* that can be gathered without the need for analytical instrumentation (shaded green) and those that provide *additional data* that may require research-grade facilities and/or specialist skills and may be time and/or budget constrained (shaded orange). These are supported by *auxiliary data* (shaded blue) to help contextualize site-specific survey results. Indicators are grouped by NC and type of data and arranged in increasing order of time requirement (8th column). Estimated time requirements to implement the proposed methods are based on our own experience and assuming normal operating UK-based conditions. Estimated time requirements for laboratory-based indicators (e.g. soil methods, above-ground biomass) do not include field sampling time, drying time (air- or oven-drying) and general laboratory preparation time (e.g. set-up, cleaning-up), and only refer to time spent conducting standard laboratory procedures (see Figure 1 for an illustration). ES classification was adapted from Mace et al. (2011). See Box 1 for NC and ES definitions, and see Solar Energy UK (2022) NC guidance report for an applied UK-based version of this protocol.

NC	Indicator	Associated ES[a]	Method	Field sampling	Laboratory methods	Materials	Time/*frequency*	References
Auxiliary data								
NA	Survey data	NA	NA	Basic survey data to be recorded, including survey date, name of surveyor and weather conditions (e.g. air temperature, wind conditions, atmospheric conditions)	NA	NA	Time required: low *Every visit*	NA
NA	Land management data	NA	NA	Land management categories can be devised to produce comparable standard summaries between sites, for example: 1. Optimal management for wildlife with conservation cutting/grazing and no herbicide use. Arisings are removed from the site. Diversity of habitats seen on site (e.g. meadows, tussocky grassland, hedgerows) 2. Conservation cutting/grazing applied, but low diversity of habitats on site (i.e. no additional planted habitats other than grassland). Arisings may be left on the site with signs of a thatch of vegetation in places. Herbicides may be used, but spot treatment 3. Site cut or grazed throughout the season leading to short sward. However, some other habitats present such as tussocky margins or hedgerows. Use of herbicides apparent (i.e. blanket spraying of fields or beneath PV panels) 4. Site cut or grazed throughout the season leading to short sward. No other habitats (tussocky margins, new hedgerows). Use of herbicides apparent (i.e. blanket spraying of fields or beneath PV panels) 5. Unmanaged or other (please specify)	NA	NA	Time required: moderate *Every visit*	NA
NA	Site data	NA	NA	Collection of information on current and past land management, seeding or planting and future plans for land management. Other information will include location, size of site, date of grid connection, PV technology, height of panels (ground to leading edge) and distance between panels	NA	NA	Time required: high *Every visit*	NA
Key data								
Biodiversity	Pollinator species richness	Food/fibre provision (**P**) Wild species diversity (**P**) Pollination (**R**)	Walking transects[b]	Surveyor walks a 100-m transect through the site and notes all butterflies and bumblebees within an imaginary 5 × 5 m quadrat in front of them (10 transects spread across the site)	NA	NA	Time required: approx. 2–3 h *Every 2–5 years (best during growing season)*	Carvell et al. (2016)

TABLE 1 (Continued)

NC	Indicator	Associated ES[a]	Method	Field sampling	Laboratory methods	Materials	Time/*frequency*	References
	Plant species richness and cover	Carbon sequestration (**P**) Food/fibre provision (**P**) Wild species diversity (**P**) Climate regulation (**R**) Pollination (**R**) Nutrient cycling (**S**) Primary production (**S**) Environmental settings (**C**)	Standard botanical quadrats	Quadrats (2×2 m) to be recorded at fixed locations within a single field: • Five quadrats directly beneath PV panels • Five quadrats between the rows of PV arrays • Five quadrats in 'enhanced' areas (e.g. diverse habitats within the lease boundary) (where applicable) • Five quadrats in 'control' areas (e.g. an adjacent field representing previous land use) (where applicable) Plant species ID and cover (%) should be recorded, as well as height of sward (cm) and bare ground/dead thatch/standing water cover (%) (if applicable)	NA	Plant ID guides, magnifying glass, sample paper bags for specimen collection, quadrat equipment (e.g. tape measure, strings, stakes)	Time required: approx. 3–5 h *Every 2 years (best during growing season)*	NA
	Nectar production[c]	Food/fibre provision (**P**) Pollination (**R**)	Nectar production potential	Use the botanical quadrats to estimate nectar production potential with existing species-specific nectar production data	NA	NA	Time required: approx. 3–5 h *With every botanical survey*	National dataset where available (e.g. Baude et al., 2015)
	Biodiversity net gain/loss[c]	Wild species diversity (**P**) Environmental settings (**C**) Recreation (**C**)	Habitat classification	Map habitats within the site boundaries using plant data (see above) and national classification databases where available to estimate biodiversity net gain/loss compared to former land use	NA	Access to a standardized national habitat classification database	Time required: approx. 5–6 h (dependent on size of site) *Every 2–4 years*	National classification database where available (e.g. UKHab, 2022)
Soil	Soil texture and structure	Water supply (**P**) Erosion control (**R**) Flood control (**R**) Pollution control (**R**) Nutrient cycling (**S**) Soil formation (**S**) Water cycling (**S**)	Hand texturing	Homogenized samples for SOM measurement (above) can be used	Wet a spoonful of soil and work the sample between fingers to identify particle sizes with the aid of a texture class guide	Soil corer, soil texture guide	Time required: approx. 1–2 h *Every 5 years*	Natural England (2008)
	Soil bulk density (BD)	Food/fibre provision (**P**) Erosion control (**R**) Flood control (**R**) Nutrient cycling (**S**) Soil formation (**S**) Water cycling (**S**)	Core sampling	One soil core (10 cm depth, 5 cm diameter) with a coring device of known volume at each of the quadrats used for SOM	Weigh large stones separately, oven-dry soil samples at 105°C for 24 h and weigh them	Soil corer, drying oven, laboratory balance	Time required: approx. 2–3 h *Every 5 years*	Emmett et al. (2008); Chapter 3
	Soil acidity	Food/fibre provision (**P**) Wild species diversity (**P**) Pollution control (**R**) Nutrient cycling (**S**)	Soil pH	Homogenized samples for SOM measurement (above) can be used	Mix 10 g of sieved soil sample with deionized water to measure pH from the resulting suspension	Soil corer, sieve (2mm), laboratory balance, shaker/stirrer, deionized water, pH meter	Time required: approx. 3–4 h *Every 5 years*	Emmett et al. (2008); Chapter 5

(Continues)

TABLE 1 (Continued)

NC	Indicator	Associated ES[a]	Method	Field sampling	Laboratory methods	Materials	Time/*frequency*	References
	Soil organic matter (SOM)	Carbon sequestration (**P**) Food/fibre provision (**P**) Climate regulation (**R**) Erosion control (**R**) Nutrient cycling (**S**) Primary production (**S**) Soil formation (**S**)	Mass loss-on-ignition (LOI)[d]	Four soil cores (10 cm depth, 5 cm diameter) at each of the botanical quadrats described above (same quadrats can be used for soil sampling)	Homogenize soil samples from the same quadrat, sieve, oven-dry (105°C for 16 h) and combust (375°C for 16 h) them, weighing samples at every stage	Soil corer, sieve (2 mm), drying oven, laboratory balance, furnace	Time required: approx. 4–6 h *Every 5 years*	Emmett et al. (2008); Chapter 4
	Soil water infiltration capacity	Water supply (**P**) Erosion control (**R**) Flood control (**R**) Nutrient cycling (**S**) Water cycling (**S**)	Field infiltration test	Field test using a cylinder or ring infiltrometer (same quadrats used for SOM sample collection can be used for infiltration test)	N/A	Shovel, hammer, hessian, ring infiltrometer, watch, bucket	Time required: approx. 12–16 h (dependent on soil substrate and land cover) *Every 5 years*	Brouwer et al. (1985); Annex 2
Additional data								
Biodiversity	Aboveground biomass[c]	Carbon sequestration (**P**) Food/fibre provision (**P**) Climate regulation (**R**) Erosion control (**R**) Pollination (**R**) Nutrient cycling (**S**) Primary production (**S**) Environmental settings (**C**)	Harvesting	Harvesting of herbaceous vegetation at surface level at the peak of the growing season (or more frequently if needed). This can be done within the same quadrats used for soil sampling (see Key Methods above)	Oven-dry vegetation (60°C until mass constancy) and weigh	Shears, drying oven, laboratory balance	Time required: approx. 1–2 h (including sample drying time) *Every 2–4 years*	Sala and Austin (2000)
	Bird species richness and abundance	Wild species diversity (**P**) Disease/pest regulation (**R**) Pollination (**R**) Environmental settings (**C**) Recreation (**C**)	Line transects with distance sampling[e]	All birds seen or heard are counted along representative transects, with perpendicular distance between observer and bird estimated (for small sites, complete counts rather than sampling may be more appropriate)	N/A	Optical equipment	Time required: approx. 10–12 h *Every 2–5 years*	Bibby et al. (2000); Buckland et al. (2008)
	Earthworm species richness	Food/fibre provision (**P**) Wild species diversity (**P**) Erosion control (**R**) Nutrient cycling (**S**) Primary production (**S**) Soil formation (**S**)	Hand sorting (and chemical expellant[f])	Block of soil (20 × 20 × 20 cm) is dug out and manually sorted to recover earthworms; earthworms are separated into three functional groups (surface dwelling, soil dwelling and deep burrowing) and counted/weighed (soil samples can be collected from the same quadrats for the methods above)	Accurate species identification is undertaken by microscope, though it is generally possible for mature adult earthworm species to be identified using a photographic key	Spade, plastic sheet, photographic key, microscope (for accurate identification)	Time required: approx. 10–12 h *Every 2–5 years*	Bone et al. (2012); Stroud (2019)

TABLE 1 (Continued)

NC	Indicator	Associated ES[a]	Method	Field sampling	Laboratory methods	Materials	Time/*frequency*	References
	Invertebrate species richness	Wild species diversity (**P**) Disease/pest regulation (**R**) Pollination (**R**) Nutrient cycling (**S**) Soil formation (**S**) Recreation (**C**)	ECN's invertebrates' protocol[g]	Light/pitfall trapping, transect surveys or soil coring (within the same quadrats used for the methods described above), depending on the indicator group chosen for survey	Count species and identify them with ID guides	Polypropylene cups for pitfall traps, light traps, soil corer (10 cm depth, 10 cm diameter), depending on the indicator group surveyed	Time required: approx. 12–16 h (dependent on indicator group) *Every 2–5 years*	ECN (1996)
	Forage nutritive value[c]	Food/fibre provision (**P**) Nutrient cycling (**S**)	Portable near-infrared spectroscopy (NIRS)	Grass sample analysis using NIRS portable system and reference procedures (samples can be analysed within the same soil quadrats, prior to harvesting aboveground biomass)	Analyse data via the cloud	IoT-NIRS portable system	Time required: approx. 12–16 h *Every 2–4 years*	Rego et al. (2020)
Soil	Soil organic carbon (SOC) and total soil nitrogen	Carbon sequestration (**P**) Climate regulation (**R**) Nutrient cycling (**S**) Soil formation (**S**)	Dry combustion	A subsample of the soil samples used to estimate SOM (see above) can be used to estimate SOC and total soil nitrogen in an Elemental Analyser (EA) by incinerating dried soil samples at high temperatures	Sieve, oven-dry (60°C to constant mass), mill and weigh samples for EA analysis (acid treatment may be required for carbonate-rich samples)	Soil corer, drying oven, ball mill (or mortar and pestle), laboratory microbalance, EA	Time required: approx. 16–18 h (including sample drying time) *Every 5 years*	JoVE Science Education Database (2022); Nayak et al. (2019); Paustian et al. (2019)
	Soil phosphorus (P) and soil potentially mineralizable nitrogen (PMN)	Food/fibre provision (**P**) Nutrient cycling (**S**) Primary production (**S**) Soil formation (**S**)	Wet extraction	A subsample of the soil samples used to estimate SOM (see above) can be used to estimate soil P (total and/or inorganic) and PMN using an Autoanalyser (AA) followed by standard wet extraction methods	Sieve, oven- or air-dry, mill and weigh samples for wet extraction of nutrients	Soil corer, drying oven, ball mill (or mortar and pestle), laboratory microbalance, reagents, fume hood, AA	Time required: approx. 20–24 h (including sample drying time) *Every 5 years*	Emmett et al. (2008); Chapter 6 for soil P and Chapter 7 for PMN
Water	On- and offsite water impacts	Food/fibre provision (**P**) Water supply (**P**) Pollution control (**R**) Nutrient cycling (**S**) Water cycling (**S**) Environmental settings (**C**) Recreation (**C**)	Handheld water quality meter	Measurement of multiple water quality parameters with field handheld meters, including temperature, dissolved oxygen, turbidity and conductivity (water features on and offsite that could be potentially impacted)	NA	Handheld water quality meter, sampling bottles	Time required: approx. 1–2 h *Every 2 years*	U.S. Geological Survey (2018)

[a]Only ecosystem services directly linked to indicators have been listed, though numerous others are possible.

[b]Surveys do not require specialist ID skills and species can simply be counted (i.e. 'butterfly species 1'). The survey is weather dependent and should be carried out during warm, dry and still weather. Two to three visits per year would give best results, though a single visit is possible if conditions allow.

[c]Biodiversity-related ecosystem service and policy-relevant measure (not strictly a measure of taxonomic richness).

[d]LOI values can be used to estimate soil organic carbon (SOC) with equation 3 of Jensen et al. (2018), as an alternative simpler method of estimating SOC to the one proposed under *Additional data* methods.

[e]Repeat visits are advisable given the impact of weather and time of year.

[f]Mustard oil solution can be added to the bottom of the resulting soil pit to expel further deep burrowing types.

[g]Surveying techniques for various invertebrate indicator groups are proposed within this suite of methods. We propose selecting the most appropriate group(s) to survey according to interest or land management objectives.

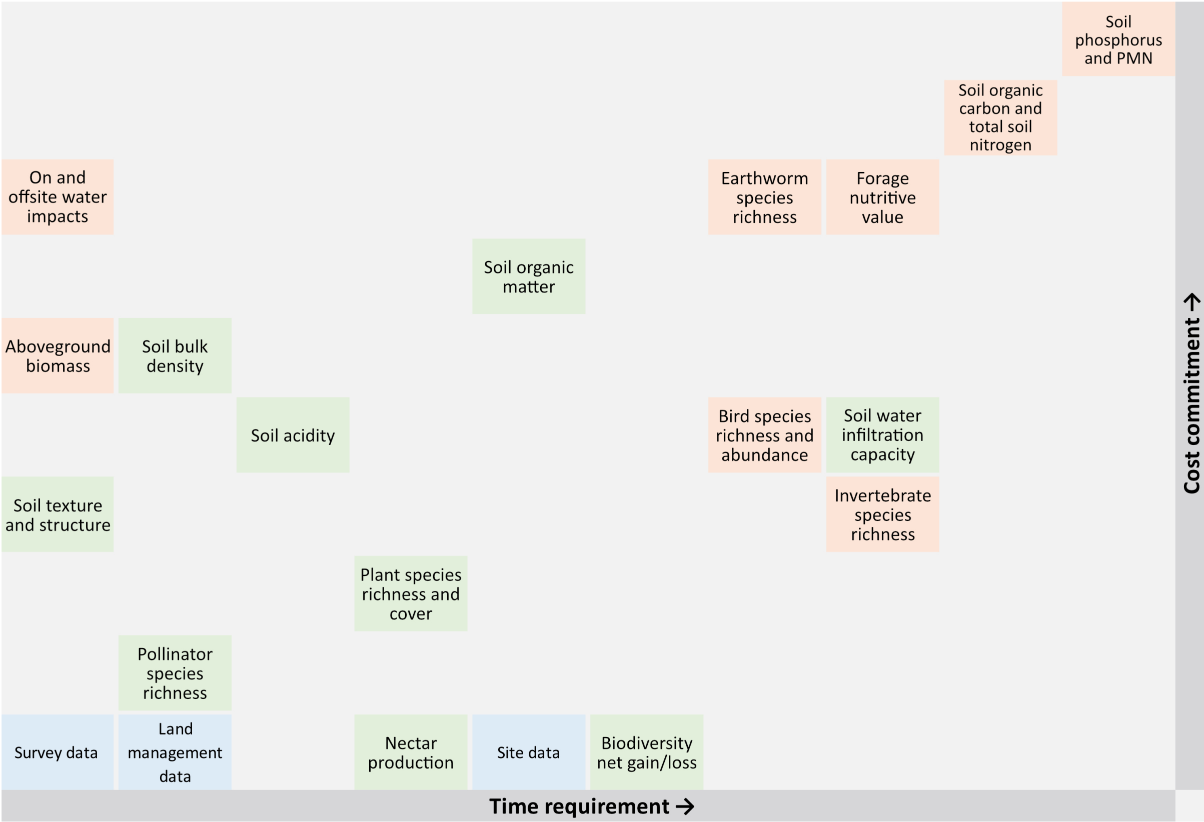

FIGURE 1 Environmental indicators for the standardized assessment of natural capital and ecosystem services in solar parks, classified into those that provide key data (shaded green) and additional data (shaded orange), supported by auxiliary data (shaded blue). Indicators are arranged from left to right and from bottom to top in increasing order of time requirement and cost commitment, respectively, of associated methods (see Table 1). Time and cost estimates of each indicator are based on our own experience and assuming normal operating UK-based conditions and common practices in UK research laboratories (see Table 1 caption for further clarifications). The time and cost axes are not to scale and are only intended to illustrate relative comparisons between the indicators shown. PMN, potentially mineralizable nitrogen.

3.3 | Analysis and reporting

Once assessed, the NC indicators need to be analysed and reported to provide meaningful insight for industry and policy. Depending on the experimental design, the indicators could be analysed relative to pre-SP baseline, to control samples taken from adjacent areas subject to the same land use as the SP before construction (enabling comparisons that account for other drivers including climate change and farming practices) or to expected values for the ecosystem in question, amassed through a review of research studies or national benchmarks where available. However, care must be taken to ensure that site-specific characteristics that may inform outcomes (e.g. soil type, climate) are considered as there might be greater potential for enhancing NC and ES at some locations. Finally, if no control samples or indicator standards are available, the indicators can be compared through time, enabling positive, neutral or negative impacts to be identified. These analyses can either be done for each 'treatment' (i.e. under PV arrays, between rows of PV arrays and in areas of enhanced biodiversity) or through weighted averages for the whole SP based on the proportional cover of the respective treatments across the SP.

3.4 | Implications

The protocol outlines tools and methods to help SP operators implement a full NC assessment process to identify and value their direct and indirect impacts on NC. It has implications for the research, practice and policy spheres, including (1) advancing scientific understanding of the links between NC, ES and environmental indicators; (2) informing industry practice, including land management practices and future accreditation schemes, as well as environment, society and governance targets; (3) helping SP owners and operators to comply with land use regulatory schemes; (4) informing land use change decisions against competing interests (e.g. agricultural production, environmental conservation); and (5) providing the basis for alternative frameworks for other renewable energy technologies, including floating solar PV (floatovoltaics), which are known to offer both risks and opportunities for ES provision within aquatic ecosystems (Exley et al., 2021). In addition, standardized assessment methodologies could aid in integrating a range of services to represent overall ecosystem health and functioning (Kareiva et al., 2011; Meyer et al., 2015) under increasing levels of SP development in several countries (IRENA, 2019). It is hoped SP

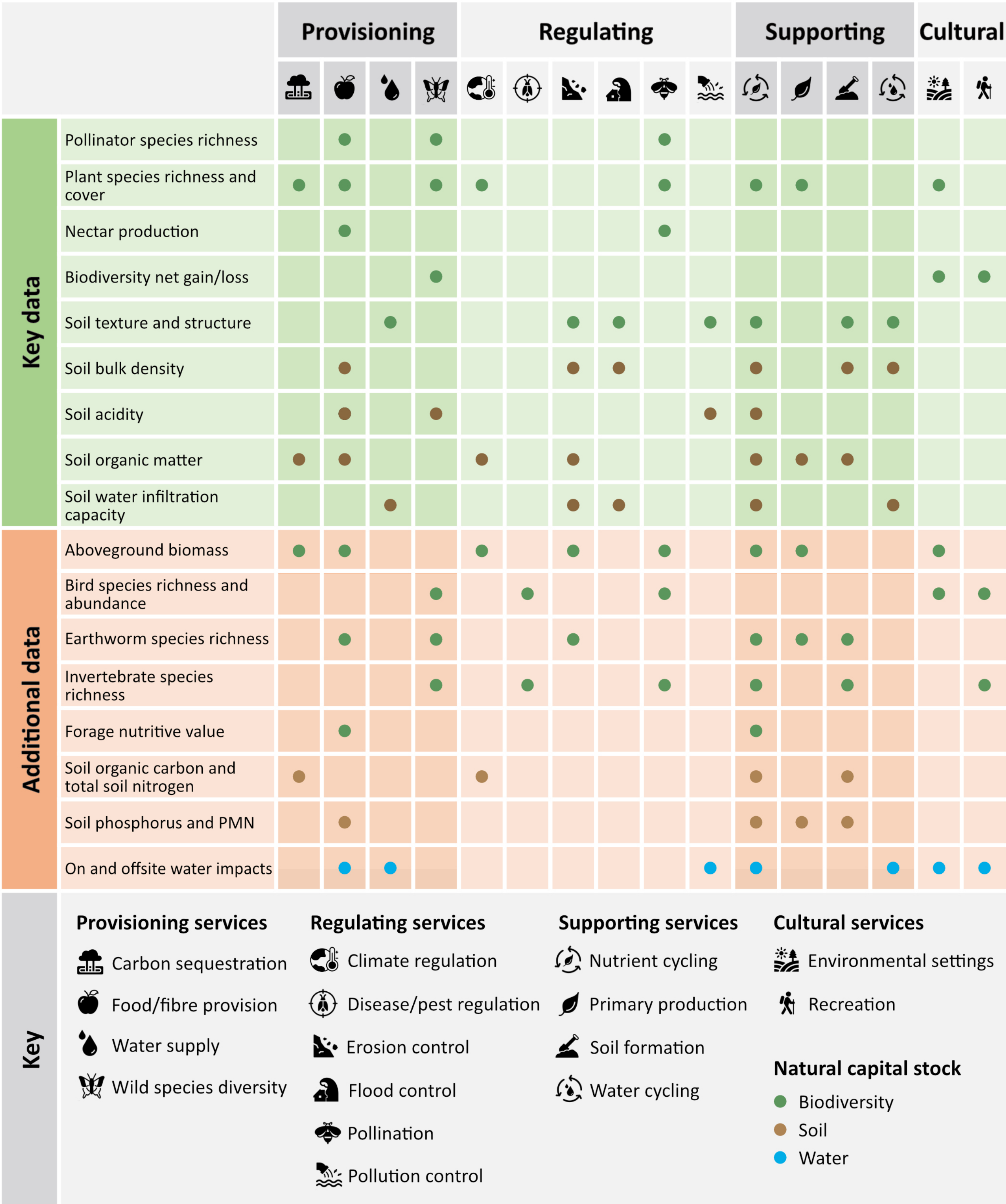

FIGURE 2 Illustrative diagram of the natural capital–ecosystem service standardized assessment protocol presented in Table 1. Environmental indicators are classified into those that provide key data (shaded green) and additional data (shaded orange) and linked to directly measurable methods and ecosystem services potentially affected by the development of solar parks (see Table 1). PMN, potentially mineralizable nitrogen.

operators will take full advantage of systematic data collection by sharing their assessment findings with the wider industry, policymakers and researchers to demonstrate risks and opportunities of SP development on NC and ES and reveal implications of site characteristics and management practices. Indeed, increasing regulatory and market forces may encourage landowners and managers to share knowledge on the impact of land use decisions on natural assets (Guerry et al., 2015; Solar Energy UK, 2019). This could open further channels of long-term collaboration between interdisciplinary researchers, practitioners and asset managers to aim towards a full systems approach (Neill et al., 2020) to integrate energy–environment–society research to better understand and communicate NC-ES sustainability within SPs. Land managers would focus on delivering locally targeted environmental outcomes, while researchers would benefit from data availability to provide research-, industry- and policy-oriented output to convey an integrated picture. Industry and academia could thus collaborate to facilitate the implementation of an accreditation standard for SPs based on environmental performance.

4 | CONCLUSIONS

Preserving or restoring NC stocks and ES flows is indispensable for economic development (Blignaut et al., 2013). Yet, developing the scientific basis for integrating NC and ES into land use change for solar-generated electricity within SPs is in its early stages, despite projected land take of SPs and potential to embed positive environmental outcomes in SP development. Our protocol (Table 1) provides a clear, unified approach, guaranteeing links between NC and ES are not missed whilst addressing notable knowledge gaps for SPs. Implementation of *key data* methods in the protocol should support SP operators to comply with regulatory requirements on land use management for the fulfilment of environmental policy targets and be used in wider policy assessment exercises, while *additional data* methods should provide valuable information for in-depth scientific research on the effects of land use change on ES provision. In addition, wider uptake of this protocol by the solar energy sector could potentially initiate the development of accreditation schemes to guide solar energy operators in the future design and management of SPs across the world. New research and data collection will also be useful to determine areas of high ecological value or areas particularly vulnerable to impacts, to which avoidance and/or monitoring financial and technical resources should be directed. The indicators and methods presented here are focused on the assessment of temperate ecosystems, though some of them (e.g. soil-related indicators) could be implemented in SPs developed in other types of environments (e.g. deserts). Lastly, it is hoped our protocol can be expanded or adapted to include indicators and variants appropriate for other types of renewable energy technology.

AUTHOR CONTRIBUTIONS

Fabio Carvalho and Alona Armstrong conceived the concepts for the manuscript. Fabio Carvalho led the writing of the manuscript. All authors contributed text, revised the drafts and gave final approval for publication. Rachel Hayes and Cameron Witten provided policy insight and Belinda Howell, Hannah Montag and Guy Parker provided industry insight.

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CONFLICT OF INTEREST

Hollie Blaydes is co-funded by Low Carbon Investment Management Ltd, Fabio Carvalho is co-funded by Clarkson & Woods Ltd, Giles Exley is currently employed by WRC Group, Rachel Hayes is employed by Solar Energy UK, Belinda Howell is employed by Natural Power, Hannah Montag is employed by Clarkson & Woods Ltd, Guy Parker is founder and co-director of Wychwood Biodiversity Ltd, Lucy Treasure is co-funded by Eden Renewables LLC and Cameron Witten is currently employed by Green Alliance.

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DATA AVAILABILITY STATEMENT

This manuscript does not use data; therefore, no data are archived.

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