Mutually-Beneficial Renewable Energy Systems

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Abstract

Recognizing the present mass extinction of species and populations worldwide, considerable effort is underway to resolve tensions between achieving high levels of renewable energy development and protecting ecosystems and biodiversity. Moving beyond common mitigation measures designed to avoid or minimize adverse impacts, this paper takes a relational view of energy futures to explore the opportunities and implications of rethinking renewable energy systems as processes for restoration and healing of human-nature relationships. In a relational view, avoiding or minimizing harm is necessary but insufficient for establishing healthy, enduring relationships based on mutual benefit between humans and nonhuman nature. The primary aim of the paper is to identify a set of practices for renewable energy technologies that support ecological enhancement through their deployment and use, as discovered through recent research and practice. The paper first presents the case for mutual benefit as a crucial principle for guiding renewable energy developments due to reasons of practice, ecology, and ethics, and goes on to provide examples of mutually-beneficial energy development across a range of technologies. The study reveals options for renewable energy systems as a whole to be assembled, operated, and repurposed for the co-benefit of humans and nonhuman nature.

Keywords: biodiversity; co-benefits; conservation; ecosystems; energy and environment; energy ethics; energy landscapes; mutual benefit; renewable energy transition; restoration.

1. Introduction

Despite widespread commitments to renewable energy, conflicts with ecological conservation goals, such as proposed siting in ecologically-sensitive areas, threaten to slow or reduce deployment. In response, advocates of renewables commonly assert that, while all renewable energy systems can negatively impact ecosystems and biodiversity (Acar and Dincer 2017; Gasparatos et al. 2017; Gibson, Wilman, and Laurance 2017), their net benefits for environment and society exceed the growing net costs associated with the continued use of fossil fuels (Azzellino et al. 2013; Allison, Root, and Frumhoff 2014). This net-benefit narrative increasingly serves to coalesce diverse interests and social groups while inspiring a proliferation of research initiatives, standards, guidelines, tools, practices and collaborations over the last decade (e.g., BLM 2009; BirdLife Europe 2011; USFWS 2012; Science for Environment Policy 2015; van der Winden et al. 2015; Khalil 2016; RSPB 2016; WWF-Canada 2016; AWWI 2017; TNC 2017; BRI 2018; MMC 2018). Such efforts are seen to address the potential, yet not insurmountable, tensions between achieving high levels of renewable energy while also protecting life on land and in the world's ocean, as articulated in the United Nations' Sustainable Development Goals (UNEP 2016).

This paper begins from a precautionary assumption that these important efforts will not fundamentally shift present trends of large-scale biological loss. Conventional efforts to reduce or minimize impacts of development, while making important contributions in specific cases, have not worked to change the basic pattern of mass extinction and loss of nonhuman life in the aggregate (Ceballos, Ehrlich, and Dirzo 2017; Wagler 2018). Increasing the development of renewable energy systems at the scale and pace envisioned while simultaneously reversing the present crisis of biodiversity compels a careful appraisal of how these global imperatives can be successfully integrated.

Moving beyond common measures to mitigate biological loss, this paper takes a relational view of energy futures, emphasizing and shifting attention toward the role of nonhuman elements of renewable energy systems, to explore opportunities for rethinking renewable energy systems as processes for restoration and healing of human-nature relationships. The necessity for expanding renewable energy while also protecting the biosphere suggests that efforts to transition to renewables fundamentally address the crisis of nonhuman species and communities from the outset. Bringing together these two large-scale, ambitious, and overlapping global priorities requires an approach to the development of renewable energy systems that results in measurable improvements to ecosystems and biodiversity at the site level as well as in the aggregate.

This relational approach opens toward a fundamental repurposing of renewable energy development, seeking not only new ways of converting energy for human use, but also new opportunities for ecological enhancements (BirdLife Europe 2011), meaning enduring benefits for nonhuman life. A shift in the orientation of renewable energy development is proposed, from that of doing "less bad" to one of creating "more good" (McDonough 2017) for human and nonhuman communities alike. Attention to enhancements and co-benefits through renewable energy is neither new (Goetzberger and Zastrow 1982; Stremke and Koh 2010) nor assured; yet, with increasing adoption of policies, development, and ensuing conflicts, the relevance of these approaches will likely increase over the coming decades.

This research aims to identify a set of strategies for ecological enhancement through deployment and use of renewable energy technologies. More broadly, the research explores ecological and technological implications of the normative position taken here, thus encouraging an alternative to a dominant energy paradigm, renewable and otherwise, that views nonhuman natures as passive reserves and resources for human exploitation (Frigo 2017). Supporting the objectives of this special issue, the concept of *mutual benefit* enables rethinking, redefining, and renegotiating renewable energy conversions as shared processes among human and nonhuman participants for producing mutual wellbeing.

The following section presents a rationale for this mutually-beneficial approach, supported for reasons of practice, ecology, and ethics. The focus on practice demonstrates the salience of the question of energy-ecology interactions in the context of these broader goals and trends, while ecology and ethics provide a foundation for this approach, emphasizing human understanding and acceptance of, as well as responsibility for, inter-relatedness with all of life. Section 3 presents the results of a review of academic literature, grey literature and reports, and websites, demonstrating that technologies and practices are presently available to support this approach. This review extends the work of Gasparatos et al. (2017), Santangeli et al. (2016), and others by drawing together multiple fields of study including geographies of energy (Bridge et al. 2013; Huber 2015; Calvert 2016), conservation sciences (Noss et al. 2012; Martin, Maris, and Simberloff 2016), ecological restoration, planning, and design (McHarg 1969; Anker 2010; Higgs 2012), sustainable and multifunctional energy landscapes (Stremke and Koh 2011; Howard et al. 2013; de Waal and Stremke 2014; Lokman 2017; Pasqualetti and Stremke 2017), natural infrastructure (Bennett, Cassin, and Carroll 2016), and techno-ecological synergies (Bakshi, Ziv, and Lepech 2015; Hanes, Gopalakrishnan, and Bakshi 2017). Technologies were selected from those that convert energy sources continuously replenished by the sun or other natural cycles into modern forms of energy, including solar and wind power, hydroelectricity, bioenergy and ocean energy (Ellabban, Abu-Rub, and Blaabjerg 2014). Initially included, geothermal energy technologies were ultimately removed from the set of stand-alone technologies due to the relatively few concerns for ecosystems and biodiversity stemming from their small footprint, and the limited opportunities identified for ecological enhancements beyond conservation of surrounding areas. Section 4 discusses key findings, implications, and risks, before closing in section 5 with a summary and suggestions for further research.

2. RENEWABLE ENERGY AND THE NATURAL WORLD: RELEVANCE, RELATIONSHIPS, AND RESPONSIBILITY

When viewed in their overlapping spatial and temporal contexts, the global imperatives of renewable energy transition and biodiversity and ecosystem conservation and restoration raise several considerations for their simultaneous achievement. In a manner not seen since the pre-industrial era (Hornborg 2013), harvesting energy sources at the Earth's surface on a global scale implies a deep restructuring of physical space (Smil 2015; Huber and McCarthy 2017), exacerbating tensions around existing and future use of lands and oceans (Gasparatos et al. 2017; Huber and McCarthy 2017). Although continued use of nonrenewable energy sources requires ongoing expansion (Allred et al. 2015), compared to these conventional systems, renewable energy technologies require more physical space to deliver the same amount of power (i.e., lower rate of energy flow per unit of surface area) (MacKay 2010; Smil 2015; Capellán-Pérez, de Castro, and Arto 2017). Power densities of efficient petroleum and coal sources vary from around 1000-10,000 We/m^2, while renewables generally range from highs for hydroelectricity of around 0.5-200 We/m^2, to lower power densities for solar and wind around 0.5-10 and less than 1 We/m^2 for biomass and biofuels (Smil 2015; Capellán-Pérez, de Castro, and Arto 2017). These systems may additionally require new transmissions and inputs of raw materials, including fossil fuels systems during transition, collectively extending spatial demands (Heinberg and Fridley 2016; Capellán-Pérez, de Castro, and Arto 2017; Huber and McCarthy 2017). While only a small fraction of total available planetary surface area (Jacobson and Delucchi 2011), in relative terms these new energy infrastructures may require areas 1 to 3 orders of magnitude larger than existing systems worldwide (Smil 2015), exceeding available land area for many highly industrialized regions (Capellán-Pérez, de Castro, and Arto 2017). This new pressure comes at a time when conservation sciences indicate that many regions require 25 to 75 percent of the area to be managed with conservation as a primary objective (Noss et al. 2012; Dinerstein et al. 2017). The potential for energy sprawl further compels an account of qualitative changes to diverse ecosystems and the living beings inhabiting them (Labussière and Nadaï 2017). Temporally, many renewable systems will require upgrading, decommissioning, and disposal within a period of approximately 30 years (Gasparatos et al. 2017), implying an ongoing process of negotiation of competing spatial requirements within these emerging energy land- and seascapes (Pasqualetti and Stremke 2017). All these issues are exacerbated by high levels of energy use among industrialized nations (Heinberg and Fridley 2016). These various tensions and possibilities of sprawling renewable energy systems demonstrate the salience of the question of energy-ecology interactions in the context of broader trends and aspirations.

Given their increasing practical relevance, a relational perspective provides an important basis for addressing these interactions. Drawing especially from ecology and science, technology, and society, the idea and insight most meaningful here concerns the interrelatedness of human and nonhuman systems, in this case, human technological systems and the ecological communities and larger biosphere in which these systems are embedded. Renewable energy systems bridge social and ecological systems, serving as both technology and physical structure, and transferring throughputs of materials, energy and information (Marten 2001; Johnson 2015). From the perspective of nonhuman members of the biotic communities, there may be little distinction made between these technological artifacts and other physical features of ecosystems (Jørgensen 2014). This relational approach views human technologies for converting and making use of renewable flows of energy as embedded within and co-produced through their engagement with the nonhuman world, meaning that these energy systems emerge through collective practices of inter-related human and nonhuman participants within broader social, political, ecological, and technical assemblages (Chilvers and Pallett 2018). Nonhuman actors, namely diverse species and ecosystems are at least as critical to the resulting technological system as human agents in government, business, research, finance, local communities and so on (Fatimah and Arora 2016). For renewable energy transitions, this way of representing inter-related social, natural and technological systems becomes embodied within practical, material and organizational forms (Jasanoff 2004), raising the question, what kind of energy system is consistent with living inside a living being (Kelly 2012, 102)?

This understanding broadens ethical concerns and urges renewable energy practices that anticipate and take responsibility for these human-nature interrelationships (de la Bellacasa 2011; Donovan 2014; Chilvers and Pallett 2018). The physical qualities of renewable energy, including their proximity and visibility, also make it less likely for people to avoid responsibilities of human energy use (Pasqualetti 2000). From this relational perspective avoiding or minimizing harm is necessary but insufficient for establishing healthy, enduring relationships based on mutual benefit among humans and nonhuman nature. Over the coming decades, we aspire to produce measurable improvements in both advancing renewable energy and protecting nonhuman ecosystems and biodiversity. The need here is not only to recognize and accept their interrelatedness, but to also take responsibility for their improvement.

New scientific concepts are needed to reflect this redefinition of human-nature relations in the context of technological development (Larson 2011). As a form of symbiosis, the concept of mutualism offers a starting point for understanding and emphasizing opportunities for long-term cooperation and enduring co-benefits across human and nonhuman communities (Bronstein 2015). In ecological terms, mutualisms involve direct and indirect interactions between two species that result in benefits to both (Boucher, James, and Keeler 1982; Bronstein 2015). While the perspective here is informed by the ecological concept of mutualism, the term *mutual benefit* is preferred, reserving mutualism for its ecological usage (West, Griffin, and Gardner 2007) until a greater consensus can develop regarding its implications as a novel metaphor (Larson 2011). As inspired by Berry (1999) and other ecocentric perspectives (Washington et al. 2017), the transition to renewable energy would involve shifting sharply from outdated perspectives of human mastery over nature toward worldviews that value mutually-enhancing human-nature relations. Mutual benefit is based on the view that human beings are neither the center nor the unique subjects in nature but rather one among many participants and members in inter-related processes, all deserving of moral respect (Berry 1999; Martin, Maris, and Simberloff 2016; Jakobsen 2017). Although this view may be insufficiently represented in energy and climate policy and research at present (McShane 2016; Sovacool et al. 2017), an emphasis on mutual benefit can help reinforce these not-only-anthropocentric values by making more transparent the belief in some degree of intrinsic value of nonhuman nature (Batavia and Nelson 2017).

In contrast to one-sided approaches that consider nonhuman needs secondarily to the conversion of energy for human use, mutually-beneficial renewable energy refers to an approach to planning, developing, implementing and adapting these technologies to produce ongoing benefits to humans (in the form of renewable energy) and nonhumans (in the form of biological diversity and ecosystem structure and function). In this sense, mutual benefit draws from deeper etymological roots, in which "mutual" suggests reciprocal relationships and sharing and holding in common, while "benefit" means an act of kindness, in service to another, and producing effects that promote wellbeing. The value of this conceptual framing lies in the way it draws attention to the sociotechnical and ecological dimensions and their interrelationships as integrated measures of achievement.

As a practice informed by this relational view, mutually-beneficial renewable energy would seek to demonstrate ongoing, cumulative improvements in both direct and indirect ecological outcomes, such as increased community diversity and restored biodiversity and ecosystem functions. Elements of this approach are already evident in efforts such as "wildlife-friendly renewable energy" and "renewables for nature" (CBD 2015; WWF-Canada 2016). While mutual benefit also involves net benefits, in that there can also exist costs that are outweighed by the positive effects (Bronstein 2015), the key difference from the current trend of net-benefit thinking is that mutual benefit seeks positive effects in both direct, local and indirect, global relations.

Mutual benefit offers a unique form of energy ethics and energy justice that accounts for the needs of inter-related human and nonhuman members (Frigo 2017, 9-10; Sovacool et al. 2017, 680-682), urging human responsibility for flourishing species and ecological communities. This practical, ecological and ethical framing provides a basis for advancing the development of renewable energy systems in a manner that ensures measurable improvements to ecosystems and biodiversity locally and globally, year after year, representing a fundamental shift from present trends. The following section demonstrates how this can be initiated using existing renewable energy technologies.

3. EXAMPLES ACROSS TECHNOLOGIES AND SCALES

3.1. *Solar*

Solar photovoltaics (PV) and concentrating solar power (CSP) use sunlight to generate electricity while solar thermal uses sunlight to provide heat and hot water (Ellabban, Abu-Rub, and Blaabjerg 2014; Gasparatos et al. 2017). Common mitigation measures for solar energy include selecting areas of low conservation value and implementing biodiversity-friendly operating procedures (Gasparatos et al. 2017). Mutually-beneficial opportunities for solar energy broadly involve flexible siting options, supporting use of degraded lands and water bodies, co-location with other uses and technologies, restoration of ecosystem functions and habitats within and adjacent to installations, and integration within built environments (Stoms, Dashiell, and Davis 2013; Hernandez et al. 2014; Hoffacker, Allen, and Hernandez 2017; Moore-O'Leary et al. 2017).

Conversion of degraded lands may include converting cultivated lands to prairies and meadows, or making use of brownfields, abandoned mining lands, salt-contaminated lands, or existing transportation and transmission corridors (BirdLife Europe 2011; Northmore 2014; Hernandez et al. 2015; Hoffacker, Allen, and Hernandez 2017; UCS 2017). Integration within built environments can take increasingly diverse forms, from common rooftop solar systems (Moore-O'Leary et al. 2017; UCS 2017) to building-integrated PV (Cannavale et al. 2017; Moore-O'Leary et al. 2017; Jakica 2018), green roofs (Gasparatos et al. 2017), clear window modules (Hoffacker, Allen, and Hernandez 2017), various construction components (Uyterlinde et al. 2017), noise barriers (Hoffacker, Allen, and Hernandez 2017), solar road panels (Northmore 2014), and solar PV sculptures and solar trees for public art and education (Ferry, Monoian, and Koh 2012; Hyder, Sudhakar, and Mamat 2018).

Ecological land management can be used across the lifespan of solar technologies. During site preparation, practices include conserving original vegetation (Macknick, Beatty, and Hill 2013) and installing arrays without grading (Beatty et al. 2017). During operations, solar energy accommodates native vegetation under and around panels; modified height and spacing of PV panels to allow rough pasture, prairie, meadow and grassland habitats to flourish; pollinator-friendly habitat and planting of wild bird seed, nectar mixes or cover crops between rows; nest boxes and roosting, perching and hibernating structures within control buildings; wildlife-friendly hedges for fencing; and management for nutrient cycling and erosion control (BirdLife Europe 2011; Macknick, Beatty, and Hill 2013; Montag, Parker, and Clarkson 2016; Beatty et al. 2017; Benage 2017; Hoffacker, Allen, and Hernandez 2017; Moore-O'Leary et al. 2017). Solar energy may support restoration of wetland habitats in former agricultural and industrial areas through purification of groundwater (Pevzner 2015). Once decommissioned, solar infrastructure may be retrofitted, or deconstructed and recycled, to repurpose or restore sites (Ali et al. 2016; Moore-O'Leary et al. 2017; UCS 2017).

Siting within agriculture areas and on the surface of water bodies, i.e., agrivoltaics and floatovoltaics, has received increasing interest. For agrivoltaics, modified panel height and spacing can support sun-loving and shade-tolerant crops or allow conservation grazing by sheep, goats, poultry, and cattle, while providing shade and cover and reducing maintenance and soil erosion (BirdLife Europe 2011; Macknick, Beatty, and Hill 2013; BRE 2014; Hernandez et al. 2014; Hernandez et al. 2015, 13582-13583; Montag, Parker, and Clarkson 2016; Ravi et al. 2016; Hagen and DePillis 2017; Fraunhofer ISE 2018). Agrivoltaics also make use of farm structures including greenhouses and barns, underutilized spaces such as distribution areas and parking lots, and agriculture lands of lower soil quality (Macknick, Beatty, and Hill 2013; Hernandez et al. 2014; Hagen and DePillis 2017; Moore-O'Leary et al. 2017). For floatovoltaics, floating arrays deployed in reservoirs, dam impoundments, irrigation canals, lakes, ponds, and former mining pits adapt to changing water levels while improving panel conversion efficiency and reducing evaporation (Hernandez et al. 2014; Hanley 2017; Hoffacker, Allen, and Hernandez 2017; Moore-O'Leary et al. 2017). When combined with aquaculture (aquavoltaics), floating PV systems support food production, provide artificial fish habitat and oxygenate surface waters (Pringle, Handler, and Pearce 2017).

3.2. *Wind*

Wind energy is generated kinetically from moving air converted to mechanical then electrical energy through rotating blades of turbines (Ellabban, Abu-Rub, and Blaabjerg 2014; Gasparatos et al. 2017). Common mitigation measures include siting outside migratory pathways, minimizing overall footprints and implementing operating procedures to reduce collisions with bird and bat species (Gasparatos et al. 2017). While much of the literature on wind energy emphasizes strategies for avoiding or minimizing impacts, this review finds various practices for ecological enhancements that generally using the space between turbines to create or extend marine and terrestrial habitats and ecosystems (BirdLife Europe 2011; UCS 2017; Uyterlinde et al. 2017).

Onshore and offshore installations provide opportunities for creating or extending habitat zones by selecting sites with little existing biodiversity, such as abandoned industrial areas, transportation corridors or areas near existing development (Gasparatos et al. 2017; UCS 2017), or conversely, strategically selecting areas with significant wildlife habitat such as upland or coastal areas and marine locations of high conservation value. Because footprints of wind turbines are proportionally small, wind projects can restrict other forms of development and traffic within the project (BirdLife Europe 2011).

Managed enhancements involve controlling erosion and invasive species, restoring habitat, and protecting nesting, breeding or spawning areas for fish and terrestrial prey species. For offshore sites, enhancements include the creation of artificial reefs and shelters for marine life to increase populations of fish and benthic species and provide substrate for marine communities (BirdLife Europe 2011; Gasparatos et al. 2017; UCS 2017). With careful planning, these artificial habitats can extend existing marine reserves and protected areas, connect with important coastal habitats (BirdLife Europe 2011; OMA 2008) or provide new habitats for benthic species when using floating offshore wind farms anchored in deeper waters (Gasparatos et al. 2017). With an appropriate number and configuration of turbines, the space surrounding turbines can allow multiple functions including conservation grazing, sustainable agriculture, outdoor recreation, aquaculture, and seaweed cultivation (BirdLife Europe 2011; Uyterlinde et al. 2017).

3.3. *Hydroelectricity*

Hydroelectricity, converted by turbines from the flow of falling water, includes conventional dams and run-of-river systems of varying scales (Ellabban, Abu-Rub, and Blaabjerg 2014; Gasparatos et al. 2017). Relative to other renewable energy technologies, the effects of hydroelectricity on biodiversity are well established. These projects have significantly and permanently altered habitats, created fragmentation, and displaced human and nonhuman communities. Common mitigation measures include the use of technologies such as upstream fish ladders, downstream fish-friendly turbines and bypass flows, and site-selection to reduce the size of reservoirs (Gasparatos et al. 2017; UCS 2017). Opportunities for ecological enhancement broadly relate to supporting or restoring ecological flow patterns and non-flow habitats and retrofitting or replacing existing facilities (van der Winden et al. 2015; Sale, Hall, and Keil 2016; UNEP 2016; UCS 2017).

Restoring ecological flow regimes involves practices that mimic natural flow cycles through management of flow releases, including enhanced quantity, quality and timing of flows and periodic releases from large reservoirs. Non-flow practices work to protect and restore watersheds using shoreline buffers, streambank restoration, native vegetation on adjacent lands, protection of threatened and endangered species, and adaptive management and monitoring programs (van der Winden et al. 2015; Sale, Hall, and Keil 2016; UCS 2017).

Given their legacy, successful implementation may require that certain dams be retrofitted or replaced with improved technologies. Retrofitting dams with artificial fish passageways upstream and downstream can reconnect fragmented rivers within the watershed while improving and restoring fish migration patterns and riparian habitats (van der Winden et al. 2015; Sale, Hall, and Keil 2016; UCS 2017). Use of run-of-river technologies increases the possibility for enhancements, supporting natural flow patterns, reducing land area, and allowing for flexible and distributed installations that may limit the need for transmission (Ebenhack and Martinez 2014; Sale, Hall, and Keil 2016; UCS 2017).

3.4. *Bioenergy*

Modern bioenergy chemically converts diverse sources of organic matter, including wood, crop residues, livestock waste, and biodegradable municipal waste into bioheat, liquid biofuels and biomass power (Ellabban, Abu-Rub, and Blaabjerg 2014; Gasparatos et al. 2017; Malinauskaite et al. 2017). Mitigation generally includes implementing ecologically-sensitive agricultural and forestry practices, siting on degraded or marginal lands, and carefully collecting, transporting, handling, converting and disposing waste resources (Gasparatos et al. 2017; Moya et al. 2017).

Bioenergy systems present a complicated and contested set of prospects for ecological enhancement, involving persistent debates on their use for modern energy rather than for non-energy uses such as food production and soil health (Breeze 2018; Malinauskaite et al. 2017). A hierarchy of uses of bio-based materials prioritizes prevention, reuse and recycling of waste materials prior or in addition to the conversion of energy from waste (European Commission 2017). Combustion or landfilling of waste is low on this hierarchy (Breeze 2018). Opportunities for ecological enhancement using bioenergy are limited here to practices that make use of residual organic waste streams produced through ecologically-enhancing land and water management or that produce energy as a byproduct of site restoration. [1] Such practices are best implemented within broader strategies for circular economies that prevent, reuse and recycle biodegradable and non-biodegradable materials, including waste management systems that producing energy to support materials cycling (European Commission 2017; Moya et al. 2017).

The vast majority of organic, biodegradable waste, including food and vegetative waste, livestock manure, and human sewage, could be turned into

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[1] Energy from site restoration is technically not renewable since, yet the legacy of waste sites worldwide compels its inclusion here.

compost and other fertilizers and returned to the soil (Breeze 2018), while energy may be produced as a by-product. Aerobic composting can provide a reliable supply of heat, well-suited for use in buildings (Irvine, Lamont, and Antizar-Ladislao 2010; Walther et al. 2017). Manures may not be sufficiently compostable, and in such cases, anaerobic digestion can be used to produce biogas as well as fertilizers for soil amendments (UCS 2012; European Commission 2017). Similarly, non-compostable oils and fats may be available for transport biofuels. Some woody residuals may not be compostable, and if not buried (Breeze 2018), may be available for biomass energy production (UCS 2012). These woody residuals include post-consumer wood waste that has already gone through a reuse and recycling stage, unusable residues from wood industry operations that do not involve additional harvesting, and possibly forest residues that would otherwise rapidly decay (Brack 2017; European Commission 2017), reserving combustion as a last resort.

To support ecological enhancement, agricultural and forestry methods would include various practices such as tree patches, riparian buffers, habitat corridors, conservation areas, native vegetation, perennial and mixed cropping, short rotation coppice systems, hedgerows, rotational or strip harvesting, crop rotations, and agroforestry (van der Winden et al. 2015; Baumber 2017; Gasparatos et al. 2017). Restoration of degraded land, water or waste sites may also support collection of energy as a byproduct, by producing crops on degraded or contaminated sites to increase biodiversity, reverse soil erosion, desertification and high salinity, increase soil carbon, and improve water quality (Baumber 2016; Gasparatos et al. 2017), or by using algal turf scrubbers on degraded surface waters to produce biofuels and recover phosphorus (Adey, Kangas, and Mulbry 2011; Roy 2017). Restoration of existing waste sites may use technologies such as anaerobic digestion, pyrolysis, landfill gas utilization and biorefineries (Seltenrich 2016; Moya et al. 2017) within the context of broader restorative efforts and waste hierarchies.

3.5. *Ocean energy*

Ocean energy technologies convert diverse oceanic processes including tides and currents, surface waves, and thermal and pressure gradients into electricity (Ellabban, Abu-Rub, and Blaabjerg 2014; Gasparatos et al. 2017; Hammar et al. 2017). Little is known regarding the long-term ecological impacts of ocean energy (UCS 2017), thus mitigation measures remain relatively untested. Suggestions include adjusting rotor speeds of conversion devices, minimizing disturbance to marine habitats and sea bottoms during construction, and designing beneficial elements for tidal barrages (dams) including fish-passes (Liu 2015; Gasparatos et al. 2017).

Potential ecological enhancements include creating artificial reefs, habitats, and shelter for marine and coastal species, and designating new or extended marine reserves and protected areas. At the level of individual installations, marine renewable energy systems may be used to limit fishing and recreation, increase the surrounding density of some fish species, and provide fish aggregations devices, new spawning grounds and nursery areas (Inger et al. 2009; BirdLife Europe 2011; Copping et al. 2016). Ocean energy facilities can be integrated within broader marine planning efforts to support marine ecosystems and biodiversity (Copping et al. 2016; Hammar et al. 2017). Designating marine and coastal areas around connected facilities as marine protected areas or otherwise restricting fishing and other maritime activities can protect fish stocks, spawning areas, seabird breeding colonies and migrating birds (BirdLife Europe 2011; Gasparatos et al. 2017).

3.6. *Integrated technologies and plans*

Co-locating complementary technologies provides additional opportunities for ecological enhancement, including solar with wind power (Hernandez et al. 2014), aquavoltaics with hydroelectricity (Pringle, Handler, and Pearce 2017), and aerobic composting and solar hot water (Walther et al. 2017). Integration can smooth daily or seasonal variability, provide additional functions such as water conservation and food production, and reduce overall area required. Similarly, co-locating battery and pumped hydropower storage supports optimization of variable energy technologies, extends facility lifespans, reduces land area, and makes use of degraded sites in proximity to new or existing installations (Pevzner 2015; Hoffacker, Allen, and Hernandez 2017; Immendoerfer et al. 2017). Transmission systems provide opportunities beyond conventional mitigation strategies (e.g., buried lines, insulated cables, single-level arrangements (BirdLife Europe 2011; UNEP 2016), such as restoring landscapes beneath and around power lines, integrating habitat and perching, roosting and nesting sites for bird species not at risk of collision, and co-locating solar PV (BirdLife Europe 2011; Uyterlinde et al. 2017).

Beyond individual projects, practices for linking ecological conservation and renewable energy planning broadly involve integrating within and around urban areas (Stremke and Koh 2010; Lokman 2017) and deploying renewable systems and grid interconnection as elements of large-scale conservation and restoration efforts. Cities and regions provide specific contexts for visioning, learning and demonstration across spatial scales (Späth and Rohracher 2012). Opportunities are found in co-designing industrial ecologies including renewable energy within eco-industrial parks and renewable energy corridors. These initiatives involve the cycling and sharing of material and energetic inputs and outputs (e.g., waste water, district heating) supported by technologies such as solar, wind and geothermal energy, to re-introduce ecological dimensions within former industrial zones (Subhadra 2011; IABR 2014; Leung Pah Hang et al. 2016). Integrating rural and urban areas supports a shift beyond local projects toward hybrid, multi-scalar and dynamic infrastructures of human and non-human systems (Lokman 2017). This approach takes advantage of the opportunities to position renewable technologies such as solar PV within and across an ecologically degraded urban-agricultural landscape and in proximity to existing infrastructure (Stoms, Dashiell, and Davis 2013).

Thinking in terms of broader land- and seascapes then points to opportunities for supporting regional and global ecological connectivity, positioning renewable energy systems as subsystems within conserved and restored ecological systems (Sørensen 2017). This approach requires the integration of planning and development processes from the beginning, accounting for unique technological and ecological qualities, and emphasizing interconnection across large spatial scales, to advance rather than conflict with the scientifically-grounded pursuit of large-scale conservation and restoration of ecosystems and connectivity (Noss et al. 2012). Additional benefits include the use of diverse energy sources and technologies to minimize variability of electricity generation and the potential for increasing collaboration across neighboring regions (UCS 2017).

Depending on energy sources and technologies, integrating energy development within patterns of ecological conservation might involve solar PV within landscape-scale ecological networks (BirdLife Europe 2011), basin- or watershed-scale development strategies (Sale, Hall, and Keil 2016), interconnections of offshore wind projects (Uyterlinde et al. 2017) cross-jurisdictional marine planning and infrastructure (OMA 2008; Hammar et al. 2017), and repurposing of hydro "legacy landscapes" to develop networks of pumped hydro-storage projects (Pevzner 2015). For electrification, transmission infrastructure can serve as ecological energy networks (IABR 2014) while seeking to minimize the need for transmission as much as possible (Capellán-Pérez, de Castro, and Arto 2017). Existing transmission systems may be re-routed or combined with ecological habitat and recreation (Uyterlinde et al. 2017) and new transmission corridors may be planned to reverse fragmentation and support widespread regional connectivity (Stoms, Dashiell, and Davis 2013; Pevzner 2015).

4. DISCUSSION

The set of practices reviewed here are offered in a context of increasing calls to advance renewable energy while reversing the loss of biodiversity and ecosystems worldwide over the coming decades. Present trends suggest both projects risk failure, compelling an integrated approach that creates renewable energy systems in a manner complementary to the biosphere and resulting in measurable improvements to human and nonhuman life. Mutually-beneficial renewable energy systems are proposed due to their practical relevance, the inter-relatedness of technological and ecological dimensions of these systems, and the broadened set of ethical concerns that these relations inspire. This review finds a set of practices and outcomes of renewable energy systems beneficial for ecosystems and biodiversity (see *tab. 1*). Beneficial practices are generally supported by integrating plans for habitat and ecosystems from the outset, identifying sites and technologies in addition to or in advance of resource potential. These practices can be combined with conventional practices that avoid and minimize impacts to sensitive areas and wildlife habitat, account for impacts of technological life cycles, engage diverse publics through robust procedures and ownership models, and reduce overall use of energy.

Solar energy systems demonstrate promise in terms of their integration within developed and degraded landscapes and their potential for co-location and layered functions. Onshore and offshore wind and ocean energy offer potential to extend and create new protected areas and habitat zones, while run-of-river hydro can support riparian and watershed restoration. Bioenergy sources present challenges that require critical assessment, but if well-implemented, may support ecological and restorative practices while providing energy as an addition. Combining technologies and infrastructures offers further potential for benefits. Taking this approach to scale points to greater deployment in urban and peri-urban areas and degraded landscapes and suggests a view of renewable energy systems as subsets of large-scale conservation and restoration efforts. These examples collectively seek to improve connectivity and extend ecosystem structure and function as a *primary objective* of renewable energy development.

Various practical and theoretical implications follow. Technologically, the approach proposed here is likely best implemented using diverse technologies to correspond with the diversity of places where these technologies are used and to vary the types of impacts (Ebenhack and Martinez 2014; Hussain, Arif, and Aslam 2017), suggestive of a new, ecological form of responsible innovation (Owen, Bessant, and Heintz 2013; Chilvers and Kearnes 2015).

Table 1. – Beneficial practices of renewable energy systems for ecosystems and biodiversity

RENEWABLE ENERGY SYSTEM	BENEFICIAL PRACTICES	SELECTED SOURCES
Solar	• Conversion of degraded areas • Integration in the built environment • Restorative land management and site repurposing • Co-location with vegetation and habitat • Agrivoltaics • Floatovoltaics	Macknick, Beatty, and Hill 2013 Hernandez et al. 2014 Beatty et al. 2017 Hoffacker, Allen, and Hernandez 2017 Moore-O'Leary et al. 2017 Hyder, Sudhakar, and Mamat 2018
Wind	• New and extended protected areas • Artificial reefs and sea life shelter • Floating offshore wind farms • Multifunctional use of space surrounding turbines	OMA 2008 BirdLife Europe 2011 UCS 2017 Uyterlinde et al. 2017
Hydro	• Ecological flow patterns • Non-flow habitat protection and restoration • Dam retrofitting or removal • Artificial fish passageways • Run-of-river systems	van der Winden et al. 2015 Sale, Hall, and Keil 2016 UCS 2017
Bioenergy	• Reuse and recycling of residual waste • Ecological/multifunctional agriculture and forestry • Co-production with restoration of degraded sites	van der Winden et al. 2015 Baumber 2016 Brack 2017 European Commission 2017 Gasparatos et al. 2017 Walther et al. 2017 Breeze 2018
Ocean	• New and extended protected areas • Artificial reefs and sea life shelter	Inger et al. 2009 Copping et al. 2016 Hammar et al. 2017
Complementary technologies	• Hybrid renewable energy systems • Storage in degraded sites • Combined transmission-generation-restoration	Hernandez et al. 2015 Pevzner 2015 Immendoerfer et al. 2017 Pringle, Handler, and Pearce 2017
Integrated ecological-energy systems	• Urban and peri-urban development • Regional and global connectivity	Stremke and Koh 2011 Noss et al. 2012 Pevzner 2015 Santangeli, Toivonen, et al. 2016 Lokman 2017 Sørensen 2017

Technological permanence and the degree to which impacts during construction or operation are reversible should be considered, to establish improved conditions following the end of the project (Pasqualetti and Stremke 2017). This process would allow nonhuman nature to redirect or resist human intention over space and time (Fatimah and Arora 2016). Accordingly, protecting wildlife would be accounted for similarly to other natural processes influencing measures of resource potential.

Spatially, the review points to prioritization of sites that require restoration, accommodate shared uses, integrate within urban and periurban landscapes, and/or support greater connectivity across fragmented ecosystems, while avoiding minimally-disturbed ecological habitats even when well-designed. Previously disturbed or degraded sites including brownfields, mine pits, landfills and agricultural fields, would be selected, using projects to clean up contamination. Site selection would also minimize distances between energy generation and end use to limit the need for additional transmission systems, likely favoring decentralized energy systems (UCS 2009; BirdLife Europe 2011; Lieberman, Lyons, and Tucker 2014; CBD 2015). Renewable energy systems would expand "inward" while ecosystems expand "outward" in a manner that extends ecological spaces into humanized spaces (Martin, Maris, and Simberloff 2016) and connects discrete installations (Braham et al. 2015; Labussière and Nadaï 2017). This implies an opening for analysis and experimentation beyond suitability of each facility to include assessment and broader planning for biodiversity and ecosystem function.

Temporally, planning will demand greater engagement across stages of technological lifecycles. If renewable energy systems are to endure as the name would imply, then long periods of coevolution of sociotechnical-ecological systems should be expected. Practices may include assessments of reversibility and restoration of projects, repowering of existing facilities with improved technologies, and removal of poorly-sited facilities upon decommissioning. The pace of renewable energy development may slow or, as advocates assert, this combined approach may reduce conflict and facilitate development. In either case, the complexity and sense of urgency of problems of transition do not eliminate the responsibility of humans for nonhuman life any more than they would for marginalized human groups (McShane 2016).

This integration of energy and ecology implies the need for supporting systems of governance that link relevant international goals and timelines for achieving renewable energy and biodiversity at all levels. Ecological improvement may also be well served through cross-scalar coordination, siting facilities for the greatest benefit to biodiversity, human health and energy access (Santangeli, Di Minin, et al. 2016; Santangeli, Toivonen, et al. 2016; Dinerstein et al. 2017). Such efforts require broadened political and financial commitments and increased participation of diverse stakeholders (BirdLife Europe 2011). To achieve broad benefit, integrated ecological-energy systems at larger scales imply that both publicly- and privately-owned areas deserve assessment for compatibility, recognizing for example that areas most in need of restoration are often under private control (Stoms, Dashiell, and Davis 2013). Understanding and assessing benefits requires responsive governance (Chilvers and Pallett 2018) including ongoing monitoring of actual effects and publicly-available data on beneficial practices (Lintott et al. 2016; RSPB 2016; Moore-O'Leary et al. 2017). Various policies hold promise, including standards, certifications, limited licensing terms, community benefit agreements, and funds for ecosystem enhancements (Science for Environment Policy 2015; Gasparatos et al. 2017). These efforts would provide a foundation for learning over time, an essential quality of enduring mutualistic behaviors. Establishing a clear voice for nonhuman interests at site and regional levels would further ensure that conservation objectives remain paramount (Fatimah and Arora 2016).

Several specific cultural practices are likely important to enroll within a mutually-beneficial approach. Formal and informal education can be engaged beginning at a young age, potentially promoting pro-environmental behaviors (Noss et al. 2012, Ellabban, Abu-Rub, and Blaabjerg 2014; Quinn, Castéra, and Clément 2016). Planning and mapping procedures can serve to structure our knowledge of nonhuman nature (Jørgensen 2014). The increased inclusion of conservationist and ecologists in renewable energy development (BirdLife Europe 2011) can provide cultural legitimacy to this approach. Integrating art, technology and ecological sciences, including more thoughtful and creative approaches to engaging with the unique visual properties of renewable energy technologies (Apostal et al. 2017), can reinvigorate historical traditions and relationships of people to technologies (Anker 2010; Ndubisi 2014). Over time, renewables may develop into culturally meaningful landmarks and sites of local identity (Uyterlinde et al. 2017). These and innumerable other practices can give cultural expression to the practical, ecological and ethical dimensions of mutually-beneficial renewable energy systems.

This approach is not without risks, including poor implementation, and cooptation, for example, praising localized benefit while downplaying lifecycle or cumulative impacts (Ferrario and Castiglioni 2017). More fundamentally, this approach may be interpreted as an opportunity to advance technomodernism (Brinkman and Hirsh 2017) and a techno-scientific energy paradigm (Frigo 2017, 13). If taken as technocratic or hyperintentional design, a remaking of nonhuman nature may result, wherein historically-informed restoration is subsumed to conscious reinvention, domestication and simplification of ecosystems, overly constraining nonhuman agency and dissolving nonhuman nature within techno-economic systems (Higgs 2012; Keulartz 2012; Crist and Kopnina 2014; Kidner 2014; H. Washington 2018). An emphasis on ecological conservation may also be used to depoliticize energy transition, consolidate ownership, or facilitate further growth and capital accumulation. These risks deserve serious consideration to prevent justification of the status quo and to promote technologies of humility rather than hubris (Jasanoff 2018).

5. Conclusion

As a novel contribution to scholarship and practice of renewable energy transition, this research positions the renewable energy systems as opportunities for broadly applied conservation and restoration, connects human-nature relational perspectives to practices of renewable energy, draws together established and emerging beneficial practices for a range of renewable energy systems, and proposes a unique energy transition pathway during a time of early and increasing deployment. This work can be extended by defining and assessing available degraded areas; improving measures of outcomes; studying particular interactions between species and ecosystems and technologies; implementing, monitoring and sharing results of projects and plans across a variety of systems, locations and time periods; and developing institutions to integrate efforts for renewable energy and biodiversity conservation at all levels of governance.

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