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Valuing Ecosystems in Equitable Energy Transition Planning

November 2022

Katie K Arkema
Simon Geerlofs
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U.S. DEPARTMENT OF ENERGY

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Abstract

In this report we explore three areas of research and practice needed to scale clean energy sustainably: 1) advancing the predictive science to quantify positive and negative outcomes of energy development for the wellbeing of communities, environments, and disadvantaged groups; 2) scenario design using this science to shape renewable energy solutions for nation-wide decarbonization while delivering tangible, local benefits; and 3) participatory science-policy processes to understand what people want for the places where they live and work and how incorporating renewable energy can help or hinder their goals. Together these three components – quantifying social-ecological values, scenario design, and participatory processes – form the basis for a framework for valuing ecosystems to inform a more equitable energy transition.

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1.0 Introduction

Climate change is putting communities across the US and around the world at risk. The Intergovernmental Platform on Climate Change (IPCC) Sixth Assessment Report on Impacts, Adaptation, and Vulnerability warns of global sea-level rise, flooding, and droughts[1]. In the US, western states experienced record high temperatures this year, with Sacramento reaching 116ºF, Puerto Rico was plunged into darkness after another hurricane, and firefighters battled hundreds of thousands of acres of wildfire. Such impacts disproportionately affect disadvantaged and vulnerable populations.

To address this climate crisis, the Biden Administration and Congress have passed a series of executive actions and legislation. In 2021 the United States rejoined the Paris Climate Agreement, committing to a 50% reduction in emissions by 2030 and ultimately achieving net-zero emissions by 2050. Combined with the Infrastructure Act and the Inflation Reduction Act, these initiatives aim to increase high-quality jobs, invest in more resilient infrastructure, and spur American technological innovations, especially in clean energy. However, there is a tension between scaling renewable energy to meet nation-wide decarbonization goals and achieving positive, place-based outcomes for local communities, including, but not limited to communities of color.

To avoid past mistakes going forward, government agencies, industry, investors, civil society, and scientists have an historic opportunity to leverage and advance sustainable development approaches that have gained traction internationally over the past decade. These approaches include mainstreaming of natural capital and nature-based solutions, as well as the development of justice-centered benchmarks that are now embraced and increasingly widely employed by multilateral development banks. The United Nation's 2030 Sustainable Development Goals recognize that poverty reduction, health, economic growth, and other social goals are intertwined with the health of ecosystems and the urgency of tackling climate change[2]. The World Bank is exploring global ecosystem products as a complement to traditional metrics like Gross Domestic Product (GDP) and the Inter-American development bank has mainstreamed social-ecological values and climate change into its policies and programs.

The United States is making progress too, especially around investing in nature-based solutions for increasing resilience to natural hazards. The US Army Corps of Engineers recently spearheaded the development of international guidelines for incorporating nature-based solutions for flood risk mitigation which accounts for a suite of social and economic values of ecosystems[3]. In the wake of Hurricane Sandy, the Department of Interior spearheaded a program to invest in conservation and restoration of shoreline ecosystems to reduce risk from coastal hazards all along the eastern seaboard. The

Biden Administration recently established the federal Justice40 initiative and the White House Task Force on environmental justice to address the disproportionate health, environmental, and economic impacts that have been borne primarily by communities of color[4].

However, quantifying the social and economic value of ecosystems as part of renewable energy planning and development with a goal of benefiting local communities is still nascent. There is an opportunity to leverage natural capital approaches and tools to inform an equitable energy transition. In this report, we ask three main questions:

1. How do we quantify the socioeconomic values of ecosystems to inform community-driven energy planning processes?
2. How can energy solutions be shaped to support nation-wide decarbonization goals while delivering tangible, quantifiable local benefits?
3. How do we increase local interest in energy transitions so that demand rises to meet the coming supply of technological solutions?

We propose a framework that addresses these three questions through the application of 1) an ecosystem services assessment approach, 2) design of qualitative and quantitative scenarios, and 3) development of participatory science-policy processes for incorporating ecosystem services into renewable energy transitions (Figure 1). Taking a more interdisciplinary and community-driven approach to clean energy development will foster local demand for renewable technologies and result in a more equitable energy transition.

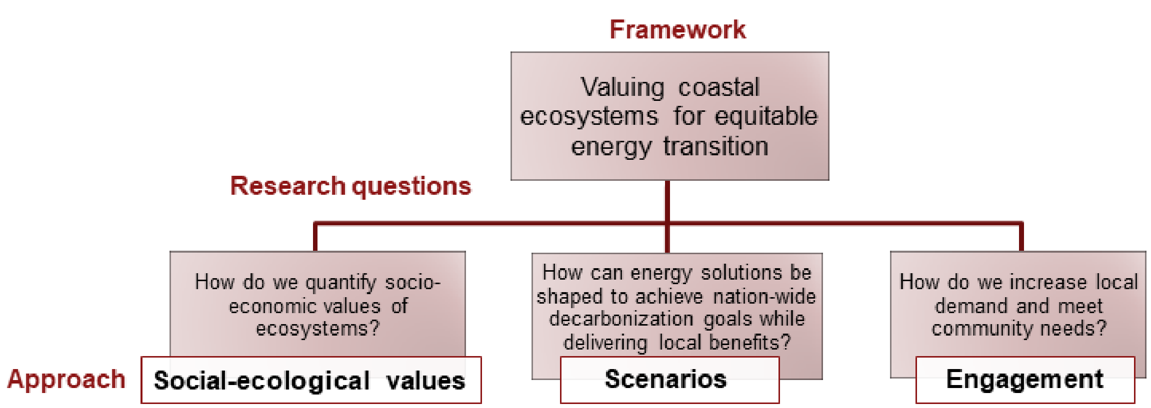

Figure 1. Framework for valuing ecosystems for equitable energy transition

2.0 Framework for Valuing Ecosystems in Equitable Energy Transition Planning

2.1 Modeling of social-ecological values with natural capital assessments

Natural capital is the stock of natural resources, including soils, air, water, and all living organisms that generate the ecosystem services underpinning economies and societies[5]. Natural capital assessments—as applied to sustainable development decisions—incorporate interdisciplinary models that reveal how infrastructure projects of all kinds (e.g., transportation, energy, commercial, residential development etc.) influence the socioeconomic benefits of ecosystems for human wellbeing[6–8]. These natural capital frameworks can be used to understand the outcomes of siting, design, and other infrastructure decisions for different groups of people based on a combination of qualitative and quantitative information[9,10]. They are also explicitly designed to explore trade-offs and synergies among a suite of social equity, economic prosperity, and environmental health outcomes that underly human wellbeing, rather than focusing only on cost and economic objectives considered in traditional optimization modeling[11].

All people and all communities depend on ecosystems – a concept referred to as “ecosystem services” or more recently as “nature’s contributions to people”[5,12]. Natural capital is the stock of natural resources which generate ecosystem services. For example, forested watersheds retain sediments and cycle nutrients, maintaining clean water for drinking and recreating[13,14]. Healthy soils and pollinator habitat support agriculture[15]. Coastal habitats such as wetlands, corals, oysters, seagrasses, and dunes help to attenuate waves and surge, reducing nearshore flooding and stabilizing shorelines[16]. Nearshore vegetation and reefs provide nursery habitat for fish, supporting commercial and subsistence fisheries that provide sustenance and livelihoods [17,18]. All types of vegetation, on land and in the ocean, store and sequester carbon, contributing to climate stabalization[19]. The challenge is that the value of these benefits is not often recognized until they are lost. If we can understand and account for the ways in which healthy ecosystems provide societal and economic benefits before development decisions are taken, we can avoid unintended consequences, ensuring that both and nature and people thrive[20,21].

Since the publication of the millennial ecosystem assessment nearly two decades ago, scientific understanding of the myriad ways in which nature benefits people has exploded[12,22]. So too has the development of natural capital approaches and tools for informing sustainable development[23]. Thousands of papers categorize, quantify, and explore nature's contributions to people in the peer-review and grey literature. Decision support tools provide more transparent and accessible approaches for practitioners to explore how climate and land-use scenarios will influence composition of land and seascapes and how these changes lead to changes in water quality, climate regulation, resilience to natural hazards, agricultural productivity, and many more of nature's services[24]. Scientists, stakeholders, and policymakers are using this information to guide a variety of conservation and development decisions[25]. Calls for mainstreaming ecosystem services and natural capital into decision-making are being put into practice nationally and globally[2,3,26–28]. The time is right, and the science is there to leverage natural capital tools and approaches to inform renewable energy development and implementation[29].

Application of natural capital tools and approaches for renewable energy is growing. Several papers have illustrated how efficiency frontiers, as adopted from the field of economics, can be used to reduce conflicts and improve outcomes[30,31]. Efficiency frontiers identify a set of optimal solutions to a decision (e.g., siting) where one objective cannot be increased without diminishing returns to another objective. In this way efficiency frontiers can be used to explore trade-offs among objectives, for example, highlighting sites for renewable energy development that have the greatest potential to deliver energy resources and reduce risk to ecosystem services provided by land or seascapes.

Example applications for offshore wind include using efficiency frontiers to maximize net benefits across a range of preferences for offshore wind, whale conservation, and fishing[30] and offshore wind and viewsheds[31]). A study in 2015 found that, in contrast to nuclear and offshore oil, which lead to predominantly negative effects on marine ecosystem services, offshore wind has a mix of positive and negative effects on cultural, provisioning and supporting services, while the effect on regulating services (e.g., water quality, shoreline protection, sediment retention) was not studied[32]. This year Trifonova and colleagues published a natural capital framework that combines environmental and socioeconomic implications of offshore wind that would be broadly applicable to other renewable energy technologies[33].

Analysis of multiple benefits provided by ecosystems can help support place-based approaches to renewable energy by quantifying the benefits and costs of alternative development scenarios. The first and most fundamental step of assessing ecosystem services is explicitly recognizing and assessing how changes in natural features, as a result of infrastructure development, may lead to changes in ecosystem functioning and in turn the provision of societal benefits (Fig. 2 top row)[34].

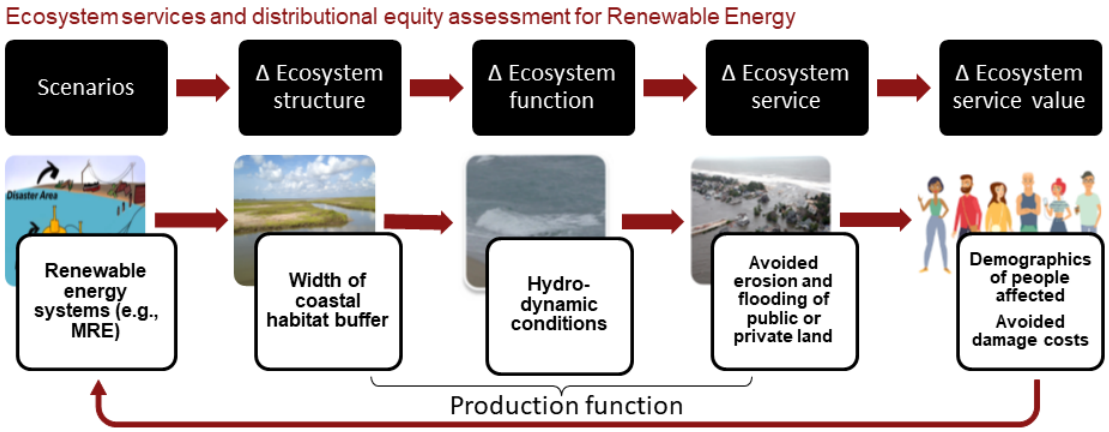

Figure 2. An ecosystem service assessment for marine energy and coastal risk reduction.

For example, through extraction of wave energy, marine energy systems could create a calmer nearshore environment conducive to recruitment and growth of nearshore and shoreline vegetation such as seagrasses and saltmarshes. These coastal habitats in turn can help to retain sediments and reduce wave action, leading to lower coastal erosion and flooding of public or private land. The risk reduction provided by coastal ecosystems may in turn benefit coastal communities by reducing damage costs from storms and high tides (Fig 2. bottom row). As another example, photovoltaic solar panels can support pollinator habitat by providing partial shade for flowering plants[35]. An increase in the diversity and abundance of pollinators throughout the growing season could in turn support agricultural production, especially in regions suffering from warming temperatures and drought. Improved stewardship with implementation of solar in previously barren areas could also support water quality through sediment and nitrogen retention. These positive outcomes can in turn result in increased demand for the energy system.

For the most part, the scientific literature has focused on ecological impacts of renewable energy technologies and not necessarily extended these to changes in societal values that may result from ecosystem degradation [36,37]. To better understand the potential influence of renewable energy development on social-ecological values, we conducted a review of the literature on different renewable energy technologies and ecosystem services (Appendix A). We developed a set of attributes to track 1) the focal renewable energy technology, 2) the ecosystem services considered, 3) whether alternative scenarios were developed, and 4) the extent to which the studies were integrated within science-policy processes to inform decision-making. Several recent studies have shown the potential impacts of renewable energy development on regulating services such as air and water quality and natural hazards, food production, and cultural services such as aesthetics and inspiration, sense of place, and recreation and tourism opportunities (see Ref [38] for a review and Appendix A for database of findings)[38]. Understanding these impacts is an important part of the design and siting of renewable energy infrastructure to meet local goals. More research and example case studies are needed on the ways in which renewable energy can help to achieve local economic and societal goals through positive influences on ecosystem services and by supporting nature-based economies[39].

Two key aspects of natural capital assessments can help to support place-based renewable energy design and implementation. First, ecosystem service assessments are inherently spatial. Because key social and ecological variables that influence benefits vary spatially, models that quantify ecosystem services tend to take in spatial information and produce spatial outputs. These have the advantage of supporting siting decisions related to energy generation, transmission, and storage and allow for exploring alternative scenarios that could reduce conflicts or safeguard as opposed to degrade, ecosystems and the societal benefits they provide[20]. Second, ecosystem services are frequently quantified using a diverse set of metrics[40,41]. While monetary metrics are useful for shining a light on previously unrecognized ecosystem services, other metrics such as numbers of people or demographic groups benefiting, or the production of goods can resonate more with certain stakeholders. Both the spatial information and the multiple metrics for valuing ecosystem services can help to elucidate the beneficiaries of renewable energy development and the geographical communities and demographic groups potentially impacted by the development. This information can in turn be used to inform financing mechanisms to compensate those impacted or incentives for communities to participate[42].

2.2 Scenario design

President Biden's renewable energy goals require major investment in infrastructure to support renewable energy generation, transmission, storage, and resilience[43]. Infrastructure development of any kind (e.g., transportation, commerce, housing, energy) can impact land- and seascapes, altering ecological systems and the benefits they provide to people. However, the relationship between infrastructure development and environment isn't just about impacts of people on ecosystems. Informed infrastructure development and stewardship of ecosystems can also enable communities that rely on natural resources to prosper[6]. For example, sustainably designed investments in processing plants that draw on local renewable energy resources to process fish, agricultural products, or other commodities can enable communities to reap higher profits from local, harvested goods. Well-planned roads, reliable, electric ferries, and green accommodations can facilitate tourism in beautiful places. The same is true for the development of renewable energy systems. Community-designed renewable energy projects could help cities and towns on their journey towards sustainable prosperity. The key is to understand how future scenarios of renewable energy development influence ecosystems and the benefits they provide to people[44].

Several papers we reviewed include the development of scenarios for exploring outcomes of renewable energy projects on ecosystem services. Scenarios are "plausible description[s] of how the future may unfold based on a coherent and internally consistent set of assumptions about key driving forces ... and relationships"[1]. They are useful for exploring how actions taken today might play out in the future. Scenarios are increasingly recognized as a key component of sustainable development planning[45].

Scenarios often consist of both qualitative storylines and quantitative information[46]. They provide an opportunity for stakeholders, communities, scientists, and policymakers to come together to develop multiple options or pathways, to capture and reflect back alternative perspectives and opinions about what that future may look like, and to explore trade-offs. In the case of renewable energy, scenarios could involve comparing different technology options, siting locations, or design proposals. Alternative scenarios could be co-developed to explicitly explore trade-offs and synergies between achieving national scale decarbonization goals and local outcomes. We are still exploring the scenarios documented in the literature for renewable energy and ecosystem services and how these could be advanced to tackle the tension between place-based and national-scale goals (Appendix A).

Scenario design often includes the development of several written storylines describing the social, economic, and environmental conditions under alternative futures. Scenario design may also include hand-drawn maps where community members have depicted current and future elements of the land and seascape which they would like to see developed (e.g., new energy infrastructure or development projects requiring additional power) or protected (e.g., ecosystems, viewsheds, recreational access points, commercial or subsistence fishing locations)[46]. Scenarios may also include quantitative information in tables or maps describing social, economic, and environmental conditions under the different possible futures.

2.3 Participatory process

To increase the decision relevance of natural capital assessments and scenarios, there is a need to link this science with better understanding of the needs and values of communities that may interact with renewable energy infrastructure[47]. There is also a need to explore trade-offs in not only monetary metrics, but also human health and demographic metrics that may resonate with different world views and perspectives. In collaboration with local populations and stakeholders, this information can in turn be used to shape the design and development of renewable energy technologies, as well as incentive programs, to achieve positive social, ecological, and economic outcomes and assure benefits of development projects for communities[33].

Traditional approaches to infrastructure development have pursued stakeholder and community participation primarily through elicitation of stakeholder feedback on proposed projects. However, more recent approaches to community-based development projects and community-based natural resource management involve collaborating with local populations and stakeholders throughout the planning and implementation phases. At the beginning of a process, scoping and convening stakeholders and/or community members involves understanding the challenges a community is facing, the overarching goals of the community for the future of where they live and work, and how these goals may relate to potential renewable energy interventions. A truly participatory process would also involve working closely together in each phase, including incorporating local knowledge into data collection, developing alternative scenarios for the future that incorporate differences in community perspectives and preferences, ensuring parameters in models reflect assumptions agreed on by the community, providing interim results for review and input from community members, and iterating on the analysis to ensure community input is incorporated.

A participatory process is inherently iterative and not all communities or energy transitions will proceed through the various steps and stages in the same order. A key part of an iterative process is not just integration of knowledge gained from monitoring, evaluation, and stakeholder feedback into future planning and projects (i.e., adaptive management), but also the feedback from stakeholders, community leaders, and other partners during each step in the planning process and the role of these partners in framing the research or technical assistance in the first place. Iterative and sustained collaboration with community members and key stakeholders fosters community ownership of the energy transition and enables identification, analysis, and monitoring of social, economic, and environmental goals that underpin sustainable development and the blue economy. Coproduction of information among researchers, communities and policy-makers maximizes the chances that scientific results will be salient, credible, and legitimate[48,49]. Processes that incorporate active participation, information exchange, transparency, fair decision-making, and positive participant interactions are more likely to be supported by stakeholders, meet management objectives, and fulfill community development goals.

3.0 Conclusion

Achieving national decarbonization targets and communities' economic, social, and environmental goals requires interdisciplinary and participatory approaches to a renewable energy transition. The framework we lay out in this report outlines three key components of a natural capital approach to sustainable development that we believe can be effectively applied to renewable energy. These components include 1) quantifying the social-ecological outcomes of alternative renewable energy options, 2) design of qualitative and quantitative scenarios for future infrastructure development, and 3) development of participatory science-policy processes for incorporating natural capital and justice benchmarks into renewable energy transitions.

Several major next steps are needed to test and implement this framework and these approaches. These steps include building out the conceptual and quantitative models that capture relationships between renewable energy development and social-ecological systems. Second, there's a need to identify key elements of alternative future energy scenarios that will allow us to explore the tension and realize synergies between local and national goals. Third, capacity building and cultural change within government, industry, and academia are needed to support the transferability of best practices for participatory science-policy processes from other sectors to the energy sector. Lastly, there's a need to test and refine our framework for valuing ecosystems to inform the renewable energy transition by applying it—in collaboration with government, industry, academia, and communities—to real-world planning processes and development decisions.

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Appendix A – Renewable energy and ecosystem values

Literature Information				Research Questions and Metadata										Ecosystem Services									Methods	
Citation	**Study Location**	**Study Type**	**Energy resource**	**Research Question**	**Scenarios**	**Action / management**	**Engagement**	**Policy window**	**Iterative process**	**Beneficiaries**	**Pollination**	**Agriculture**	**Fisheries**	**Recreation**	**Climate mitigation**	**Coastal resilience**	**Water quality**	**Water quantity**	**Sediment**	**Flood mitigation**	**Renewable energy**	**Other Activities**	**Model/ Assessment Employed**	**Limitations of Study**
Burkhard and Gee, 2012	German North Sea	Case Study	Offshore Wind	Seeks to highlight potential regime shifts in the marine ecosystem and the possible transitions that may result from OWF development in the socioeconomic system on the coast of Northern Germany.: ● Do the Coastal Futures results provide evidence of potential regime shifts occurring as a result of OWF introduction? ● Partly as a result of regime shifts in the sea, will OWF introduction lead to a transition in the socioeconomic system on the coast? What factors would need to come into play for this transition to occur? ● What theoretical framework is able to capture and describe any cross-scale effects?	Y	N	Y	N	N	N	N	N	N	Y	Y	N	N	N	Y	N	N	Full list in Table 1; cultural services discussed, including visual aesthetics, heritage, habitat/species value, sense of place, seascape character; ES not quantified, instead the study models "regime shifts in the respective subsystems and the impact of the respective trajectories on selected ecosystem services" as seen in Table 2	Because the majority of these OWFs have not yet been built (see Fig. 1), the Coastal Futures project worked with future scenarios assuming different OWF developments in the case study area (Lange et al. 2010). Different ecological models were used to assess the environmental impacts of the assumed scenarios (Burkhard et al. 2011a). In a parallel investigation, interviews and expert assessments were used to evaluate the potential effects of OWF expansion on seascape values and related ecosystem services, as well as the secondary effects on human well-being in the case study area	
Casalegno et al., 2014	Cornwall, UK	Case Study	Solar and Wind (as an ecosystem service)	Aims to prioritize areas for ecosystem services, urban development and renewable energy provision together, serves as a tool for optimizing their provision, and for promoting their consideration during the landscape management decision making processes. To do this, the authors address the following fundamental questions: (i) how are the values of key services spatially distributed?; (ii) what are the spatial covariances between services and the consequences for the spatial co-occurrence of services?; and (iii) where are the priority areas (locations where one or multiple service provision is greatest) for environmental service provision?	Y	N	N	N	N	N	N	Y	N	Y	Y	N	N	N	N	Y	Y	Cultural services included: tourism (distance traveled by visitors to natural sites), aesthetics (individuals uploading photographs); Plant production (normalized differential vegetation index) and urban development (urban land cover as living space service) included	Overall patterns of spatial variation within maps were quantified using Moran's I index [61]. Moran's I index approaches a value of 1 when there is a high degree of clustering, whereas values approach zero for disperse and random distribution patterns. We determined the spatial covariance between each of the environmental service layers in Cornwall using the Clifford Richardson Hemon correlation method	
Causon and Gill, 2018		Review	Offshore wind	Aims to specifically link changes to biodiversity, in relation to OWFs with ecosystem services through associated processes and functions.	N	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	N	N	None		
Chenoweth et al, 2018	Case Study 1: Surrey, UK; Case Study 2: Raleigh, NC, USA; Caste Study 3: Seattle, WA, USA	Discussion through case studies	Green infrastructure - not RE	Use case studies to offer perspectives on the relationship between green infrastructure and natural capital related to ES						N	N	N	N	N	N	N	N	N	N	N	N			

Copping et al., 2020	International	Review/State of the Science	Marine energy	Compiles the most current and pertinent published information about interactions of marine renewable energy (MRE) devices and associated infrastructure with the animals and habitats that make up the marine environment.	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Literature Review	
Custudio et al., 2022	Belgian Continental Shelf	Stakeholder engagement method	Predominantly offshore wind	This study presents a process for stakeholder engagement process and its outcomes, namely a list of ES priorities and the linkages between those ES and marine activities. These results help to understand the priorities of the blue economy sectors and establish a baseline for ES prioritization in upcoming assessments. It is anticipated that this pragmatic approach can be adapted and applied to other geographical areas to capture stakeholder knowledge quickly and efficiently. The study also presents a conceptual diagram was co-developed linking marine activities and ES to highlight potential synergies and trade-offs, with a focus on offshore wind	N	N	Y	N	N	N	N	Y	Y	Y	Y	Y	N	N	N	N	Y	biodiversity, wild plants	Es to include in the participatory discussions were identified through a Web of Science review and using CICES - list of 14 relevant ES is outlined in table 1	
Datta et al., 2020	Western Canada	Scoping Review	Pipelines and Indigenous communities	This paper reports on a scoping review of critical issues in sustainability, particularly energy pipelines and their impact on Indigenous peoples' drinking water access.	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA		
Davis et al., 2018	Oklahoma, USA	Case Study	Wind Energy and Unconventional Gas	To examine the land-use changes caused by unconventional gas and wind development in the Anadarko Basin of the Woodford Shale in west-central Oklahoma, then calculate the ecosystem services costs associated with these land-use changes. They chose this region as a case study because the area has seen the rapid development of both unconventional gas wells (from 0 to 228 wells) and wind turbines (from 0 to 418 turbines) from 2008 to 2015. They measured the amount of land developed and the associated ecosystem services costs and standardized these measurements on a per unit basis (i.e., well or turbine) and on a per unit energy produced (i.e., gigajoules). The goal was to determine which type of energy development is associated with higher environmental costs, in terms of habitat modification and ecosystem services due to land-use changes.	Y	N	N	Y	N	N	N	Y	N	N	N	N	N	N	N	N	Y	Land-use (hectares per gas well/hectares per turbine). See Table 1	GIS-based analysis; energy and ES calculations were based on a 25-year life span. Obtained habitat-specific ecosystem services (ES) values from a previous study (Moran et al. 2017). Annual ES costs per unit (well or turbine) were calculated by multiplying the number of hectares developed for each respective habitat by its estimated ES value (from Moran et al. 2017) and summing the values of each habitat. We then calculated the ES cost on a per gigajoule basis to acquire a standard ecosystem cost per unit of energy produced. In all calculations, monetary values were adjusted to USD 2015.	the time frame of 25 years is somewhat arbitrary, but it serves as a reasonable estimate to compare the two sources of energy production. assumed modified habitat still possessed ES values, so the cost of that modification was calculated as the difference in ES value between the new habitat and original habitat (Moran et al. 2017).
Egli et al., 2017	Switzerland	Modeling Method/ Case Study	Wind energy	They propose a method to apply the ES approach in a spatially explicit setting combined with an optimisation tool to evaluate, assess, and quantify the trade-offs resulting from wind electricity development.	Y	N	N	N	N	N	N	Y	N	Y	N	N	N	N	N	N	Y	'Intellectual and representative interactions', which is termed 'Aesthetics' in the present study, and 'Physical and experiential interactions' which we refer to as 'Tourism'. Presents proportional change based on scenarios.	Marxan was used as optimisation software to evaluate, assess, and quantify the trade-offs between ES provisioning and wind electricity production. Marxan is optimisation software that was designed as a tool to provide decision support for systematic nature conservation planning. To minimise cost while maximising benefits, the program evaluates different potential spatial management decisions. Ecosystem Service selection was based on the current Common International Classification of Ecosystem Services	Since Marxan was originally designed as a conservation planning tool, some of the inputs, outputs, and parameters were necessarily adjusted for use in the present study.
Emanuel et al.	US	Desktop study	Natural gas pipeline and social vulnerability	Study compared the density of natural gas gathering and transmission pipelines to social vulnerability on a county-by-county basis for all the pipeline-containing counties in the US using geospatial data.	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	compared the density of natural gas gathering and transmission pipelines to social vulnerability on a county-by-county basis for all the pipeline-containing counties in the US using geospatial data from the social vulnerability index (SVI) for 3,142	No counties in Hawaii, and only one county in Alaska contained any gathering or transmission pipelines

																							US counties and county-level equivalents with the US natural gas gathering and transmission pipeline network from the EIA	in the EIA shapefile. Thus, the results apply mainly to the 48 contiguous states. Also, the CDC did not compute the 2018 SVI for one county (Rio Arriba, NM) due to a US Census data collection error
Galparsoro et al., 2022	NA	Review	Offshore wind	Assesses the ecological impacts of OWE devices by mapping the full set of interactions between the latter and marine ecosystem elements (i.e., species, habitats, ecosystem structure and function) useful to planning processes.	NA	Y	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Literature Review	
Gee and Burkhard, 2010	Presents case study on the German North Sea - comprising all German waters including the Exclusive Economic Zone	Conceptual discussion with case study	Offshore wind	The paper aims to understand and disentangle the nature of cultural ES and tools to elicit them. In order to identify and describe regional cultural ES in the German part of the North Sea we address the following specific questions: •Other than purely economic value, what are the sea's key values in the case study area? •Can these values be translated into CES? •Are offshore wind farms likely to have an impact on the CES identified?	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	Focus on cultural ES; to understand the gaps between function and valuation, the study looks at landscape (and seascape, respectively), understood here as the visual manifestation of (coastal and marine) ecosystem structure and operation, whilst place is employed to add dimensions such as place dependence, place attachment and identity. Cultural ES is not quantified, but discussed - "Although these CES also play an important role in generating feelings of "home",2 rootedness and local identity, those same cultural services find expression in hard economic currency (jobs, local income) in sectors such as tourism."	based on definition of cultural ES in the Millennium Ecosystem Assessment	Note: Since no offshore wind farms exist in the German case study area as yet, these views are based on local residents' imagination of what they might look like in this particular context.
Gill et al., 2020	NA	State of the Science	Offshore wind	State of the science rather than addressing a research question or objective	NA	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	None		
Graham et al., 2021	Eagle Point Solar Plant, Jackson County, Oregon	Research Study	Solar	(1) To determine if pollinators would visit flowers in the solar array and (2) document the species abundance, richness, diversity, and composition of insect pollinator and plant communities across shade gradients (microclimates) within the solar array.	-	-	N	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	Agriculture as affected by pollinator ES		No broader quantification of ES
Grilli et al., 2013	Rhode Island, USA	Framework	Offshore Wind	-	-	-	-	-	-	-	-	-	Y	-	-	-	-	-	-	-	Y		Ecosystem-based management (EBM) conceptual framework used. An ecological typology of the coastal area is developed on the basis of ecological variables, using spatial multivariate principal component and cluster analyses. Then, the sensitivity of the resulting ecological subregions to wind farm impact is assessed through the construction of ecological services impact indexes.	
Grodsky and Hernandez, 2020	Ivanpah, California, USA	Research Study	Solar	The primary objectives were to determine effects of solar energy development decisions on the native desert scrub plant community with respect to the ES values (ESVs) of plant functional groups and species and to test the efficacy of an ESV system as a sustainability assessment tool to measure the socioecological effects of renewable energy development.	Y	Y	N	N	N	Y	Y	Y	N	N	Y	N	N	N	N	Y	Y	Cultural ES to include things like indigenous tools, traditional medicine and others (see fig on page 1038); quantified all ES values by species of desert plant - see figure on page 1038.	Developed an ES-value system for a model desert plant community (here designated 'desert scrub') occurring in the Ivanpah Valley of the Mojave Desert, California. They define ESVs as ESs (and disservices) of desert plants contributing to a value system with the capacity to guide human judgments and actions pertaining to solar energy development in deserts.	
Hanes et al., 2017	Applied models to renewable energy in central Ohio	Modeling Framework with Case Study	General RE, biomass conversion,	Presents techno-ecological synergy (TES) as a concept that can be used to develop a design methodology that simultaneously incorporated technological and ecological decision making, a life cycle system	Y	N	N	N	-	N	N	N	N	N	Y	N	N	N	N	N	Y	None	TES Design methodology, which is used to make simultaneous technological and ecological design decisions within a multi-scale system in order to both decrease demand and increase supply of multiple ecosystem services. The method helps	Simplifications had to be made in the modeling process, ex: climate regulation/carbon

	based on land use and biomass conversion activities already established in the region and those activities which have the potential to be economically and technically feasible		solar and wind	boundary, and supply/demand of ecosystem services; the methodology is demonstrated by a renewable energy application in Ohio																			avoid the risk of identifying sub-optimal design decisions that either shift ecosystem service demand and the accompanying environmental impacts outside the system boundary, or decrease ecosystem service demand without considering if the decreased demand can be sustainably supplied by supporting ecosystems. TES also promotes land uses that preserve and restore ecological functions and increase ES supply. This is a method in contract with traditional life cycle design (see Table 2 for comparison); the model was implemented in Python, and the combination of activities in the energy production system and their life cycles were captured using a process to planet (P2P) modeling framework; several models were run including biomass conversion, wind turbine,and solar panel models, farming activity models (used EPIC software), a forest ecosystem model (used iTree design software), scale of ecosystem services (focus on GHG and carbon sequestration)	sequestration was modeled only at the regional scale; air quality was modeled only based on available data - only N2O and sequestration was considered; wind turbines and solar panels were assumed to have zero ES supply and demand at the farm level; no water resources or considerations were included
Hastik et al, 2015	Alpine Area, Europe	Review	Alpine Renewable Energy - mostly wind power, agricultural biomass and ground-mounted PVs, as well as geothermal . Offshore wind power, tidal energy are excluded from this study.	Existing studies on the impacts of several resources are reviewed and elaborated from an ecosystem services perspective with an emphasis on possible ES impacts listed in the CICES classification. The focus is on impacts of RE at the production sites, in the context of the Alpine area; a set of ES particularly affected by expanding RE are identified, and primary, secondary and marginal issues are distinguished	N	N	N	N	N	N	N	Y	N	Y	Y	N	Y	Y	Y	Y	Y	Forest biomass, includes forest-related activities, road infrastructure, transport activities and combustion - discusses several implications, including natural hazard protection, soil quality, water quality, air quality, etc	Literature Review	Off-site impacts caused by production, disposal or recycling of power plant elements and lifecycle analyses (e.g. carbon lifecycle emissions) are not considered in this study; it was not possible to conduct a quantitative analysis of existing publications due to the wide range of environmental aspects involved, the variety of potential keywords, the different languages used in the Alpine region and the number of REsources assessed.
He et al., 2019	California, USA	Framework and Case Study	Solar/Wind	To examine the added value of solar and wind energy in reducing sustainability trade-offs, we use this framework to quantify how optimal strategies maximizing hydroelectricity and agricultural income, whilst avoiding groundwater depletion, are altered by the penetration of solar and wind energy.	Y	N	N	Y	N	N	N	N	N	N	N	N	N	Y	N	N	Y	None	Trade-off frontier (TF) and expansion path (EP) modeling	human dimensions are simplified in the framework, where they assume unchanging human behavior and decision making (e.g., water use, irrigation activities, crop choices).
Hooper et al, 2017	NA	Review	Offshore wind	Provides a more comprehensive evaluation of the implications of offshore wind farms for ecosystem services. In doing so, it further tests the concept of an ecosystem services approach to energy impact assessment by considering a wider range of metrics and an expanded hierarchy of the ecosystem services onto which the services map, compared to the work of Papathanasopoulou et al.	N	N	Y	N	N	N	N	N	Y	N	Y	N	Y	N	N	N	N	Cultural impacts; The only ecosystem services to be assessed directly were the effect of offshore wind turbines on people's perception of seascapes and sense of place.	A review of 78 publications in the peer-reviewed and grey literature was undertaken to establish the environmental and socio-economic parameters considered in assessment of the impacts of offshore wind farms; mapped ecosystem services using the Common International Classification for Ecosystem Services framework and was supplemented by the Millennium Ecosystem Assessment to include the impacts of energy deployments that affect the environmental processes that provide ES	No attempt was made to attribute species- or community-level changes to particular supporting services such as food web dynamics or nutrient cycling mainly because each species/ community is likely to support ecosystem maintenance in several ways.

Howard et al., 2013	Bedfordshire, England.	Case Study	Land based renewables	To determine how an understanding of the energyscape and ecosystem services could help guide the deployment of land based renewables through presenting a a one year pilot study to discover the potential benefits and obstacles in using a whole system approach to evaluate the energy system. Also to examine energy system options in the context of the wider landscape by taking into consideration the interactions both between the energy components and ecosystem services.	Y	N	Y	N	N	N	N	N	N	N	Y	N	N	N	N	N	N	Recreation/culture and conservation (provisioning of habitat for farmland birds)	The existing land use was described through field survey and remote sensing and the production through the key provisioning ecosystem services was modeled (Fig. 4). Other ecosystem services that were assessed include the regulation of biochemical processes (e.g. soil carbon), culture (e.g. recreation) and conservation (provision of appropriate and sufficient habitats for farmland birds). The local energy demand was also mapped (Fig. 5)	Within this paper only a brief indication of the outputs from the case study analysis has been presented by way of a demonstration of the potential of this approach.
Intralawan et al, 2018	Mekong River, Southeast Asia	Tradeoff Analysis	Hydropower	This study builds on previous assessments of Mekong River basin-wide scenarios with updated inputs including electricity price, loss of capture fisheries, fish price, hydropower project data, values of wetlands, sediment loss and social and environmental mitigation costs.	Y	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Y	Discusses economic impact		
Jonasson et al., 2019	Canada	Discussion/ Case Study	Pipelines and Indigenous communities	Analyses Canadian environmental impact assessments used for fossil fuel expansion failed to include health impacts and risks of spills; uses Trans Mountain Pipeline Expansion and impacts on the Tsleil-Waututh Nation as a case study for discussion	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA		
Jordaan et al., 2021	Chihuahuan Desert, USA	Case Study	Wind, solar, also natural gas	To develop and implement a novel approach for quantifying both land requirements and ecosystem services values based on The Economics of Ecosystems and Biodiversity framework.	N	N	N	N	N	Y	N	Y	N	N	N	N	N	N	N	N	Y	The ES is based on land-use intensity and doesn't necessarily go to the specific ES level - land uses included are grassland, shrubland, woodland; Note the total ecosystem services value of the Chihuahuan Desert has recently been estimated at $367 per hectare (2016 USD) using the well-established TEEB framework	builds upon the framework for LCIA of land use developed by the United Nations Environment Programme (UNEP)/Society of Environmental Toxicology and Chemistry (SETAC) Life Cycle Initiative working group; distinguishes between three types of land-use impacts in our methodology: transformation, occupation, and permanent impacts.	
Kilcher et al., 2020	USA	Review/ Resource Characterization	Marine energy	Provides a concise and consolidated summary of the location and quantity of utility-scale wave, tidal current, ocean current, ocean thermal, and river hydrokinetic resources. The information presented herein is intended to help improve understanding of the locations and characteristics of the resources and how they might contribute to the future energy portfolio of the United States.	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Model	
Kim et al., 2012	Vancouver Island, British Columbia, Canada	Modeling Framework /Case Study	Wave energy	To develop a freely available decision-support tool capable of 1) providing spatially-explicit information for siting wave energy conversion facilities and 2) helping decision-makers tackle challenges for integrated coastal and marine spatial planning related to wave energy projects. The analysis presented illustrates how a spatially-explicit estimation of economic returns from wave energy conversion and exploration of the compatibility of promising energy sites with existing uses can help decision-makers and stakeholders decide where to install devices to maximize value from wave energy while minimizing potential conflict with existing uses of coastal and marine ecosystems.	Y	N	Y	Y	Y	Y	N	N	Y	Y	N	N	N	N	N	N	Y	ecological characteristics, shipping, and transport - compares the annual wave energy value to a representative annual value of the existing use for which economic data are available.	Presents a Wave Energy Model as a component of the InVEST, also conducted a compatibility analysis to identify where wave energy conversion facilities and existing marine uses are most compatible. he wave energy model uses the ecosystem services framework proposed by Tallis et al. [19] and consists of three parts: 1) assessment of potential wave power based on wave conditions ("supply metrics"), 2) quantification of harvestable energy using technology-specific information about a wave energy conversion device ("service metrics"), and 3) assessment of the economic value of a wave energy conversion facility over its life span as a capital investment ("value metrics"). The second component included a compatibility analysis to identify where wave energy conversion facilities and existing marine uses are most compatible.	Does not take into account cultural and local benefits of fishing activities in the study area. The study also notes the compatibility analysis can be improved in several ways. The data used for the commercial fisheries analysis reflect fisheries and other human uses from 1993–1996. More recent data on fishing regulations, fleet activity and the abundances of target species would lead to a more accurate

																								evaluation of current compatibility.
Leslie and Palmer, 2015	Massachusetts, USA - Muskeget Channel Tidal Energy Project	Case Study/Review	Marine Energy - Tidal	To illustrate the value of this approach in evaluating the potential impacts of an MHK project, we present the case study of the Muskeget Channel Tidal Energy Project (United States) and identify the types of data and analytical tools that could be used to develop an ecosystem service assessment of MHK development in this study region.	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	None	conducted a review of the published literature on tidal energy projects and other MHK projects, focusing particularly on the extent and content of research to date on the environmental aspects of tidal energy capture. To evaluate impacts to the ES level,	While a full assessment of the ecosystem services of the Muskeget Channel study region and the possible consequences of MHK development in this location is beyond the scope of this paper, here we begin this process by identifying the types of data and analytical tools that could be used to develop a full ecosystem service assessment in the future.
Mangi, 2013	UK	Review	Offshore wind	Aims to describe the ecosystem services likely to be impacted (positively and negatively) by OWFs, and assess the potential to provide socioeconomic benefits through multiple use, added value, and improved ESto describe the ecosystem services. The paper identifies data needs to enable quantification and valuation of ecosystem services to allow for effective assessment of renewable energy generation from the sea to ensure that OWFs do not compromise the ability of the marine ecosystems to continue providing benefits needed for human wellbeing. To achieve these objectives, two separate literature reviews were conducted; (1) to identify and clarify the effectiveness of OWFs in maintaining, restoring, and enhancing ecosystem goods and services needed for human wellbeing; and (2) the potential environmental, social, and economic effects of OWFs.	N	N	N	N	NA	N	N	N	Y	N	N	N	N	N	N	N	N	Reef effect/habitat creation; impacts to birds, marine mammals, marine habitats	Used Boolean logic to conduct two separate literature reviews were conducted; (1) to identify and clarify the effectiveness of OWFs in maintaining, restoring, and enhancing ecosystem goods and services needed for human wellbeing; and (2) the potential environmental, social, and economic effects of OWFs.	
Martínez-Martínez et al., 2022	Biobío and Nuble Regions, south-central Chile	Research Study (desktop)	Focus on solar, biomass, wind, and solar and bioenergy feedstock production	Aimed to identify the more suitable areas for renewable energy development and discuss the potential trade-offs between energy supply and priority ESs in Chile through the combination of GIS-based multi criteria method and land suitability analysis.	N	Y	Y	N	N	N	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Land uses, consumptive water, GHG were criteria used because they could be indirectly correlated with ES; discussed that 73% of regional income comes from forest products; quantified native forest as 78.6% supplier of priority ES; cultural ES emerged as the most valued by stakeholders	GIS-based approach	The ES matrix constitutes a valuable tool for assessing and mapping ecosystem services' supply capacity in the region, using land cover data and expert opinions. However, all values in the matrix are based on expert's opinion, which strongly depends on the expert's knowledge, experience, attitude and objectivity; thus they are subject to uncertainty; calls on need for more sustainable energy planning, such as social participation processes,

																								environmental impacts, policy, etc.; not all results were consistent with local studies, which requires better comparison analysis
Ozkan et al., 2022	Dauphin Island, Alabama, USA	Research Study/Case Study	Marine Energy - Wave	To use the numerical morphological model XBeach to simulate the impacts of wave energy conversion on coastal erosion on a barrier island on the U.S Gulf Coast. They perform a case study, focused on Dauphin Island, AL, where they use XBeach to simulate baseline (i.e., with no wave farm) and wave farm scenarios under severe storm (Hurricane Ivan and Hurricane Katrina) conditions, and analyze the impact of WECs to beach profiles, dune heights, total water levels (TWL), i.e., total elevation of storm-induced water levels including storm surge, astronomical tide, and wave runup, bottom shear stresses, and total sediment volume/area of the coastline.	Y	N	N	N	N	N	N	N	N	N	N	Y	N	N	N	N	Y	None	XBeach model - an open-source, process-based numerical model, developed to simulate hydrodynamic and morphodynamic processes and their impacts on sandy coastlines. Specifically, it can simulate wave-induced currents and consequential sediment transport and morphological changes.	
Papathanasopoulou et al., 2015	No geographical boundaries were stated	Systematic Review	Focuses on offshore wind, and compares to nuclear and offshore oil sectors	What impacts do the construction, operation and decommissioning of offshore oil and gas, offshore wind and offshore structures of nuclear installations have on biodiversity, habitat, structure, and function of marine ecosystems, and their relation to human well-being? Considerations include: types of exposure (i.e. type of energy system); populations (i.e. marine ecosystem components); outcomes affected by the exposure (e.g. biodiversity); the lifecycle stages of the energy systems (i.e. construction, operation and decommissioning); and impacts on humans and the general public. The second core objective was to translate these ecosystem impacts into impacts on ecosystem services using a classification framework which would provide a standardised description of ecosystem services and contribute to standardising the approach.	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	None	A systematic review approach to compile existing evidence on the impacts of offshore wind, offshore gas and oil, and the offshore components of nuclear on marine biodiversity and ecosystem processes; the results of the review on ecosystem impacts are presented and then translated into ecosystem service impacts using an explicit and transparent ecosystem service classification framework - explicitly employing the ecosystem services classification frameworks proposed by Haines-Young and Potschin [52] and Millennium Ecosystem Assessment (MEA) [50].	Only standard practices of energy operation were considered in this review; ES categorized as cultural, provisioning, regulating and supporting
Picchi et al., 2019	NA	Literature Review	Renewable energy (general); results from review showed 34 papers linking ES and RE discussed wind power, 13 with biomass, and 4 for solar and hydropower	The objective of this paper is to report which approaches and methods can be found in literature to analyze the spatial relationship between RET and ES themes and groups, and, more particular, which spatial reference systems better describe the spatial trade-offs among ES in landscape planning and design. Aims to inform approaches/methods for decision making and landscape planning/design	N	-	Y	Y	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Two-stage literature review, (1) current frameworks for assessing relationship between RE and landscape; and (2) understand what methods and spatial reference systems are used to apply spatial tradeoffs among ES in laddnscape planning/design-particularly in regard to cultural ES. Used sciencedirect and scopus; spatial reference system was a parameter tracked during analysis; Found the social attitude approach, the impact assessment approach and the planning approach can be preparatory (collecting data or planning a specific RET) of the integrated planning approach: complexly a mixed strategy of inquiry; for spatial mapping, found Land use and land cover (the most used spatial reference system in planning related literature) are not capable of describing the landscape infrastructure networks that could properly inform landscape design principles. These should be considered as a planning tool in the integrated planning approach because different landscape design principles could reduce trade-offs and enhance synergies; To support the assessment	The study of the relationship between the RE generation and the landscape has been simplified in this review as a study between the RET installation and the modification of the spatial reference systems. The reasons for this choice must be found under the scope of this paper: we decided to refer to the most common spatial reference systems as in literature to safeguard consistency throughout the papers analysis; ES framework never defined

																							of both regulating and cultural ecosystem services, a combination of land use and land cover maps with information on landscape metrics and landscape infrastructure is favorable. Cultural ecosystem services can be studied effectively with non-expert stakeholders making use of participatory mapping.	
Pilogallo et al., 2019	Basilicata, Campania and Puglia, Italy	Case Study	Solar PV and wind energy	This study presents the results of an ex-post analysis carried out to assess the effects of rapid growth of renewable energy plants in a low-density area with a strong agricultural vocation, characterized by an important industrial center and areas of high natural values based on the following ES:carbon stock and storage, crop production, crop pollination and habitat quality. A spatial combination has been performed in order to assess ecosystem services cumulative loss. the present work aims to describe the effects of a widespread and scattered growth in RES plants in terms of cumulative ES loss in a context characterized by a low population density and a fragmentation degree ranging between medium and high	Y	-	-	Y	-	-	Y	Y	N	N	Y	N	N	N	N	N	N	Habitat quality	InVEST used to assess ES; further analyses carried out in GIS environment were then produced in order to obtain a representation of the spatial distribution of the overall cumulative impacts on ecosystem and its capacity to provide ES	
Randle-Boggis et al., 2020	UK	Review/ Methods with Research Component	Solar PV	To introduce the SPIES DST as an acessible, evidence-based assessment of the effects of solar park management practices on biodiversity and ecosystem services in the UK, and evaluate the tool using two commercial case studies	Y	Y	Y	Y	Y	N	Y	N	N	N	N	N	N	N	N	N	N	Flood regulation, air quality regulation, biomass provision, cultural/educational, food provision, soil erosion regulation, spiritual/religious, climate regulation, habitat/biodiversity, pest/disease regulation, pollination, pollution regulation, recreation/aesthetic, water cycle support, water quality regulation were all ES assessed in the evaluation of case study using the tool - none quantified, all relative based on management practices and available evidence	Development of SPIES DST involved 5 stages: (1) identification of potential solar park land management actions and ecosystem service classification done using an existing Ecosystem Services Transfer Toolkit and stakeholder interviews; (2) a systematic literature review to collate evidence of the effects of land management actions on ecosystem service provision - articles that speculated on affect but did not assess it within the study were removed; (3) development of an evidence database that details the direction and scale of land management action impacts on ecosystem services and the strength of the evidence; (4) development of the tool's structure and function; and (5) evaluation of the DST	More information needed for more robust evidence dataset - for example there were fewer than ten pieces of evidence for air quality, biomass material provision, food provision, pollution regulation, recreation and aesthetic interactions, and spiritual or religious enrichment and water cycle support and 21 of the management actions effects were supported by fewer than ten pieces of evidence
Rosenthal et al., 2015	NA	Framework	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA		
Schetke et al., 2018	Germany	Desktop study/conceptual framework	Renewable energy (general)	To estimate the importance of ES – especially abiotic ES – in the two legal domains of climate protection and urban land-use planning in Germany we analyzed all climate protection laws (CPL) of the federal states and climate protection concepts (CPC) of 26 cities and counties in Germany. We also analyzed the ES-relevant implications of the amendment of the federal building code (BauGB), which determines the framework for urban land-use planning at local level. 1.To what extent has the concept of ES been integrated in the legal and organizational framework of climate protection in Germany? 2. Which ES are highlighted by climate protection? 3.How could potential renewable energy ecosystem services be integrated into ecosystem service assessments?	N	N	N	Y	N	N	N	Y	N	N	Y	N	Y	Y	Y	Y	Y		uses the CICES-classification, aimed at distinguishing between biotic and abiotic services; analyzed laws, regulations and concepts at the German local and federal state planning levels which explicitly focus on climate protection.	

Scorza et al., 2020	Melfi municipality in the Basilicata region, Italy	Framework /methodology	Wind/Solar ; case study site includes 79 wind turbines and 7 solar farms. The estimated installed electricity production capacity is close to 200 MW.	How to improve the territorial monitoring system so as to achieve an appropriate landscape and environmental assessment in renewable energy planning? Consequently, how to develop effective innovations in the normative planning framework in order to improve long-term sustainability for territorial transformation on a local scale?	Y	N	N	Y	N	N	Y	Y	N	N	Y	N	N	N	N	N	Y	Habitat quality; measured bny habitat quality and degradation	InVEST used; Presents ex-post-impact assessment methodology based on cumulative ecosystem services losses; a multi-criteria analysis conducted by means of the Spatial Analytical Hierarchy Process method, further analyses were carried out using GIS	
Stebbings et al., 2021	UK	Framework and Case Study	Offshore Wind	This study therefore defined the capacity of a system to supply specific benefits through a combination of natural and human factors. It attempts to measure different environmental benefits by describing them as the product of different forms of capital: natural capital as described in environmental accounts or NCA, as well as inputs from within the production boundary of national accounts. Indicators were chosen for each of the factors and a composite index was calculated that described the capacity to supply benefits (Section 2). The related economic sectors were identified, and the economic contribution of these benefits was estimated. The application of this approach was demonstrated with case studies from the UK for four marine benefits: seafood, offshore wind energy, wildlife watching and water sports.	-	-	N	N	N	N	N	N	Y	Y	N	N	N	N	N	N	Y	None	Assessment was based on multi-criteria assessment and composite indicators; a detailed assessment of individual ES was undertaken (i.e. this approach went beyond the high-level categories of provisioning, cultural or regulatory services)	
Stokesbury et al., 2022	International, presents a mock-up framework for wind farm development in Massachusetts	Framework	Offshore wind	Outline a framework for ecosystem-based management to quantify tradeoffs among ecological, economic, social, and institutional pillars over multiple ocean use sectors, with considerations to both windfarms and fisheries including their interactions. Ecological objectives include productivity and trophic structure, biodiversity, and habitat and ecosystem integrity. Economic objectives include economic viability and prosperity, livelihoods, and distribution of access and benefits. Social objectives include health and well-being encompassing food supply, green energy supply, recreation, and leisure, reduced stress in the work environment, safety, and ethical considerations. Institutional objectives include good governance structure, effective decision-making processes, and legal obligations.	-	-	Y	Y	NA	NA	NA	NA	Y	NA	NA	NA	NA	NA	NA	NA	Y	NA	The "systems" framework categorizes data on spatial scales of 1 cm2 to 1 km2 (individual turbines/fishing vessels), 1–1000 km2 (companies), and >1000 km2 (regions), and by their ecological, economic, cultural, and institutional impacts. The framework should be repeated over temporal scales of the wind farm: pre-development (1–3 years), construction (1–2 years), post-construction (20–40 years), and decommission.	
Tallis et al., 2012	NA	Framework	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA		
Tallis et al., 2012	NA	Framework	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	InVEST, LPJmL	
Torres et al, 2021,	NA	Review	NA	(1) Provide an update of the progress in ecosystem services research, (2) Identify dominant and emerging areas of interest in the ecosystem service field	-	-	-	-	NA	N	N	N	N	N	N	N	N	N	N	N	N		Systematic literature review	Differences among databases influences outputs, identification of key themes and approaches carries subjectivity, approach

																								not able to exclude publications that do not belong in the intended category
[Trifonova et al, 2022]()	North Sea, UK	Framework	Offshore renewables	To examine the prospect of combining an ecosystem-based modelling approach that measures changes in natural capital to illuminate how ecosystem changes manifest into the socio-economic outcomes to support decision-making of ORE developments in the marine environment in the context of climate change. The proposed framework provides a data-driven whole system approach which supports identifying and assessing marine net gain.	Y	Y	Y	Y	Y	Y	N	N	Y	N	N	Y	N	N	N	N	Y	Includes socio-economic valuation based on fish ES results	Multicriteria analysis (MCA) used to assess trade-offs; also uses a cost-benefit analysis (CBA) as a structured valuation technique that provides a quantification of all the costs and benefits (including non-market goods) associated with projects or policies to establish their likely impact; supports a a marine net gain approach, based on the value of the marine environment to people via ecosystem services and natural capital, is essential; The ecosystem-based natural capital evaluation framework builds on a BaYian modelling approach, that uses long-term historical data on physical (e.g. temperature), biological (e.g. fish stock biomass) and anthropogenic marine use (e.g. fisheries catch) components to model ecosystem status; used Input Output analytical model to run a time series of the installed capacity are coupled with deployment costs, leakage rates, and GVA effects to obtain GVA results associated with the different project phases and components; INVEST used to incorporate habitat risk	No new data were created or analysed in this study.
[Voke et al., 2013]()	Pembrokeshire, UK	Case Study	Marine Energy - Tidal and Wave	This paper assesses the value of the marine environment around St. David's, Pembrokeshire, UK, where a tidal stream turbine demonstration project is underway and larger array developments, both wave and tidal, are planned for the next few years. It was found that the marine environment contributed, on average, to 78% of visitors' total enjoyment of the area. The study provides a valuation of the natural marine environment in a marine energy resource area and investigates the changes to this valuation caused by energy installations. Therefore some understanding of public perception to marine energy in the region can be gained.	Y	N	Y	N	N	N	N	N	N	Y	N	N	N	N	N	N	N	Travel cost assessed - A Travel Cost value was determined for each respondent by calculating individual distance costs and time costs.	A Contingent Valuation Method (CVM) and Travel Cost Method (TCM) used data collected from questionnaires at the case study site to produce cost and valuation results. CMV and ITC can be combined in one questionnaire and provide both indirect observable and hypothetical valuations from the respondents for the area. A secondary section in the questionnaire asked interviewees about the importance of the marine environment as part of their visit.	Certain activities were under-represented due to the difficulty in obtaining responses from people involved in the activity. Recreational diving is underrepresented as no divers were approached during the survey days. Water-sports are also underrepresented due to the difficulties in obtaining answers to questionnaires by people while they are actively pursuing water sports.
[Walston et al., 2021]()	Midwestern USA	Research	Solar PV	What are the multiple ecosystem service benefits of solar-native vegetation compared to pre-existing land uses and other types of vegetation management practices at solar facilities?	Y	-	N	N	N	N	Y	N	N	N	Y	N	N	Y	Y	N	Y	Agriculture	InVEST: Pollinator Model (for pollinator habitat quality), Carbon Storage Model, Sediment Delivery Ratio (SDR) Model (for soil retention), and Water Yield Model (for water retention)	The models do not take into account the influence of solar panels on ecosystem processes, the study should be used to understand relative implications rather than actual ecosystem service value calculations; no calculation of beneficiaries
[Wang et al., 2015]()	UK	Review	Onshore Wind	Attempts to quantify the impacts of onshore wind farms on ecosystem services for the UK at local and global scales, building on the Life Cycle Analysis approach used for UK wind technology b. The resultant ecosystem service impact matrix at local and global scales presented is intended to be used to guide the development and deployment of	N	N	N	N	N	N	Y	-	-	N	Y	N	-	N	N	N	N	Positive impact to local air quality identified,	LCA approach and a systematic literature review for local impacts of onshore wind farms on ecosystem services and a 'Broadbrush' approach for global impacts on ecosystem services; The ecosystem services follow the Millennium Ecosystem Assessment (MEA) classification system	Only identified the countries having direct transactions with the UK in terms of materials of onshore wind farms.

				onshore wind farms. The focus of this paper is to examine the impacts of one energy technology (i.e. onshore wind farms) on ecosystem services, rather than the energy generation potential.																				
Wang et al., 2022	central and northern California	Case Study	Offshore wind	This study aims to help address this need by describing the recent spatiotemporal dynamics of California fisheries in terms of commercial landings and ex vessel value (revenue) across different fisheries groups over the past 15 years (2005–2019).	N	N	N	N	N	N	N	N	Y	N	N	N	N	N	N	N	N	N	This study used commercial fisheries landings receipts (fish ticket data) for California commercial marine fisheries, provided by the California Department of Fish and Wildlife (CDFW) through a data sharing agreement, from 2005 to 2019 (CDFW, unpublished data).Each fish ticket recorded the landing weight and unit price (i.e., price per pound) of the fish species caught, the landing date and port, and a fishing block catch location, as well as unique identification numbers for vessels, fishers, and businesses. To assess potential overlap between offshore wind development and commercial fisheries in California, we used fish ticket data to estimate fishing activity in relation to the Humboldt and Morro Bay wind energy areas and calculated the relative importance of landings and value for each fishery group in the Humboldt and Morro Bay regions and WEAs by summing data in the following way: (1) all local ports in the respective regions, (2) all blocks that overlapped with the WEAs in the respective regions, and (3) all blocks that overlapped with the WEAs in the respective regions and were also within the biological depth limits of a given fishery group.	analysis only considers data from the three-digit blocks since data from four-digit blocks have little to no useful spatial information.
White et al, 2012	Massachusetts	Framework and Case Study	Offshore wind	Used examples of wind farms in Massachusetts to show the value-added from doing MSP over conventional single-sector management, which focuses on maximizing sectoral values. In particular, we (i) generated alternative wind farm development scenarios driven by single- versus multisector management decisions; (ii) calculated the resulting value of energy and other sectors with which there are spatial conflicts in the marine ecosystem of Massachusetts; (iii) compared sector values arising from alternative development scenarios to show how tradeoffs among sectors can be quantified, and then reduced, by choosing specific MSP scenarios; and (iv) quantified the potential value added to sectors by using MSP over a single-sector approach.	Y	Y	Y	Y	N	N	N	N	Y	Y	N	N	N	N	N	N	N	Conservation, bundled with whale watching	Visualized tradeoffs by plotting sector values against each other in relation to potential management strategies; used heuristic algorithms to identify optimal strategies delineating the efficiency frontiers; pairwise tradeoff plots provide more tractable illustrations of the potential value of MSP to each sector. constructed a spatially explicit, coupled biological–economic model with eight hundred sixty-eight 2 × 2 km patches to estimate the spatial distribution and net present value (“value”) of four sectors in Massachusetts Bay in response to wind farm development. Linked assumptions to the fishery sectors via spatially explicit, age-structured lobster and flounder population dynamic models.	A number of simplifying assumptions about the dynamics of these services and the marine ecosystem may influence our results. For example, conservation values other than whales (e.g., birds) are affected by wind turbines. A wind farm also may affect coastal viewshed and property values, and its submarine infrastructure may affect fish more than we assumed. Furthermore, other industrial sectors, such as shipping, already have high value in Massachusetts Bay and may have implications for conservation and MSP. Consideration of tradeoffs among these sectors may alter the solutions presented here; therefore, our spatial results should be considered heuristic rather than prescriptive.

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