

**Balancing Energy and Ecosystems:  
Exploring the spatiality of renewable energy development for a low-  
carbon future**

By  
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A Thesis Submitted in Partial Fulfillment of the  
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We acknowledge and respect the Lək'wəḡən (Songhees and X<sup>w</sup>sepsəm/ Esquimalt) Peoples on whose territory the university stands, and the Lək'wəḡən and W̱SÁNEĆ Peoples whose historical relationships with the land continue to this day.

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## Abstract

Fossil fuel energy production, as one of the most significant drivers of climate change, is causing extreme social and environmental harm worldwide. These circumstances necessitate a transition to low-carbon energy sources. A key factor in the expansion of low-carbon energy systems is the potential impact this development may have on other benefits provided by the environment, such as food or materials, commonly referred to as ecosystem services. There is currently limited knowledge beyond the regional scope of how energy development is impacting these services; an important consideration, as local studies cannot consider the full spectrum of global environmental impacts. The research outlined in this thesis uses an exploratory methodology to examine the spectrum of environments in which renewable energy projects are constructed in, and which ecosystem services are most likely to be impacted by the expansion of renewable energy globally, both for single-technology and clustered renewable energy power plants. First, in Chapter 3, I analyse the land cover and associated ecosystem services surrounding global power plants. In Chapter 4, I reproduce this analysis on a growing global dataset of renewable energy projects that utilize multiple types of resources, known as clusters. These results are compared with those discussed in Chapter 3 to assess how the configuration of energy systems influence the land they are constructed on. I find that hydropower and wind power show the highest occurrence in ecosystem service rich environments, creating the largest risk of ecosystem service loss from renewable energy production, while clustered energy systems are placed in areas which decrease the risk of ecological trade-offs. As renewable energy continues to develop, incorporating other land considerations will be critical in ensuring the energy transition minimizes harm to the natural environment for which we all rely on.

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# 1. Introduction

Energy is a crucial environmental resource for human wellbeing (UNEP, 2017). The energy sector is a permitting factor in the global economy, and access to energy is one determinant of social standing and opportunities (Kanagawa & Nakata, 2008). Established energy systems sustain various sectors such as medicine, agriculture, technology, and business.

Over the past century, the global provision of energy access and technology adoption has led to a significant increase in electricity demand, rising from 18,000 to 168,500 TWh, primarily fueled by coal or oil (Ritchie et al., 2020). This trend is expected to continue, with the International Energy Outlook projecting a 44% increase in global energy demand between 2006-2030, most of which will come from developing nations exiting energy poverty (International Energy Agency, 2023). Scholars have found early-stage growth in energy demand to be correlated with a reduction in poverty and increase in wellbeing, attributing it in part to the economic benefits derived from energy access and generation (Ahmad & Zhang, 2020; Hall & Klitgaard, 2012). Despite some of the advantages of energy, the surge in fossil fuel energy production has led to an increase in CO<sub>2</sub> emissions, creating severe environmental and societal repercussions (IPCC, 2023). Under the evidence of harm that fossil fuel-dominated energy systems currently cause, there have been calls to action for an energy transition to low carbon resources from communities, activists, scientists, and local governments (Brulle, 2023; Temper et al., 2020).

While low-carbon energy systems help address some environmental concerns, such as greenhouse gas emissions, and there is a clear need for an energy transition, there are many challenges to low-carbon energy (Seto et al., 2016). Despite the documented social and

environmental benefits, transitioning away from fossil fuels is complicated and non-uniform. There are significant lock-in barriers to implementing renewable and low-carbon technology, all of which interact in sometimes non-obvious ways, which slow or prevent an energy transition. A theory that describes the set of complex factors preventing a transition away from fossil fuels is known as carbon lock-in (Seto et al., 2016). Lock-in literature seeks to identify and works to address the systems ingrained in social norms, law, and technology that perpetuate a fossil-fuel centered energy economy, despite their production not being beneficial for most.

One challenge facing the energy transition is the land required to produce renewable energy and the land impacts of developing renewable energy sites (Poggi et al., 2018; Sliz-Szkliniarz, 2013). It is well established that fossil fuel energy produces extremely harmful environmental impacts, both at the energy site and throughout the life cycle of extraction, generation, and consumption, which make renewable energy a clear and necessary improvement. However, renewable energy resources have lower power density than fossil fuels, meaning to replace the amount of energy produced by fossil fuels with renewable energy systems, significantly more land is required (Smil, 2015). While low-carbon energy systems help address some of the environmental concerns caused from fossil fuel usage, this new dimension of land development will be an increasingly important consideration during the expansion of renewable energy production.

The type of land preferred for renewable energy production (open areas, regular sun, streams and lakes, etc.) also overlaps with the type of land required for agriculture. Expanding renewable energy production and other land development therefore creates the potential for competing interests for the same landscapes in the coming years (Hoffacker et al., 2017). There

is a small but growing discussion in literature on how the increased area of land needed for renewable energy will interact with other land demand in the future. Some previous scholarship has focused on risk of competition between renewable energy and agriculture in particular, which, like energy, has been rapidly expanding as populations rise and demand increases. (Hertel, 2011). Other scholarship is emerging to address concerns of competition between the two by creating land planning scenarios that result in a “win-win” where both energy and food production are able to meet growing demand (Power, 2010), although it is currently unclear how this would manifest in practice.

One theoretical framework for studying the interactions between land and energy is ecosystem services, which seeks to describe the benefits and goods provided by ecosystems to humans (Hastik et al., 2015; Picchi et al., 2019). Using ecosystem services to assess the environmental and land impact of the energy transition allows for a holistic assessment of the development of new energy projects that considers both the wellbeing of people and the environment (Hastik et al., 2015). Because energy is widely considered an ecosystem service itself, ecosystem service framework can compare the trade-offs that occur when land that previously provided other ecosystem services such as food or a space for wildlife is developed into an energy site. For example, the multitude of benefits that a forested areas provides (food, water, nutrient cycling, spiritual benefit, etc.) is lost if the forest is removed and the area developed into a solar park in order to access energy, resulting in a trade-off between energy and all other ecosystem services.

Beyond land concerns, renewable energy resources face limitations to generating reliable power (power that can withstand instability or uncontrolled events), creating additional

challenges in facilitating an energy transition (Hoicka et al., 2025; Muruganantham et al., 2017). Reliable power systems have been shown to improve healthcare, education opportunities, and governance to those who have access to it (de Almeida et al., 2020). Resource types such as wave, wind, and solar power require specific weather conditions for energy to be generated (e.g. regular solar radiation). As a result, a single-technology energy system using these resources can struggle to provide consistent, reliable power. Resources such as hydropower and geothermal sites can produce relatively consistent power, however, these systems require locations with specific environmental circumstances (e.g. steady, accessible flowing water, etc.).

Cumulatively, land requirements, energy resources that are dependent on climate conditions, and unevenly distributed growth in energy demand make the low-carbon energy transition a spatially variable process (Bridge et al., 2013; Poggi et al., 2018; Sliz-Szkliniarz, 2013). Studies have called for increased attention to the development of a theoretical understanding behind the multiple and non-linear relationships among ecosystem services, as well as the trade-offs and synergies that result from using provisioning services, or altering the landscape in ways that affect multiple services (Bennett et al., 2009). Trade-offs arise when the provision of one service is enhanced at the cost of reducing the provision of another service, and synergies arise when multiple services are enhanced simultaneously (Raudsepp-Hearne et al., 2010). Both trade-offs and synergies can be managed to either reduce their associated costs to society or enhance landscape and human wellbeing, respectively. Jaccard et al. (1997) discusses potential synergies between urban design for liveable cities, energy objectives, and environmental impacts of energy systems, emphasizing that human-land and energy concepts should be considered together. In part due to these factors, the transition to renewable energy has

led to an increase in decentralized, integrated energy systems with a variety of actors not typically involved in the energy process (Brisbois, 2019). Understanding energy production through a place-based lens allows the benefits and limitations of different resources for a variety of environments to be considered, especially as energy demand becomes a major driver of land cover change in the coming years (Bridge et al., 2013).

One emerging type of place-based energy system is the co-location of multiple types of energy technology operating as one system, known as clustering. Hoicka et al. (2025) describe shared renewable energy clusters as a connected energy system involving a range of actors which results in complimentary, reliable shared power from low-carbon technologies. By clustering multiple different types of renewable energy sources to create one system, the limitations of one resource can be supported by another. For example, a solar, and biomass system could produce reliable power during overcast days. Similarly, a wind, battery storage, and geothermal system could provide heating and cooling using geothermal energy, and the battery can provide power when there is limited wind capacity, reducing the reliance on and expense of using any one technology. Optimized engineering models have posited that, hypothetically, clustered/hybrid energy systems address many reliability challenges that come with using renewable energy (Bekirsky et al., 2022; Mancarella, 2014). The potential reliability benefits of combining energy resources are particularly important in regions without connection to a central power grid, which in many rural areas can be an incredibly expensive process (de Almeida et al., 2020).

In the past decade, there has been a growing effort from scholars in both energy transitions and ecosystem service fields using geospatial techniques to assess the impact that different types of energy systems have on ecosystems (Dai et al., 2024a; Hastik et al., 2015; Hernandez et al.,

2015; Howard et al., 2013; Jones et al., 2015; Jordaan et al., 2021). The limitations with current published work are three-fold:

1. The use of modelling potential energy projects rather than existing ones (Aziz, 2023; Hernandez et al., 2014; Hoffacker et al., 2017; Jordaan et al., 2021). There is robust previous literature on how renewable energy is not diffusing the way that other technologies typically do (Jacobsson & Johnson, 2000). Combined with the multitude of complex factors preventing a transition away from fossil fuels including infrastructural challenges, institutional barriers, and resistance to behavioral change (Seto et al., 2016), modelling where energy projects are likely to occur accurately is extremely difficult (Hoicka et al., 2025). The limitation in basing current knowledge of ecosystem service impacts of the energy transition on modelled energy systems is the identified concerns may not accurately reflect the reality of where renewable energy development is impacting the environment.
2. Current research is heavily limited in regional scope, typically spanning no more than a few hundred kilometers (Hoffacker et al., 2017; Hernandez et al., 2015; Jordaan et al., 2021). By studying renewable energy development impacts of specific geographic regions, the multitude of diverse landscapes and ecosystems services around the world cannot be captured, and the focus of the research will naturally highlight ecosystem services which are most relevant to the study area, which may not translate well to broader concerns.
3. Most of the studies focus on one or two renewable energy resources, rarely used in tandem, and never clustered. As reliability challenges are most prevalent with single-

technology renewable systems, the intersection of creating reliable and land-compatible low-carbon energy sites is currently lacking.

As Hastik et al. (2015) stated:

“Fewer studies still, compare local environmental impacts caused by multiple renewable energy sources and develop approaches defining sustainable levels of [renewable energy] production... a broader perspective, which includes alternative [renewable energy] with their multifaceted environmental and societal repercussions, is required in order to develop [renewable energy] expansion strategies”

Because land-energy interactions have been identified as important in protecting ecosystem services, understanding the impacts that these energy systems have is critical in informing decision-makers on how and where they should be implemented. A broader perspective that considers the land implications both of single-technology power plants, and more recently emerging clustered energy systems is needed. Drawing from literature gaps identified in previous scholarship, my research seeks to understand the question: *in what ways are renewable energy systems interacting with ecosystem services?* I will examine this question through the following objectives:

- Describe the environments and ecosystem services that renewable energy development is occurring on.

- Assess the extent of overlap between renewable energy sites and agricultural land to determine trade-offs between the provisioning services of food and energy.
- Compare the geography and ecosystem interactions of single technology renewable energy power plants with projects that cluster multiple renewable resources.

To describe the environments and ecosystem services that renewable energy development is occurring on, my research will first take an exploratory approach through making use of a regularly updated global power plant database created by the World Resources Institute (Byers et al., 2018). I overlay the European Space Agency's WorldCover global land classification map to identify the types of land cover in proximity to currently existing renewable energy projects (ESA, 2022). For each type of land described in the WorldCover database, I conduct a literature review to determine ecosystem services attributed in previous research, as well as their comparative importance to other land types for providing ecosystem services. As research into ecosystem service and renewable energy interactions is not well defined at this time, my findings aim to describe the range of interactions rather than confirm a hypothesis. To determine if the extent of overlap and proximity in renewable energy projects stated as a concern in literature occurs in practice, I create a geospatial map of the distance each energy site is to agricultural areas.

Expanding beyond power plants, I examine land and ecosystem service characteristics of renewable energy clusters to compare these multi-resource systems to my previous findings for single technology power plants which produce power of the same magnitude. Because the

literature surrounding renewable energy clusters has positioned them as theoretically being flexible and reliable energy systems that can serve a variety of circumstances (Bekirsky et al., 2022; Hoicka et al., 2025), I hypothesize that renewable energy clusters present unique geographic and ecosystem service interactions.

The need for an energy transition is not up for discussion; it is essential for social and environmental wellbeing. Rather than challenge this need, increased knowledge on *how* this transition is occurring in real-time, and how that is impacting the other services that our environments provide is critical to contribute to an informed energy transition, one that minimizes loss of other vital services in the pursuit of low-carbon energy. Empirical data on how land is being used for renewable energy production now can clarify how and where energy is likely to diffuse in the future as this transition grows. As renewable energy production increases, providing policymakers with accurate on-the-ground knowledge of renewable energy sites will become critical to facilitating the low-carbon transition. By identifying broader trends in how and where different renewable energy systems are, we can assess the energy transition from a more holistic socio-technical and socio-economic lens, and support policymakers and global leaders in creating systems that will minimize environmental trade-offs and maximize energy benefits.

## 2. Literature Review

Despite the potential benefits, both social and environmental, of a low-carbon future, transitioning away from fossil fuels is complicated and non-uniform. Barriers to the energy transition can interact in sometimes non-obvious ways that slow or prevent an energy transition. One theory that describes the set of complex factors preventing a transition away from fossil fuels is known as carbon lock-in (Seto et al., 2016). Lock-in literature seeks to identify and work to address the systems ingrained in social norms, law, and technology that perpetuate a fossil-fuel centered energy economy despite their production not being beneficial for most of global environment and society.

There are three main areas where carbon lock-in occurs: infrastructural and technological, institutional, and behavioral (Seto et al., 2016). Infrastructure and technological lock-in involves the physical structures that indirectly or directly emit CO<sub>2</sub> and shape the energy supply. Built infrastructure is long-lasting, while energy demand and technology change frequently and tend towards increasing (Jaccard et al., 1997; Owens, 1992). Since the first electrical grid was implemented, the available technologies have expanded so drastically that there are more than double the number of resource options. Each resource has unique means of connecting and contributing to an electrical grid, and preexisting infrastructure such as grid systems powered by fossil fuels are costly to change and are not often easily adaptable to the variable electricity produced by renewables (Martinot, 2016). This rapid need for change and high cost can increase the barriers a region is facing in being able to transition to low-carbon energy (Seto et al., 2016). Institutions and governments involve the laws and governance structures that form policies around fossil fuel production. Lock-in caused by institutions is intentionally reinforcing carbon

systems that favor their interests. Lastly, unsustainable patterns of human behavior including consumption and lifestyle choices contribute to the perpetuation of current fossil fuel demand. This includes habits such as frequent air travel and high household electricity usage (Seto et al., 2016).

Understanding how carbon lock-in shapes and constrains a low-carbon energy transitions is essential for identifying strategies to overcome these barriers (Araújo, 2014). Because many of these barriers have spatiality, it is helpful to analyze energy systems through a place-based lens. Doing so allows both the benefits and constraints of specific energy sources to be evaluated in the context of their geographic, ecological, and social environments (Bridge et al., 2013).

Three prominent fields of literature that have focused on the spatial and land-based aspect of energy systems include energy geography, ecosystem services, and land-energy nexus. Energy geography literature incorporates spatiality into a socio-technical understanding of energy systems. Ecosystem service literature considers energy as an aspect of broader socio-ecological systems. Finally, land-energy-nexus literature arises from scholarship in sustainable development and encouraging transdisciplinary thinking. In this section, I will discuss the value of each perspective as well as where they converge or diverge.

## 2.1 Ecosystem Services

All energy resources require environmental contribution, such as sunlight for solar power, fossilized deposits for oil extraction (Picchi et al., 2019). Currently, human use of the environment affects 70% of global ice-free land surface, much of which contains vulnerable

ecosystems and biodiversity which we rely on (Lamhamedi & de Vries, 2022). The resources or contributions that ecosystems provide can be categorized into four types: provisioning, regulating, cultural, and supporting services as seen in Figure 1 (Millennium Ecosystem Assessment Program, 2005):

1. Provisioning services are any resource that can be extracted or consumed from nature, including food, fuel, plant material, water, and more.
2. Regulating services include the benefits provided by ecosystem processes that contribute to the quality of biotic life, including pollination, climate regulation, carbon sequestration, and erosion.
3. Cultural services are the social and ethical benefits that ecosystems contribute to human life, including the role that local environments play in religious, political, and social structures, as well as how aspects of the environment play a role in culture.
4. Supporting services create stability within an ecosystem structure and prevent collapse, making all other services possible. These include processes such as photosynthesis, nutrient and water cycling.

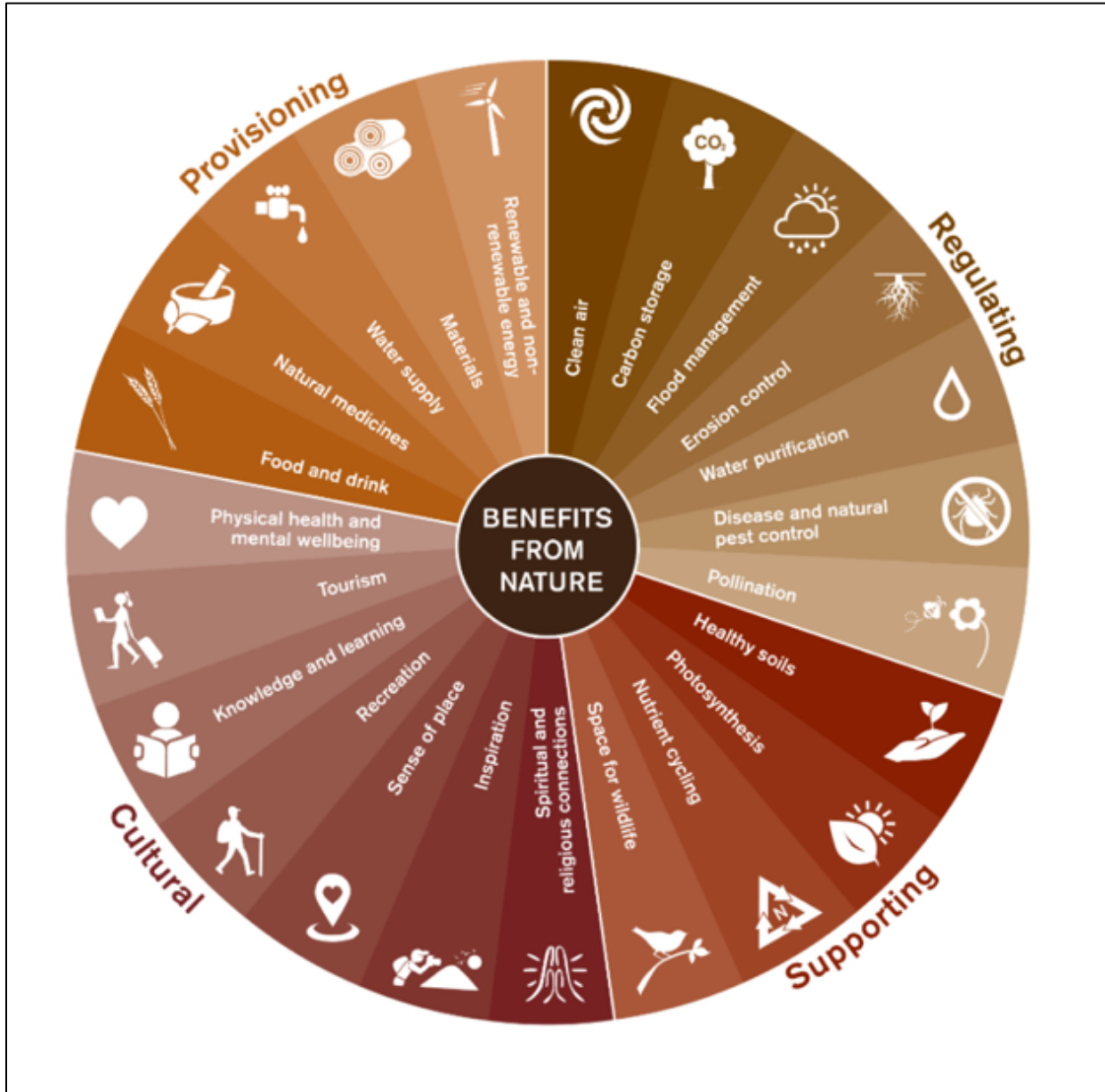


Figure 1: The ecosystem services that humans gain from the terrestrial environment, retrieved from NatureScot (2023).

Ecosystem services literature is primarily concerned with the challenges that come with balancing environmental protection and human development (Millennium Ecosystem Assessment Program, 2005). Currently, human demand for provisioning ecosystem services is growing and human development is degrading the environment, decreasing the capability of many ecosystems to meet these demands. As a result, progress in development such as increasing

food and energy production often comes at the cost of other ecosystem services and conserving biological diversity (Millennium Ecosystem Assessment Program, 2005). Studies have called for increased attention to development of a theoretical understanding behind the multiple and non-linear relationships amongst ecosystem services, as well as the trade-offs and synergies that result from using provisioning services or altering the landscape in ways that affect multiple ecosystem services (Bennett et al., 2009). Tradeoffs arise when the provision of one service is enhanced at the cost of reducing the provision of another service, and synergies arise when multiple services are enhanced simultaneously (Raudsepp-Hearne et al., 2010). Both trade-offs and synergies can be managed to either reduce their associated costs to society or enhance landscape and human wellbeing, respectively. The Millennium Ecosystem Assessment has consistently stated trade-offs as a research priority for the field in order to inform policy and management strategies, dating back to the first assessment in 2005 (Millennium Ecosystem Assessment Program, 2005). Because the availability of different types of energy sources is highly dependent on the environment (Kienast et al., 2019), understanding the relationships between energy and other ecosystem services is essential in creating a socially and environmentally sustainable future (Aziz, 2023).

Energy is a unique consideration in ecosystem services literature because it both requires environmental contributions which can result in ecosystem service harm, and is considered a provisioning ecosystem service in-and-of itself, because it is a directly consumable resource that benefits human wellbeing (Picchi et al., 2019). The adoption of energy as a provisioning service has not been consistent in literature, despite the Millennium Ecosystem Assessment 2030 Agenda for Sustainable Development providing a mainstream case for sustainable energy

technologies to be included in supply chain considerations (Hernandez et al., 2019; Millennium Ecosystem Assessment, 2005). Some researchers consider all biotic (including fossil fuels) and mechanical sources as ecosystem services (Haines-Young & Potschin, M., 2013), and others differentiate between biotic (e.g. biomass) sources, excluding abiotic (e.g. wind, solar, etc.) sources. This debate largely stems from the extent of what the field considers is part of an “ecosystem”. For example, biomass comprises of current biotic life, which is already a part of an ecosystem, whereas fossil fuel consists of plant matter that hasn’t participated in an ecosystem for millions of years. Further still related to traditional definitions of ecosystems are the atmospheric and weather processes such as sunlight and wind which produce solar and wind power. The extent of what an ecosystem consists of is frequently debated, and this extends to the inconsistent inclusion of different types of energy as an ecosystem service. Scholars such as Hastik et al. (2015) discuss this lack of cohesive language around different resource types in ecosystem service literature as a potential source of the current separation between most renewable energy and ecosystem service research.

For the purposes of my research, I consider all renewable energy types as provisioning services. By considering energy a provisioning service, the ecosystem service framework for trade-offs and synergies can be used to holistically weigh the benefits of energy access with the potential ecological harm that a new energy project could result in. For example, the potential risk of impacting ecosystem services that a river system provides can be compared to the benefit that damming the river to develop a hydro energy project would provide (Hastik et al., 2015). In some locations, access to energy may be more important, and in others, access to a free-flowing river may be the priority. Similarly, projects could make use of potential synergies that could

occur from energy project development, such as a forested area that provides regulating ecosystem services like carbon sequestration and flood management can be mostly preserved by choosing to install a wind farm rather than a solar plant. In this case, the forest and wind stations result in the co-benefits of maintaining tree cover while providing low carbon electricity.

## 2.2 Energy Geography

A consequence of the unique environmental contributions required is that renewable energy emerges as highly geographically variable (Sliz-Szkliniarz, 2013). Because of the spatial dimension of these environments. One of the ways that the energy transition can be understood is through the framework of energy geography, which considers spatially relevant aspects of an energy transition through primarily a socio-technical lens (Araújo, 2014). Given its capacity to contextualize both the social and physical spatial dimensions of energy systems, geography stands as a well-suited discipline to comprehend the shift towards renewable energy (Bridge et al., 2013). Energy geography offers insights into concepts including location, landscape, diffusion of innovations, and justice. Scholars such as Bridge et al. argue that considering the spaces, places, and people that will be impacted by renewable energy results in a higher chance of a successful transition that does not perpetuate systems of inequality. and can clarify how a low-carbon future can be realized. Three focuses within energy geography research include the diffusion of renewable energy technology, the social processes and justice during the energy transition, and the spatiality of the energy transition itself.

The combination of complex socio-economic and biophysical factors involved in implementing renewable energy systems has led to a unique diffusion of renewable energy technology (Araújo, 2014; Reddy & Painuly, 2004). The process in which technology diffuses occurs through actors, institutions, and networks (Jacobsson & Johnson, 2000). Actors initiate or contribute to the creation of a new type of technology. This includes companies, communities, or powerful individuals. Institutions are pre-existing systems that influence the diffusion of an innovation positively or negatively. These can be explicit such as governments, or implicit such as social structures or cultural norms. Networks involve the connections that actors and institutions have with those interested in the creation of a technology, those capable of creating and funding the technology, and those who will make use of and consume the technology. The culmination of lock-in, efficiency challenges, and systems of inequality are actively slowing this process for renewable energy technology, both intentionally through targeted efforts, and unintentionally through current social norms (Martinot, 2016; Reddy & Painuly, 2004; Stoddard et al., 2021).

There is scholarship within energy geography focused on understanding what determines whether old technology will be replaced with newer innovations during the diffusion process. One theory produced by scholars to describe the process of adopting renewable energy is through the “energy ladder”, which seeks to predict how the diffusion of new technology will result in a phasing out of fossil fuel use (van der Kroon et al., 2013). A foundational aspect of the energy ladder theory lies in the notion that households will transition to cleaner fuel sources as they increase in income, a phenomenon known as “fuel switching”. Van der Kroon et al. critiques this stance, finding that income and fuel choice are not nearly as correlated as suggested in energy

ladder literature, and instead household decision behavior is based upon the near biophysical environment and external political context. These complex factors lead to households tending to adopt newer technologies alongside previously used fuels, resulting in a portfolio of energy types, a phenomenon known as fuel or energy stacking (van der Kroon et al., 2013). In some cases, the use of multiple fuels can create complementarity (which refers to using a variety of different variable renewable energy at the same time to smooth outpower production (Hoicka et al., 2021) and increase the stability of an energy system, where a household or grid can rely on one energy source when another is not available (e.g. making use of a generator when there is decreased solar power during peak demand). This technique has been described in literature as clustering.

In simplest terms, clusters can be described as an agglomeration of related innovations, objects, or organizations in geographic proximity which benefit from co-location and collaboration. Clustering has begun to appear within the modelling and implementation of different renewable energy systems (Bekirsky et al., 2022; Hoicka et al., 2025). Clustering and co-locating multiple types of energy technology is a possible method of addressing challenges with location, power density, and reliability. Lowitzsch et al. (2020) describe renewable energy clusters as “the complementarity of different energy sources, flexibility, interconnectivity of different actors and bidirectionality of energy flows” working to provide reliable electricity.

Hoicka et al. (2025) typified the emergence of energy clusters and found a phenomena known as materials shared renewable energy clusters which have the following characteristics (Hoicka et al., 2025), seen in Figure 2:

1. A range of actors involved in the energy system

2. A combination of energy sources operating complimentary to one another to reduce
3. the variability that relying on an individual renewable resource can causeThe system’s ability to be flexible in response to changes in demand and supply
4. Bidirectional energy flows

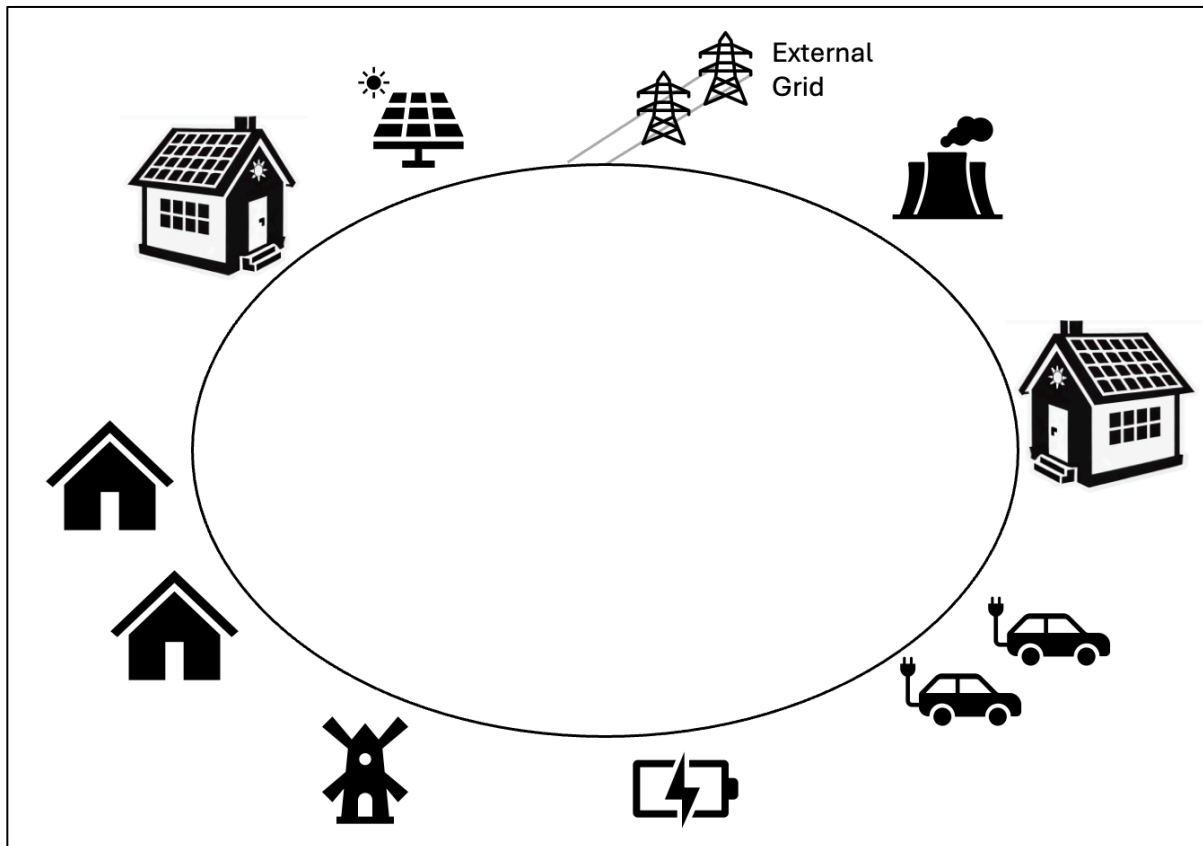


Figure 2: Representation of the multifaceted aspects of a renewable energy cluster, including users represented by houses, prosumers, storage, multiple renewable energy power plants, and a connection to the external grid.

A crucial aspect of the energy transition will be addressing the challenge of integrating highly variable energy sources such as solar and wind power (Hoicka et al., 2025). On the demand side, social change, cross-commodity sharing, and prosumership (a prospective consumer who is involved in the design, manufacture, or development of a product or service) can also contribute to creating a more reliable energy system. Because these renewable energy clusters, by definition, theoretically include a mosaic of actors, institutions, and technologies,

their design could assist in achieving a balance of available and variable sources. As complementarity and diversity in terms of energy portfolios have been expressed as essential for successful energy sovereignty in rural and remote communities (Leonhardt et al., 2023), renewable energy clusters are potentially well-positioned to address many of the technical challenges that renewable energy transitions face, as well as some of the challenges that fossil fuels systems have failed to solve.

Understanding how technology is adopted and diffused, however, is only part of the picture. Equally important is how equitable or inclusive these transitions are, raising important justice considerations in the field of energy geography. One framework for understanding core principles of justice within the context of energy systems is energy justice, which advocates for the inclusion of historically harmed communities in the energy processes, including but not limited to ownership (Jenkins et al., 2016). This field of energy transitions research provides social context for current inequalities that the energy transition has the potential to disrupt or perpetuate (Wyse et al., 2021).

The three core tenets of energy justice are distributional, recognition, and procedural (Jenkins et al., 2016). Distributional justice seeks to identify current injustices and work to understand how we can solve them within the context of an energy transition. It concerns not only access, but infrastructure and future development impacts as well. Recognition justice identifies those whose voices have been (and continue to be) ignored within energy spaces, and how those voices may be recognized properly. Lack of recognition can be through devaluation of traditional knowledge, lack of cultural respect, discrimination, or political domination. It may also include tokenism or misrepresentation of people's views. Finally, procedural justice focuses

on understanding whether or not aspects of decision-making within energy include fair process, which can reduce resistance to renewable energy development (Rand & Hoen, 2017). Special attention is paid to procedures within legal systems, but also includes practices, norms and values that determine who, when, and to what extent a group is consulted. By taking this three-pronged approach to energy justice, all elements along the value chain where injustice may occur can be considered (Jenkins et al., 2016). Scholars such as Berka & Dreyfus (2021) have posited that decentralized energy systems, such as renewable energy clusters, also present a potential opportunity to address current injustices within the fossil fuel industry. The justice tenets discussed by Jenkins et al. are not only social; they also manifest spatially, influencing where energy infrastructure is developed, who lives near it, and how land-use decisions affect both energy access and environmental outcomes.

One consideration in the spatiality of energy transitions is the correlation between different land use patterns and energy demand, a topic which there is not currently much literature (Owens, 1992). Patterns of settlements influence both per-capita and national energy demand, making land use even at a local scale an important factor in demand and supply with major energy systems (Haberl et al., 2023; Seto et al., 2021). Geography scholars have also found transportation infrastructure an influencing factor, such as higher quantities of public transport and co-locating business and housing to reduce energy demand, particularly around commuting hours. Built infrastructure is long-lasting, while energy demand and technology change frequently, making land planning an important consideration in energy transitions (Owens, 1992). The correlation between development and energy demand is not only one-sided, and scholars such as Owens (1992) recommend possible feedback between development patterns

which resulted from energy access dictating changes in energy demand to be considered in spatial planning as well. Poggi et al. (2018) and Hoffacker et al. (2017) called for scholars to look towards municipal planning and management as a possible solution to provide decision-making on how to strike a balance between urbanization, energy production, and other land uses. Bridge et al. (2013) claim the transition towards renewable energy necessitates relearning and adaptation of current understandings of the form, function and value of landscapes and spaces.

Together, the energy geography literature reviewed reveals that the renewable energy transition is not only a technical challenge, but a deeply spatial, social, and political one as well. In the following chapters, my thesis builds from these perspectives, contributing spatial insights into where renewable energy projects are placed, how those locations intersect with other land uses, and what this might mean for the ecosystems and communities that surround them

## 2.3 Land-Energy Nexus

In recent years, literature concerning energy geography and ecosystem service literature have been combined, creating a unifying framework of interdisciplinary research from which to study landscape, energy, and the environment. Linking energy transitions and ecosystem services occurred in part to bridge the gap between science and practice as well highlight how energy development can result in trade-offs with the goods and services people receive from nature typically not considered in transitions research (Hooper et al., 2017).

While there is no universal name for this combined body of literature, several terms have been coined including “land-energy nexus”, “energy landscapes” (Blaschke et al., 2013), and

“energyscapes” (Howard et al., 2013). Both energy landscapes and energyscapes literature focuses on the spatial footprints of energy projects. Land-energy nexus, also known at times as “land-water-energy nexus” or the “food-energy-water nexus” (Durand-Lasserve et al., 2017; Lamhamedi & de Vries, 2022) is a framework which focuses on the dynamic, integrated, analysis of how land and energy interact with and shape biophysical and social systems (Durand-Lasserve et al., 2017).

Stemming from the fields of geography, ecosystem services, energy transitions, and sustainability, the land-energy nexus is an interdisciplinary approach which places an emphasis on planning land use and development that considers the coexistence of sufficient energy production while safeguarding biodiversity and agricultural interests (Lamhamedi & de Vries, 2022). For the purposes of my research, I make use of the land-energy nexus field to describe the theoretical approach in literature where ecosystem services and energy transitions theories are both employed. Within their literature review of the land-energy nexus, Lamhamedi & de Vries (2022) define the land–energy debate as the diverse views, interests, and principles expressed by the different active voices in the low-carbon energy transition, as part of the climate change mitigation actions and a low-carbon economy. This includes the activities, power dynamics, and coordination between international bodies, governments, land administrations, environmental organizations, researchers, social structures, and local communities.

Lamhamedi & de Vries (2022) identify two paradigms in land-energy nexus literature: one of ecological modernization, and one of environmental and spatial justice. Ecological modernization views environmental protection and economic progress as compatible, stating them as non-opposite principles with sufficient policy regulation and technology enhancement.

The ecological modernization paradigm envisions co-benefits between energy production and natural systems. For example, solar panels placed in desert area benefit from unobstructed regular sunlight, and the use of solar panels instead of fossil fuels mitigates the extreme loss of biodiversity cause by Anthropogenic global warming. Spatial justice in land-energy nexus positions energy and land relationships as requiring land management and regulation to prioritize fair, equal and just distribution of the benefits and costs of implementing energy systems. These tenets align heavily with both ecosystem service justice and energy justice literature, although there are no current direct connections with the two. Ecosystem service justice emphasizes the need for the diverse values and needs of people from ecosystems to be incorporated into understanding their importance, rather than on monetary valuation alone.

One challenge within the land-energy nexus research that is energy geographers and land planners and ecosystem service researchers prioritize different landscapes in research surrounding the energy transition. Specifically, land-energy research by energy geographers and land planners typically focuses on urban and agricultural impacts, while ecosystem service research focuses on water systems and forest impacts. This is possibly due to the epistemological differences between the disciplines. Energy transition literature is typically more concerned with the impacts that the energy transition will have on land that provides socio-economic or socio-technical benefits, like the important role that agricultural land plays in our food and social systems, or how renewable energy could transform patterns of settlement. Ecosystem service research is typically more concerned with the impacts that the energy transition will have on land that is ecologically rich and plays a critical role for the biophysical environment which we are a part of, like the important role that forests play in providing shelter, livelihood, and resources to

over 25% of the global population (Newton et al., 2020). Because I am drawing from both fields and epistemological views for my research, I will consider both the value of ecologically rich areas from a socio-ecological perspective, as well as the importance of agriculture from a socio-economic perspective.

The approach that land-energy nexus research takes to study the synergies and trade-offs between land use, ecosystems, and energy projects is typically done through examining the land that energy projects (modelled or existing) are placed on via geospatial data or satellite imagery (Dai et al., 2024a; Hastik et al., 2015; Hernandez et al., 2015; Howard et al., 2013; Jones et al., 2015). Land classification is an environmental management and geospatial research technique which categorizes land by different characteristics, including:

- Biotic life and biodiversity
- Extent and density of built environment
- Presence of lakes, rivers, estuaries, oceans or other permanent water bodies

There have been significant and continuous efforts globally to improve the understanding of land cover by land classification through the production of geospatial maps, including NASA, the ESA, and private corporations (Townshend et al., 1991). An example of a land classification dataset can be seen in Figure 3.

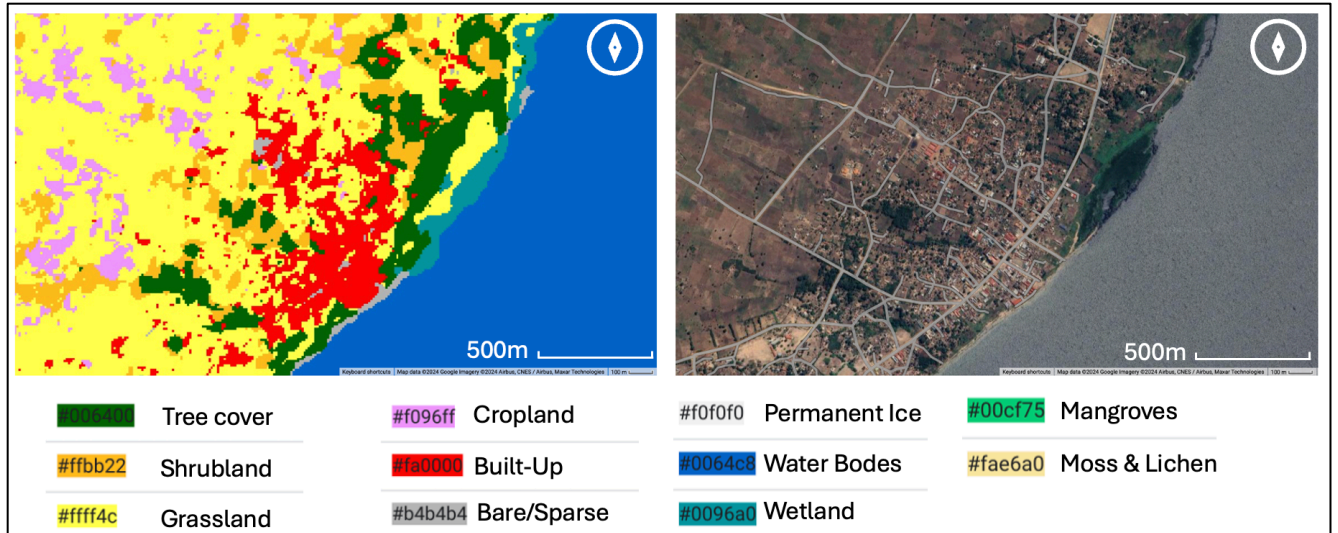


Figure 3 Land cover classification map depicting an area of land in the western region of Uganda on lake Albert. On the Left is the land delineated into the land cover by the ESA WorldCover dataset (ESA, n.d.). Retrieved from Google Earth Engine Code Editor (Gorelick et al., 2017)

Land classification can be used to understand where different features on Earth exist, and delineate where one “type” of land cover ends and another begins to measure the benefits of each (Government of Canada, 2019). Land classification also can indicate changes to land types over time by area of land type lost or gained, which can be compared to other factors such as climate conditions or human activity to identify the cause of land change (Satpalda, 2023). This technique is commonly used to measure environmental change, like deforestation (Liu et al., 2023).

There is growing scholarship that makes use of land classification and renewable energy projects in order to assess the trade-offs between energy development and other ecosystem services by land type (Aziz, 2023; Hanes et al., 2017; Hernandez et al., 2014, 2015; Hooper et al., 2017; Pilogallo et al., 2019). Some researchers have conducted longitudinal studies to show the changes to land cover following a project and/or the ecosystem services impacted

(Hernandez et al., 2014; Jordaan et al., 2021; Sharma et al., 2024). Table 1 provides a list of relevant readings in this emerging field.

Table 1 description of the current ES-energy literature, including the scope, focus, findings, and recommendations for future work.

<b>Paper</b>	<b>Geographic Extent</b>	<b>Research focus</b>	<b>Findings</b>	<b>Recommendations for future research</b>
Aziz, T. (2023). <i>Accounting impacts of renewable energy expansions on ecosystem services to balance the trade-offs.</i>	Pakistan	Modelled trade-offs between potential solar, wind, and hydropower energy expansions and ecosystem services.	<ul style="list-style-type: none"> <li>- Hydropower expansions will have the highest impact on ecosystem services, values and solar expansions the least.</li> <li>- The 2030 energy mix will impact the value of ecosystem services by \$9.6 billion annually, with a complete loss of 13%.</li> </ul>	<ul style="list-style-type: none"> <li>- Impact assessments may differ in other locations due to the unique geographies and land use patterns of specific landscapes.</li> <li>- How quickly and to what extent the ecosystem services recover after an impact.</li> <li>- Environmental costs of these renewable energy sources beyond valuation.</li> </ul>
Hernandez, R. R., Easter, S. B., Murphy-Mariscal, M. L., Maestre, F. T., Tavassoli, M., Allen, E. B., Barrows, C. W., Belnap, J., Ochoa-Hueso, R., Ravi, S., & Allen, M. F. (2014). <i>Environmental impacts of utility-scale solar energy.</i>	N/A	Literature review of environmental impacts of utility-scale solar energy development, including impacts on biodiversity, land-use and land-cover change, soils, water resources, and human health.	<ul style="list-style-type: none"> <li>- The fields of energy transitions and ecosystem services are not integrated.</li> <li>- The environmental trade-offs of solar have not been thoroughly evaluated or compare to the environmental benefits of low carbon electricity.</li> </ul>	<ul style="list-style-type: none"> <li>- Land-use and land-cover impacts of utility scale solar energy globally compared to other energy systems.</li> <li>- The extent that solar power plants are erected on degraded lands.</li> <li>- The environmental trade-offs between allocating lands to solar development versus agriculture.</li> </ul>
Hooper, T., Beaumont, N., & Hattam, C. (2017). <i>The implications of energy systems for ecosystem</i>	Northeast Atlantic, primarily UK and Denmark	Literature review of socio-economic parameters considered in assessment of the impacts of offshore wind	<ul style="list-style-type: none"> <li>- Most research efforts focused on marine mammals, birds, public attitudes, benthic communities and fish population.</li> </ul>	<ul style="list-style-type: none"> <li>- Quantitative studies of large-scale ecosystem service impacts which would help clarify the magnitude of</li> </ul>

<i>services: A detailed case study of offshore wind.</i>		compared to the ecosystem services classification system.	- Explicit use of the term ecosystem services is rare in offshore wind energy literature focused on land.	issues identified in qualitative studies.
Pilogallo, A., Saganeiti, L., Scorza, F., & Murgante, B. (2019). <i>Ecosystem Services Approach to Evaluate Renewable Energy Plants Effects.</i>	Melfi municipality, Italy	Land impacts of existing renewable energy plants.	- There is potential for competition between agriculture and renewable energy in this region. - The most compromised area is between the city center and the industrial area.	- More spatial analyses to examine the cumulative combination of impacts that renewable energy projects have on other ES.
Sarah M. Jordaan, Junghun Lee, Maureen R. McClung, & Matthew D. Moran. (2021). <i>Quantifying the ecosystem services values of electricity generation in the US Chihuahuan Desert: A life cycle perspective. Journal of Industrial Ecology.</i>	US portion of the Chihuahuan Desert	Theoretical land requirements for natural gas, solar, and wind in the Chihuahuan desert using ecosystem service valuation to find how much projects would cost in terms of ecosystem loss.	- Mean ecosystem services costs are \$0.54, \$1.39, and \$0.12 USD/MWh for electricity generated from natural gas, solar, and wind, respectively. - Results will vary with regionalized ecosystem services values and different products.	- How land may be used more efficiently over time by energy developments. - More comprehensive studies over larger areas involving more than one ecoregion. - Accounting for inter-regional variability in both ecosystem services values and energy systems.

<p>Hernandez, R. R., Hoffacker, M. K., Murphy-Mariscal, M. L., Wu, G. C., &amp; Allen, M. F. (2015). <i>Solar energy development impacts on land cover change and protected areas.</i></p>	<p>State of California, United States</p>	<p>The siting impacts of ~160 existing photovoltaic and concentrating solar power utility scale sites using modelled environmental and technical compatibility. Each installation was evaluated according to their proximity to protected areas.</p>	<ul style="list-style-type: none"> <li>- Installations average 5 km from protected areas.</li> <li>- 28% of installations are located in croplands and pastures.</li> <li>- Where energy, food, and conservation goals intersect, environmental compatibility can be achieved when resource opportunities, constraints, and trade-offs are integrated into siting decisions.</li> </ul>	<ul style="list-style-type: none"> <li>- Future studies could use model methods to explore interactions between water availability and solar energy technical potential.</li> </ul>
<p>Hoffacker, M. K., Allen, M. F., &amp; Hernandez, R. R. (2017). <i>Land-Sparing Opportunities for Solar Energy Development in Agricultural Landscapes: A Case Study of the Great Central Valley, CA, United States.</i></p>	<p>Central Valley, California, Italy</p>	<p>Land sparing potential of solar energy development across the built environment, salt-affected land, contaminated land, and water reservoirs.</p>	<ul style="list-style-type: none"> <li>- 8415 km<sup>2</sup> of non-conventional surfaces may serve as land-sparing environments for PV and CSP solar energy development.</li> <li>- Land sparing solar energy development pathways may be relevant to other agricultural landscapes threatened by trade-offs associated with renewable energy development and sprawl.</li> </ul>	<p>N/A</p>
<p>Dai, T., Jose Valanarasu, J. M., Zhao, Y., Zheng, S., Sun, Y., Patel, V. M., &amp; Jordaan, S. M. (2024). <i>Land Resources for Wind Energy Development Requires Regionalized Characterizations.</i></p>	<p>U.S. portion of the Western Interconnection.</p>	<p>Machine learning satellite imagery analysis of 318 existing wind farms.</p>	<ul style="list-style-type: none"> <li>- Projects developed in areas with little human modification have a much lower land efficiency (63.8 W/m<sup>2</sup>) and result in higher land transformation than those in areas with high human modification (447 W/m<sup>2</sup>).</li> <li>- Buffered geometry can be used to quantify the impact of a wind</li> </ul>	<ul style="list-style-type: none"> <li>- Comparisons of environmental sustainability across different energy technologies.</li> </ul>

			turbine and used to measure landscape resource demand.	
Jones, N. F., Pejchar, L., & Kiesecker, J. M. (2015). <i>The Energy Footprint: How Oil, Natural Gas, and Wind Energy Affect Land for Biodiversity and the Flow of Ecosystem Services</i> .	N/A	Literature review on the known impacts on wildlife mortality, habitat loss, fragmentation, noise and light pollution, invasive species, and changes in carbon stock and water resources for oil, natural gas, and wind.	- The literature on these impacts is unevenly distributed among energy types, geographic regions, and taxonomic groups.	- Using a landscape approach to predict and plan for the cumulative effects of development. - More information on the impacts of energy development on land-based ecosystem services is needed.

Seen in Table 1, recent research at the intersection of renewable energy and ecosystem services shows a growing recognition of the land-energy nexus, yet remains geographically limited, thematically fragmented, and heavily focused on modelling rather than existing energy sites. Studies in Table 1 utilize land cover techniques for land assessment, but are all limited to single regions or countries, such as Pakistan (Aziz, 2023), the Chihuahuan Desert (Jordaan et al., 2021), or California (Hoffacker et al., 2017; Hernandez et al., 2015), with none attempting global comparisons. The narrow scope of geography in any one study limits the generalizability of the results. Across the literature, this gap reoccurs and is identified as a future research priority (Dai et al., 2024; Hernandez et al., 2015; Jones et al., 2015).

Despite the literature in Table 1, Hooper et al. (2017) notes that ecosystem services assessment remains rare in the broader renewable energy literature, even when the focus is land or spatiality. Some studies advocate for incorporating ecosystem service valuation into energy planning (Hooper et al., 2017; Jordaan et al., 2021), while others highlight the potential of siting strategies to reduce impacts, particularly by co-locating projects on degraded, built, or low-conflict land types (Hernandez et al., 2014; Hoffacker et al., 2017). There is a growing level of attention to the impacts and potential competition between land uses, especially between agriculture and energy (Pilogallo et al., 2019). Hernandez et al. (2014) dedicates a section of their research entirely to suggested questions for future research, which includes understanding the land-use and land-cover impacts of solar energy systems globally, as well as identifying ecosystem trade-offs and synergies that occur from co-locating energy technologies, as having energy projects sharing already developed area may result in fewer land impacts. Across current literature, there is a clear need for broader study scope to provide more comprehensive data (Dai et al., 2024a; Hastik et al., 2015; Hernandez et al., 2015; Howard et al., 2013; Jones et al., 2015; Jordaan et al., 2021).

Because land-energy interactions have been identified as important in protecting ecosystem services, understanding the impacts that these energy systems have is critical in informing decision-makers on how and where they should be implemented. A broader perspective that considers the land is needed. This is where my research seeks to contribute to the land-energy nexus field.

### 3. When “Green” Meets Green: exploring the interactions between renewable energy development and ecosystem services globally

*“Understanding the full consequences of energy production is necessary for meeting demand while also safeguarding the ecological systems on which we depend.”*

-Jones et al. (2015)

#### 3.1 Introduction

From provisioning services such as food and freshwater, to cultural practices and social wellbeing, the vitality of our ecosystems and environment is crucial, contributing both indirectly and directly to health and wellbeing of societies (Bennett et al., 2009).

Ecosystem services is a framework that conceives the human and non-human environment as part of one social-ecological system in order to express the value that the environment has beyond extraction of resources (Costanza et al., 1997). Ecosystem services are important to study because changes in the ecosystem affect human wellbeing, including access, health, freedom, and security (Millennium Ecosystem Assessment Program, 2005). Access to basic necessities for life like food and water depends on both provisioning services (such as agriculture) and regulating services (such as water purification). Health is strongly linked to the quality of provisioning services such as food production as well as regulating services including air quality and safe weather temperatures. Extreme weather and poor air and food quality have both short and long-term health impacts. Beyond basic physical necessities, changes in the cultural services that impact ceremonies or spaces of importance affect social relations, which in turn can impact quality of life. Finally, security depends on the reliability of the environment and resources. Experiencing insecurity in necessary resources through drought, floods, or

erosion can create conflict or competition between communities and impact freedoms and choice (Millennium Ecosystem Assessment Program, 2005).

One necessary and increasingly in-demand resource that our environment provides is energy, an essential resource that provides means of heating, cooling, cooking, and transportation. Energy systems interact with and impact land at all aspects of the value chain, including site construction and preparation, extraction, distribution, and consumption (Lamhamedi & de Vries, 2022). Fossil fuel extraction is especially harmful during this process, both directly and indirectly. Directly, clearing land to construct work sites disturbs natural habitat, and during the extraction process sound pollution, off-gassing, and runoff degrades nearby environments (Harfoot et al., 2018). Indirectly, the use of fossil fuels results in an increase of greenhouse gas emissions, contributing to climate change which negatively impacts all ecosystem services globally (IPCC, 2023). While society is currently reliant on fossil fuels, human wellbeing is also dependent on the services and benefits that ecosystems provide, many of which are jeopardized by fossil fuel systems (Harfoot et al., 2018). This necessitates a transition to low-carbon energy systems.

Due to the harmful impacts of fossil fuel use, sustainable development advocates for reliable and efficient provision of renewable energy (Hastik et al., 2015). By transitioning away from fossil fuels to low-carbon energy systems, many of the pollution and climate change concerns can be addressed, but the potential implications of new development on ecosystems is also of concern. Because renewable energy systems emerge as highly geographically dependent (For example, hydro power availability is limited to locations with an accessible, moving body of water) (Sliz-Szkliniarz, 2013), ecosystem service scholars such as Hastik et al. (2015) have identified ecosystem services as a well-suited

theoretical framework for understanding the range of environmental challenges that can be affected by renewable energy development.

Despite the urgent need for an energy transition, there are several factors of energy production unique to renewable energy that prove challenging to overcome. One land challenge with the energy transition is that the type of land that is most convenient for renewable energy production, especially solar power, (flat open areas, regular sun, streams and lakes, etc.) overlaps with the type of land most desired for agriculture, for which land demand is also increasing as population rises (Picchi et al., 2019). The trade-offs between energy production and other land uses therefore create the potential for competing interests for the same landscapes (Hoffacker et al., 2017), (Calvert & Mabee, 2015). For example, the expansion of “Agrovoltatics” (solar power farms that are placed on land previously used for agriculture are resulting in a decrease in the agricultural economy in the Midwest of the United States, as well as resistance from farming communities (Moore et al., 2022). Similarly, the trade-offs of renewable energy projects have resulted in common land in the Global South being made inaccessible for pastoral purposes, negatively impacting Indigenous communities historical land use (Bedi, 2019). While there is a plethora of options for placing renewable energy in ways that do not further directly impact the environment such as rooftop solar, it is unclear to what extent these methods are currently being employed. The impacts of different types of energy resources have been a motivation for ecosystem service scholars to begin assessing and incorporating energy transitions into the field.

Another challenge with renewable energy systems is the area of land they require due to their power density. Power density describes the amount of power contained within a given unit volume or area (Smil, 2015). For example, coal has a power density of  $\sim 278$  w/m<sup>2</sup> while solar has a power density of  $\sim 5$  w/m<sup>2</sup> (Buceti, 2014). This means that for generating the same power as fossil fuels, renewable

energy is considerably more land intensive. The ecosystem services theoretical framework, which seeks to evaluate and conserve the contributions that the natural environment provides to human wellbeing, is well-positioned to study the resulting dynamics between land and energy.

While scholarship is growing in this emerging interdisciplinary field, the majority of literature is currently focused on local context, without findings that span multiple different regions or nations (Aziz, 2023; Hanes et al., 2017; Hernandez et al., 2014, 2015; Hooper et al., 2017; Pilogallo et al., 2019). By studying renewable energy development impacts of specific geographic regions, the multitude of diverse landscapes and ecosystem services globally cannot be captured, and the focus of the research will naturally highlight ecosystem services which are most relevant to the study area, which may not translate to broader concerns. This smaller scope of current research limits our understanding of large-scale patterns in the types of ecosystems and ecosystem services that are nearby and interacting with renewable energy development. Scholars including Hastik et al. (2015) critique current literature on land and energy that is specialized within a singular disciplinary boundary without considering the diverse environmental, economic or social issues that arise from land-energy interactions.

The rapid increase in renewable energy production and relatively recent inclusion in ecosystem service literature (Haida et al., 2016) means that the unique challenges and benefits that renewable energy systems pose for other ecosystem services has not been clearly defined yet at the global scale. As a result, my research necessitates an exploratory approach which does not intend to offer conclusive results to existing problems (Singh, 2007). My research aims to determine the nature and characteristics of potential ecosystem considerations in the energy transition to form a basis of empirical findings for future work to build upon. I explore this topic through the following research objectives:

- Determine the range of landscapes in proximity to existing renewable energy resources globally.
- Assign ecosystem services consistently associated with each landscape through literature to identify the potential risk of trade-offs different power plants have with the nearby environment.
- Quantify the proximity of renewable energy resources to agricultural land.

To determine the range of landscapes, I make use of a growing, open-source power plant database and land cover classification maps and identify patterns and trends across resource types (Byers et al., 2018). Then, to assess ecosystem services, I conduct a literature review for each land type and assess the number of ecosystem services that the range of landscapes existing in proximity to current renewable energy projects provide. Finally, I overlay the power plants with an agricultural map to identify the extent that the overlap in regions between renewable energy and agriculture is occurring in practice.

### 3.2 Review of the Literature

All energy resources require environmental contribution (e.g. sunlight for solar power, fossilized deposits for oil extraction etc.) (Picchi et al., 2019). Currently, human use of the environment affects 70% of global ice-free land surface, much of which contains vulnerable ecosystems and biodiversity which we rely on (Lamhamedi & de Vries, 2022). Because the availability of different types of energy sources is highly dependent on the environment (Kienast et al., 2019), understanding the relationships between energy and other ecosystem services is essential in creating a socially and environmentally sustainable future (Aziz, 2023). Understanding energy production through a place-based lens allows the benefits and limitations of different resources for a variety of environments to be considered (Bridge et

al., 2013). Prominent fields of literature that have focused on the spatial and land-based aspect of energy systems include energy geography, ecosystem services, and land-energy nexus. Energy geography literature incorporates spatiality into a socio-technical understanding of energy systems. Ecosystem service literature considers energy as an aspect of broader socio-ecological systems. Finally, land-energy-nexus literature arises from scholarship in sustainable development and encouraging transdisciplinary thinking.

Given its capacity to contextualize both the social and physical spatial dimensions of energy systems, geography stands as a well-suited discipline to comprehend the shift towards renewable energy (Bridge et al., 2013). Energy geography offers insights into concepts including location, landscape, diffusion of innovations, and justice. Scholars such as Bridge et al. (2013) argue that considering the spaces, places, and people that will be impacted by the renewable energy results in a higher chance of success of a transition that does not perpetuate systems of inequality and can clarify how a low-carbon future can be realized. This body of literature reveals that the renewable energy transition is not only a technical challenge, but also a deeply spatial, social, and political one (Bradshaw, 2010; Bridge et al., 2013; Hoicka et al., 2025; Rand & Hoen, 2017).

One focus in energy geography research is the correlation between different land use patterns and energy demand, a topic which there is not currently much literature on (Owens, 1992). Patterns of settlements influence both per-capita and national energy demand, making land use even at a local scale an important factor in demand and supply with major energy systems (Haberl et al., 2023; Seto et al., 2021). Geography scholars have also found transportation infrastructure an influencing factor, such as higher quantities of public transport and co-locating business and housing reduce energy demand, particularly around commuting hours. Poggi et al. (2018) and Hoffacker et al. (2017) called for scholars

to look towards municipal planning and management as a possible solution to provide decision-making on how to strike a balance between urbanization, energy production, and other land uses.

Because the availability of different types of energy sources is highly dependent on the environment (Kienast et al., 2019), understanding the relationships between energy and other ecosystem services will be increasingly important in the coming years (Aziz, 2023). Ecosystem services literature is primarily concerned with balancing environmental protection and human development (Millennium Ecosystem Assessment Program, 2005). Studies have called for increased attention to development of a theoretical understanding behind the multiple and non-linear relationships amongst ecosystem services, as well as the trade-offs and synergies that result from using provisioning services or altering the landscape in ways that affect multiple ecosystem services (Bennett et al., 2009). Tradeoffs arise when the provision of one service is enhanced at the cost of reducing the provision of another service, synergies arise when multiple services are enhanced simultaneously (Raudsepp-Hearne et al., 2010). Both trade-offs and synergies can be managed to either reduce their associated costs to society or enhance landscape and human wellbeing, respectively.

Energy is a unique consideration in ecosystem services literature because it both requires environmental contributions which can result in ecosystem services harm, and is considered a provisioning ecosystem service in-and-of itself, because it is a directly consumable resource that benefits human wellbeing (Picchi et al., 2019). By analyzing the energy transition through an ecosystem services lens, a holistic understanding of potential ecological trade-offs of energy development can be considered.

In recent years, literature concerning energy geography and ecosystem service literature have been combined, creating a unifying framework of interdisciplinary research from which to study

landscape, energy, and the environment. Linking energy transitions and ecosystem services occurred in part to bridge the gap between science and practice as well highlight how energy development can result in trade-offs and with the goods and services people receive from nature typically not considered in transitions research (Hooper et al., 2017).

Stemming from the fields of geography, ecosystem services, energy transitions, and sustainability, the land-energy nexus in an interdisciplinary approach which places an emphasis on planning land use and development that considers the coexistence of sufficient energy production while safeguarding biodiversity and agricultural interests (Lamhamedi & de Vries, 2022). For the purposes of my research, I make use of the land-energy nexus field to describe the theoretical approach in literature where ecosystem services and energy transitions theories are both employed.

Within their literature review of the land-energy nexus, Lamhamedi & de Vries (2022) define the land–energy debate as the diverse views, interests, and principles expressed by the different active voices in the low-carbon energy transition, as part of the climate change mitigation actions and a low-carbon economy. This includes the activities, power dynamics, and coordination between international bodies, governments, land administrations, environmental organizations, researchers, social structures, and local communities.

One challenge within the land-energy nexus research area that energy geographers and land planners and ecosystem service researchers prioritize different landscapes in research surrounding the energy transition. Specifically, land-energy research by energy geographers and land planners typically focuses on urban and agricultural impacts, while ecosystem service researcher focuses on water systems and forest impacts. This is possibly due to the epistemological differences between the disciplines. Energy transition literature is typically more concerned with the impacts that the energy transition will

have on land that provides socio-economic or socio-technical benefits, like the important role that agricultural land plays in our food and social systems, or how renewable energy could transform patterns of settlement. Ecosystem service research is typically more concerned with the impacts that the energy transition will have on land that is ecologically rich and plays a critical role for the biophysical environment which we are a part of, like the important role that forests play in providing, shelter, livelihood, and resources to over 25% of the global population (Newton et al., 2020). Because I am drawing from both fields and epistemological views for my research, I will consider both the value of ecologically rich areas from a socio-ecological perspective, as well as the importance of agriculture from a socio-economic perspective.

The approach that land-energy nexus research takes to study the synergies and trade-offs between land use, ecosystems, and energy projects is typically done through examining the land that energy projects (modelled or existing) are placed on via geospatial data or satellite imagery (Dai et al., 2024a; Hastik et al., 2015; Hernandez et al., 2015; Howard et al., 2013; Jones et al., 2015). Land classification can be used to understand where different features on Earth exist, and delineate where one “type” of land cover ends and another begins to measure the benefits of each (Government of Canada, 2019). Land classification also can indicate changes to land types over time through the area of land type lost or gained, which can be compared to other factors such as climate conditions or human activity to identify the cause of land change (Satpalda, 2023). This technique is commonly used to measure environmental change like deforestation (Liu et al., 2023).

There is growing scholarship that makes use of land classification and renewable energy projects in order to assess the trade-offs between energy development and other ecosystem services by land type (Aziz, 2023; Hanes et al., 2017; Hernandez et al., 2014, 2015; Hooper et al., 2017; Pilogallo et al.,

2019). Land classification is an environmental management and geospatial research technique which categorizes land by different characteristics, including biotic life and biodiversity, extent and density of the built environment, and presence of permanent water bodies. Recent research at the intersection of renewable energy and ecosystem services shows a growing recognition of the land-energy nexus, yet remains geographically limited, thematically fragmented, and heavily focused on modelling rather than existing energy sites (Hernandez et al., 2014; Jordaan et al., 2021; Sharma et al., 2024).

Previous studies utilize land cover techniques for land assessment from an ecosystem services perspective within single regions or countries, such as Pakistan (Aziz, 2023), the Chihuahuan Desert (Jordaan et al., 2021), or California (Hoffacker et al., 2017; Hernandez et al., 2015). The narrow scope of geography in any one study limits the generalizability of the results. There is a growing level of attention to the impacts and potential competition between land uses, especially between agriculture and energy (Pilogallo et al., 2019). Across current literature, there is a clear need for broader study scope to provide more comprehensive data (Dai et al., 2024a; Hastik et al., 2015; Hernandez et al., 2015; Howard et al., 2013; Jones et al., 2015; Jordaan et al., 2021)

One study of relevance that focuses on trade-offs between solar energy and ecosystem services is Hernandez et al. (2015) *Solar energy development impacts on land cover change and protected areas* which sought to determine how other ecosystem services are impacted in order to access energy through solar development. This was done by identifying the range of landscapes in which solar projects are located on 160 existing solar sites across California, both photovoltaic and concentrating solar power. A geospatial layer of the power plants was created, where each plant is represented by a point location given in latitude/longitude. Hernandez et al. then overlaid the geospatial solar plant map with the US National Land Cover Dataset at 30-m resolution to identify the impact that solar projects have on

ecosystems. Within this body of literature, ecological impact refers to the effects left on organisms (including humans) and their environment due to actions made by humans development, either indirectly or directly (Treweek, 1995). Hernandez et al. found that power plants were located in shrublands twice as often as cropland, however 28% of area with installations were installed in croplands and pastures. The authors suggest future research study co-locating multiple renewable energy resources to avoid impacting a wider variety of land.

Using similar techniques, *Accounting impacts of renewable energy expansions on ecosystem services to balance the trade-offs* (Aziz, 2023) conducted a geospatial analysis of the ecosystem service trade-offs between different potential energy developments in Pakistan. Instead of examining current energy sites, Aziz modelled future renewable electricity production using modelling software MENARA, based on projected energy demand. The resulting energy projects from the MENARA model were then overlaid with Copernicus Global Land Service Dynamic Land Cover Map at 100m resolution. Aziz then made use of a dataset created by Li et al. (2016) which provided the valuation of ecosystem services by land cover category. Li et al.'s dataset assigns a normalized unit value based on the ecosystem services it can supply out of the total of 22 ecosystem services (i.e., food, water, raw materials, genetic resources, medicinal resources, ornamental resources, air quality regulation, climate regulation, water flow regulation, water treatment, erosion prevention, soil fertility, pollination, biological control, nursery service, gene pool protection, aesthetics, recreation, inspiration for culture and art, spiritual experience, cognitive development) which are converted to 2020 US Dollars. Aziz found that the total value of Pakistan's ecosystem services is \$162,511 million per year, 20% of which will be potentially impacted by the development of renewable energy projects. Aziz argues that while developing new renewable energy projects can create economic growth, if they are built in ecosystem

service rich environments, they can result in a loss of valuable ecosystem services and ecosystem service trade-offs, which should be accounted for when considering if an energy project is worthwhile. The concern around trade-offs is greater for ecosystem services provided by forested and agricultural areas which are particularly important to Pakistan. Aziz concluded that whenever possible, areas that are already developed be used to produced energy (e.g. rooftop solar, etc.), and recommended similar methods be used for a broader study region.

All literature I have identified that utilize geospatial techniques to assess the land-energy nexus, limits their study scope to either one ecological region (e.g. alpine mountain (Hastik et al., 2015)), or nation (e.g. Pakistan (Aziz, 2023)). Most of the current work is isolated to one location or ecological species, with a disproportionate focus on particular geographic regions and energy types (see Table 1 for further details). As this field is relatively new and evolving, scholars have several suggestions for which directions future work should focus on. Hooper et al. (2017) recommends an increased focus on valuation of ecosystem services changes due to energy systems when assessing the impact of potential energy projects. Similarly, Aziz (2023) emphasizes the importance of making use of spatially explicit mapping when assessing land-energy trade-offs. Hernandez et al. (2014) dedicates a section of their research entirely to suggested questions for future research, which includes understanding the land-use and land-cover impacts of solar energy systems globally, as well as identifying environmental and economic trade-offs and synergies that occur from co-locating energy technologies, as having energy projects sharing one already developed area may result in fewer land impacts. Across current literature, there is a clear need for broader study scope to provide more comprehensive data (Dai et al., 2024a; Hastik et al., 2015; Hernandez et al., 2015; Howard et al., 2013; Jones et al., 2015; Jordaan et al., 2021). Currently, there are two major limitations that consistently arise in current land-energy nexus:

The use of modelling potential energy projects rather than existing ones. There is robust previous literature on how renewable energy is not diffusing the way that other technologies typically do (Aziz, 2023; Hoffacker et al., 2017; Jordaan et al., 2021). Combined with the multitude of complex factors preventing a transition away from fossil fuels including infrastructural challenges, institutional barriers, and resistance to behavioral change (Jacobsson & Johnson, 2000; Seto et al., 2016), modelling where energy projects are likely to occur accurately is extremely difficult. The limitation in basing the majority of current knowledge of ecosystem service impact of the energy transition on modelled energy systems is that the identified concerns may not accurately reflect the reality of where renewable energy development is actually impacting the environment.

Current research is heavily limited to regional scope, typically spanning no more than a few hundred kilometers. By studying renewable energy development impacts of specific geographic regions, the multitude of diverse landscapes and ecosystems services around the world cannot be captured, and the focus of the research will naturally highlight ecosystem services which are most relevant to the study area, which may not translate well to broader concerns.

Because land-energy interactions have been identified as important in protecting ecosystem services, understanding the impacts that these energy systems have is critical in informing decision-makers on how and where they should be implemented. A broader perspective that considers the land implications is needed.

### 3.3 Methods

To compare the types of land that renewable energy power plants are located on, I utilize satellite-derived land cover classification data from the European Space Agency and the World Resources Institute Global Power Plant Database. I apply a 1km, 5km, and 10km buffer zone around each power plant to determine the range and prevalence of land types around energy sites and compare the ecosystem services each land type is described as providing in literature. Additionally, for each energy site, I calculate the distance to the nearest agricultural land. As research into ecosystem service and renewable energy interactions is not well defined at this time, my findings aim to describe the range of interactions rather than confirm a hypothesis.

#### 3.3.1 Power Plant Database

In order to assess the interactions between renewable energy resources and ecosystems, I made use of the World Resources Institute Global Power Plant Database (Byers et al., 2018). Continuously updated since its launch in 2018, this open-source database comprises of approximately 30,000 power plants including coal, gas, oil, nuclear, biomass, geothermal, hydro, wind, and solar (Byers et al., 2018), with the date of establishment for projects up to 2023. Spanning 164 countries, each power plant contains information on its precise geolocation, the capacity of the power plant, ownership, and year established, if known.

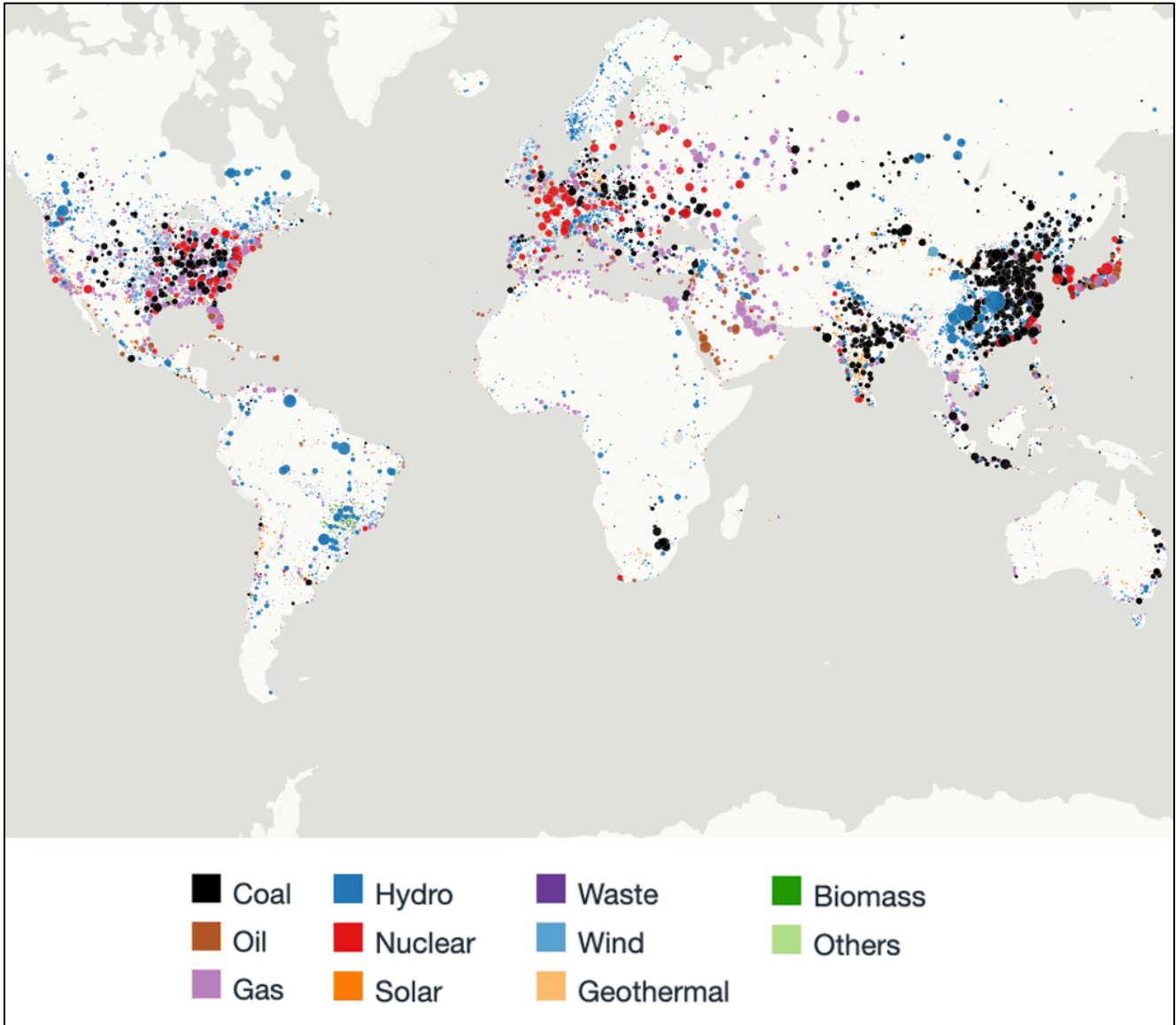


Figure 4: Visualization of Global Power Plant Database. The size of each point represents the energy capacity of that power plant. Retrieved from Byers et al. (2018)

I have selected my study scope to include renewable energy resources formally recognized by the Global Power Plant Database only, including: biomass, hydro, solar, geothermal, and wind. Nuclear energy has been excluded from my study for two reasons; the first being that it is technically not a renewable resource, and the second being that the safety concerns and extremely high power density of nuclear create unique challenges that are beyond the scope of this study. Wave energy has also not been

included as there is very little produced globally to date making the data minimal, compounded with extremely limited information on how offshore ecosystem services vary by location.

The percent total of renewable resources included in the Global Power Plant database is reported and can be found in Table 2. For statistical analysis, typically, a good sample size to measure prevalence is 10% of the population, if that results in a sample under 1000, or a total of 1000 samples if the population is larger (Conroy, 2018). As there are over 1000 power plants per resource and represent >10% of the global estimated capacity, for the purposes of my research the size of this database is sufficiently robust.

Because I am interested in the geography of these power plants, I plotted the geographic distribution of energy production in comparison to IRENA (2022) reported energy production by continent, seen in Figure 5.

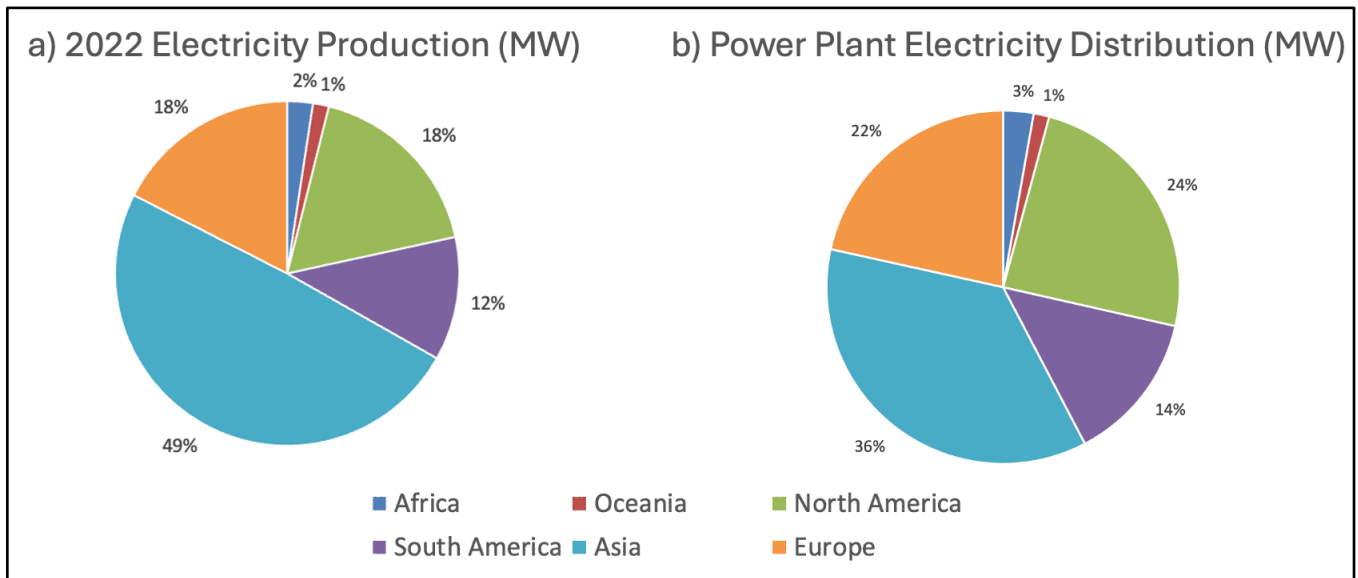


Figure 5: Geographic distribution by continent of electricity (MW) reported by IRENA and within the Power Plants Database (Byers et al., 2018; IRENA, 2025).

Figure 5 shows very similar patterns of distribution, with a slight over-representation in North America and Europe for data. Because the dataset and the IRENA report shows the same order of magnitude in values, the power plant dataset is sufficiently representative for my results.

*Table 2: Global coverage of energy production by resource type contained within the Power Plant database (Byers et al., 2018).*

<b>Fuel type</b>	<b>Percent of reported total global capacity</b>
Geothermal	93.88%
Biomass	67.5%
Hydro	66.27%
Wind	37.34%
Solar	17.93%

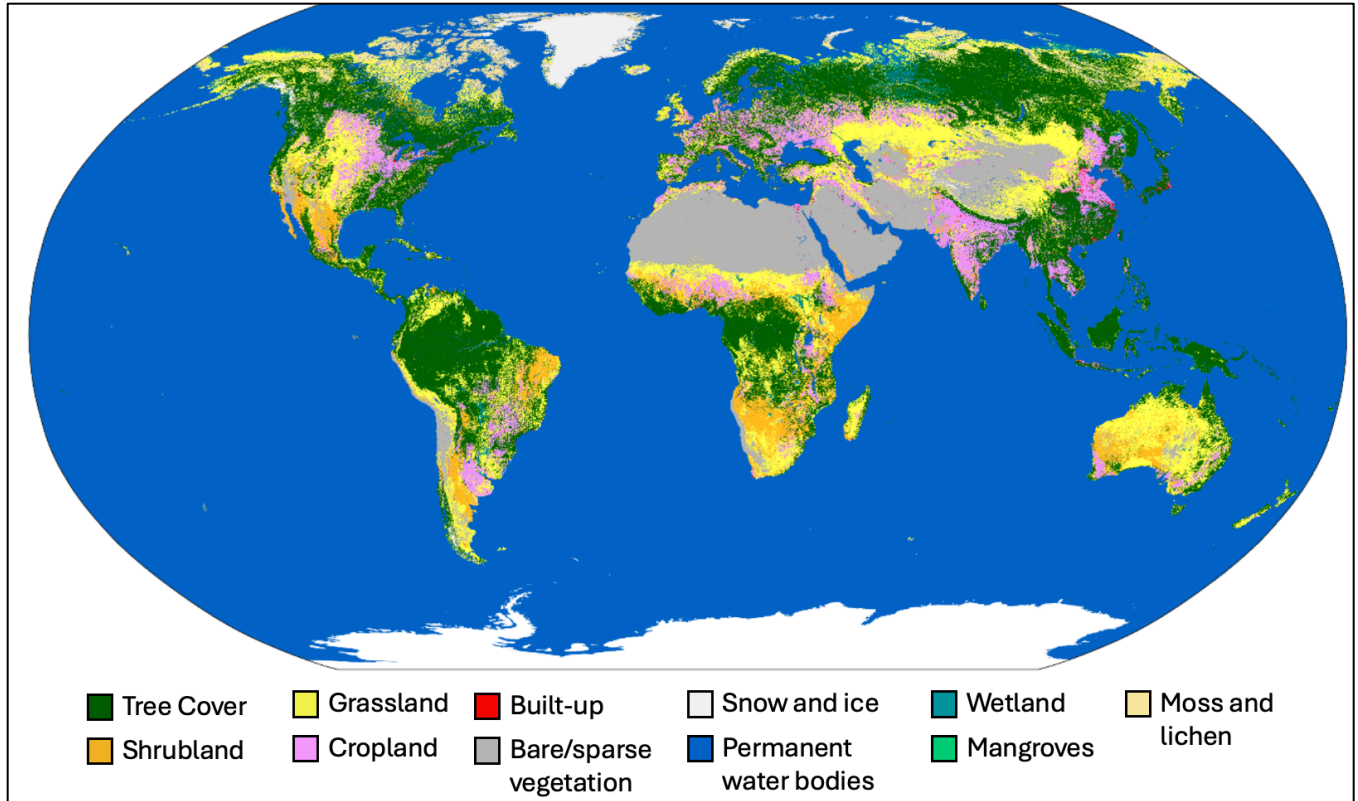
The power plants in this resource were identified using a data-driven approach to find open source, publicly available data, including information from government agencies, companies, public utilities, and non-government organizations. The power plants contained in this dataset represent ~85% of globally installed energy capacity (Byers et al., 2018).

Only 38% of power plants had resources which provided their exact geographic location. In order to geolocate the remaining power plants, Byers et al. (2018) matched power plants identified using this methodology by those already contained in Enipedia, which provided the location of 30% of power plants in the dataset. The remaining 3,726 power plants that were not possible to identify using either of these methods were manually located using satellite imagery. This database has been continuously expanding since its launch in 2018, with regular updates.

### 3.3.2 Land Cover Database

I utilized additional publicly available data on the land cover type in conjunction with the Power Plant Database to identify how often currently existing renewable energy projects are operating near agricultural land, as well as any patterns between land cover type and resource combination.

Land classification is the method of organizing Earth's surface through dividing areas into discrete categories according to the attributes of the land cover, primarily vegetation and surface composition (soil, water, grass, etc.). There is a plethora of available datasets offering land cover data oriented towards different focuses and using different geospatial techniques. For the purposes of my research I selected the European Space Agency's World Cover V200 dataset (see Figure 6) (ESA, 2022).



*Figure 6: World Cover dataset provided by the European Space Agency. Retrieved from ESA (2022).*

The ESA World Cover data is a 10m resolution global geospatial dataset which describes land cover according to the categories seen in Table 3 (ESA, 2022). Created using high-resolution optical Earth observation data from Sentinel-2 as well as synthetic aperture radar data from Sentinel-1, the World Cover dataset is the first of its kind to combine both geospatial techniques at the global scale. This was done by first processing and removing clouds, cirrus and saturated pixels, training a classifying model on 10% of each type of land cover data. As the leading industry standard, organizations which rely on this database include (but are not limited to) the UN Convention to Combat Desertification, the World Resources Institute, the Center for International Forestry Research, and the Food and Agricultural Organization (ESA, n.d.).

The ESA World Cover dataset, while not without its limitations, currently outperforms other global

land cover models using a variety of methodological tests. With a self-estimated accuracy of 76.7% (ESA, 2022), Ding et al. (2022) found a mean accuracy of 81.1%, (P. Xu et al., 2024) an 83.8% accuracy, and (Chaaban et al., 2022) found 78.3%, all of which outperform comparable geospatial datasets.

*Table 3: Land cover classification types as seen in the ESA (2021) World Cover dataset*

<b>Land Cover Class</b>	<b>Definitions</b>
Tree Cover	Any geographic area dominated by trees with a cover of 10% or more.
Shrubland	Any geographic area with 10% or more coverage of natural shrubs, defined as wood or perennial plants with persistent and woody stems and without any defined main stem, less than 5m tall.
Grassland	Any geographic area dominated by natural herbaceous plants.
Cropland	Annual cropland that is sowed/planted and harvested. This category does not include greenhouses.
Snow and ice	Any geographic area persistently covered by snow or glaciers.
Permanent water bodies	Any geographic area covered by for >9 months of the year by water bodies including oceans, lakes, reservoirs, and rivers.
Herbaceous wetland	Land covered by natural herbaceous vegetation that is regularly or permanently flooded by water.

Mangroves	Taxonomically diverse, salt-tolerant tree and other plant species that thrive in intertidal zones.
Moss and Lichen	Land covered with composite organisms formed from the symbiotic association of fungi and algae.
Bare/sparse vegetation	Land with exposed soil, sand, or rocks and never has more than 10% vegetated cover during any time of the year.
Built-up	Land covered by buildings, roads, and other human-made structures including railroads. Waste deposits and extraction sites are considered bare.

Due to their similar characteristics, for the purposes of my research, I aggregated mangroves and herbaceous wetland, as well as sparse vegetation and moss and lichen.

### 3.3.3 Ecosystem Service Assessment

I identified the range of ecosystem services that each land class provides as well as using the rank proportion of importance by land type that Costanza et al.'s research resulted in, which describes the comparative importance each land type has for human wellbeing. This rank proportion is as follows:

1. Herbaceous wetland/Mangrove
2. Permanent water bodies
3. Tree cover
4. Grassland

5. Shrubland
6. Cropland
7. Value not assessed/significant: moss and lichen/bare/sparse vegetation, snow and ice, built-up

Because a comprehensive list of ecosystem services provided by each of the WorldCover land types has not been conducted explicitly, I undertook a literature review for each land type described in Figure 6, pulling from previous scholarship that had recognized the services that each land class offers (see Figure 7). Where literature exists, sources covering different global regions were included in my literature review to increase the diversity of knowledge on each land type. In the cases where an ecosystem service was stated in one paper but not explicitly in another, I included it. None of the literature I reviewed disagreed on resources. For example, several papers discuss how knowledge and learning is an ecosystem service that tree cover provides, and some papers did not discuss knowledge and learning as an ecosystem service that tree cover provides, but no papers explicitly stated knowledge and learning as a service that tree cover does *not* provide, but rather it was not assessed.

Table 4: List of ecosystem services that each land type provides according to previous scholarship, delineated by ecosystem service type. Land types that have 22 ecosystem services provide all ecosystem services recognized by the Millenium Ecosystem Assessment as described in Figure 1. The complete table including the literature review for each can be found in Appendix B

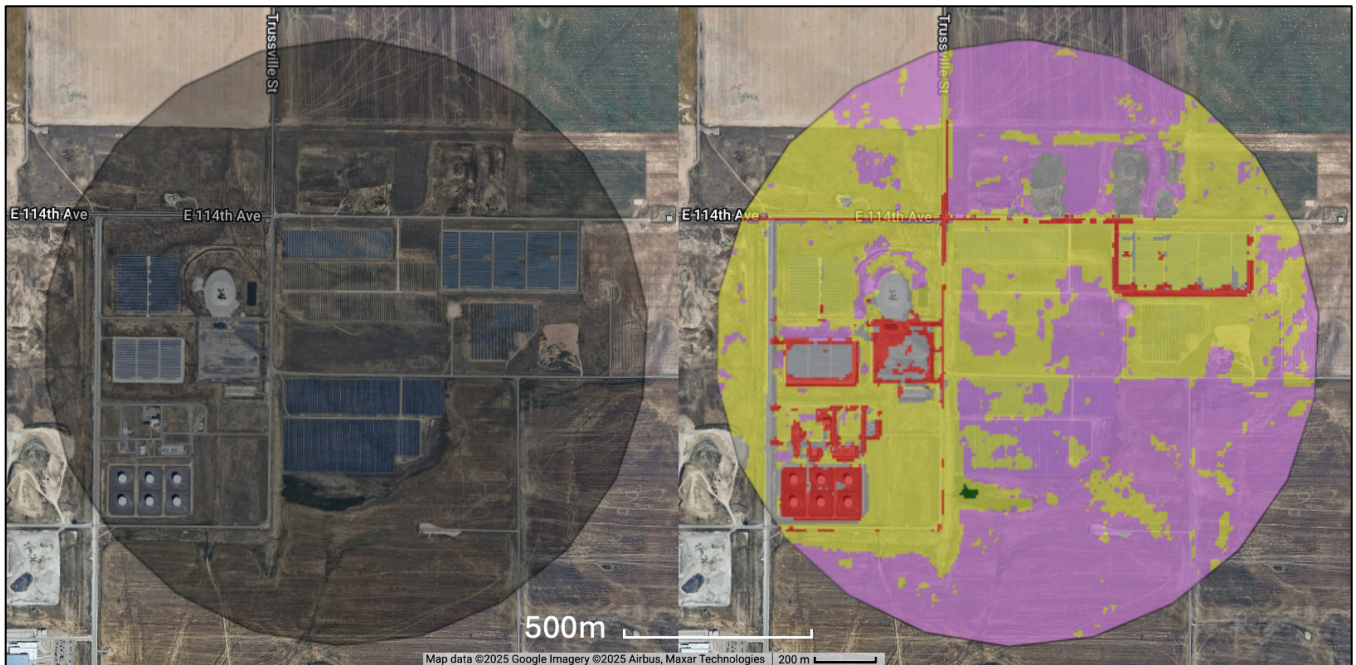
	Ecosystem Service	Tree Cover	Shrubland	Grassland	Cropland	Built-up	Bare/sparse	Snow & Ice	Permanent Water	Herbaceous Wetland/Mangroves
Provisioning	Materials	X	X	X				X	X	X
	Food and drink	X	X	X	X			X	X	X
	Natural medicines	X		X					X	X
	Water supply	X							X	X
Regulating	Clean air	X	X	X	X				X	X
	Carbon storage	X	X	X	X			X	X	X
	Flood management	X	X	X				X	X	X
	Erosion Control	X	X	X					X	X
	Water Purification	X	X	X					X	X
	Disease and natural pest control	X	X	X				X	X	X
	Pollination	X	X	X					X	X
Supporting	Health soils	X		X					X	X
	Photosynthesis	X		X	X				X	X
	Nutrient Cycling	X	X	X	X				X	X
	Space for wildlife	X	X	X				X	X	X
Cultural	Physical health & mental wellbeing	X		X				X	X	X
	Tourism	X		X	X			X	X	X
	Knowledg & learning	X	X		X			X	X	X
	Recreation	X	X					X	X	X
	Sense of place	X		X				X	X	X
	Inspiration	X		X				X	X	X
	Spiritual & religious connections	X		X				X	X	X
	Total /22	22	13	19	19	0	0	13	22	22

It's critical to note that Table 4 is not concluding that all land in each land type provide explicitly and exclusively the indicated ecosystem services at all locations and times. Ecosystem services are by-definition human-related, and therefore many of these values, especially the socially oriented ones, are dependent on the perceptions and cultures of those in their environment. The services identified in Table 4 are from repeated observations in literature (see Appendix B for complete list). Table 4 shows herbaceous wetland, permanent water bodies, and tree cover as the three land types that provide all 22 ecosystem services. This aligns with the top three ranked ecosystem services by Costanza et al. (1997,2020), indicating these three in particular are critical.

### 3.3.4 Analysis

To identify the ecosystem services that are interacting with renewable energy systems, I created a 1km, 5km, and 10km buffer surrounding the point location of each power plant in Google Earth Engine Code Editor (Gorelick et al., 2017). Socio-ecological systems theory positions land interacts and impacts as highly complex and not limited to any set geographic limit. As I am seeking to determine the types of land cover in proximity to power plants rather than measure the scope of their impact, I will make use of all three buffer regions to provide this context.

I utilized the ESA WorldCover classification data to determine the types of land that each buffer area around energy sites are comprised of (ESA, 2022) through the Google Earth Engine Python package Geemap version 0.23.2 (Wu, 2020). Using Geemap, I wrote code which identifies the percent distribution of land cover type present at each renewable energy site (see Figure 7).



*Figure 7: Maps adapted from Google Earth Engine showing the location of solar power plant contained in the World Resources Institute Global Power Plant database (Byers et al., 2018), with a 1km buffer surrounding it. The left map is the Google Earth satellite background map, the right is the same map overlaid with the ESA land cover database. Retrieved from Google Earth Engine Code Editor (Gorelick et al., 2017)*

Following logic used in (ESA, 2022), each land cover type comprising of at least 12% of the buffer areas I created around each power plant was counted as present for that energy site, with 12% set as the threshold because it is the estimated uncertainty within the ESA Land Cover Dataset (Chaaban et al., 2022).

Using this methodology, I determined the presence and extent of each land cover nearby power plants. Combining these results with the information gathered from literature in Table 4, I identified the number of ecosystem services in proximity to each power plant and used data visualization tools to identify patterns of land and ecosystem service presence in regions where renewable energy is currently being produced. Finally, due to concerns around land competition between agriculture and renewable

energy that have been specifically stated in previous energy transitions literature, I calculated the median percent coverage agricultural land around each power plant site, as well as the average distance each plant is from the nearest agricultural region using SciPy version 1.10.1 (Virtanen et al., 2020) and NumPy version 1.24.4 (Harris et al., 2020) Python packages for calculations, and the Matplotlib version 3.7.1 (Hunter, 2007) Python package for plot production.

### 3.4 Results & Discussion

From the described methodology, the results are presented in three main parts. First, the distribution of land in proximity to different types of power plants is analyzed, revealing distinct spatial patterns dominated by tree cover, grassland, and agriculture. This spatial overview then provides the foundation for identifying and classifying the dominant ecosystem services each land type typically provides. Finally, once again making use of the land cover results, the proximity of these power plants to agricultural land is examined. Within each section, I first focus on granular results and then connect each finding to previous literature and broader implications. Together, these findings provide insight into how land use and ecosystem services intersect with energy infrastructure, offering a foundation for understanding potential environmental interactions and impacts.

#### 3.4.1 Land cover distribution

The land cover distribution of power plants provides the foundation for my results, and we see in Figure 8 that the distribution of land cover types within 5km of power plants varies by resource type. The box plots a-e in Figure 8 show the distribution of values for each category, from the lowest to highest fraction of land type “n” observed in the dataset. The height of these boxes indicates how varied

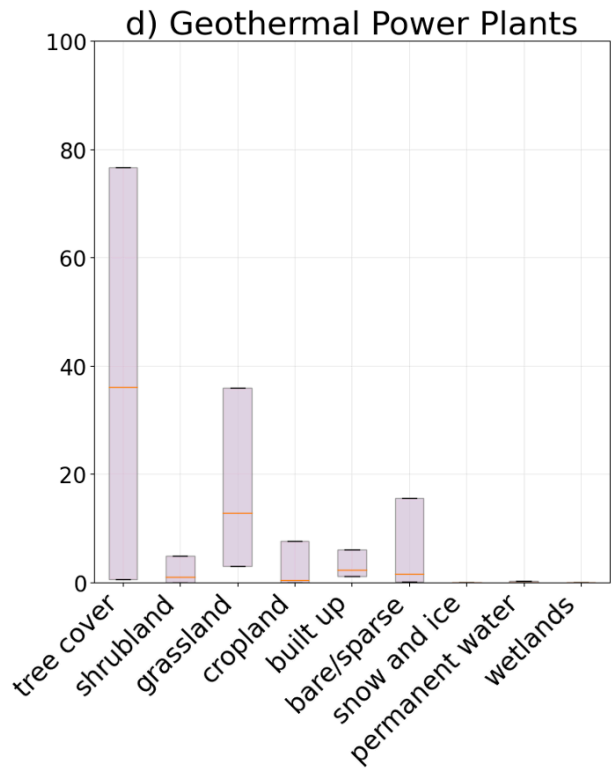
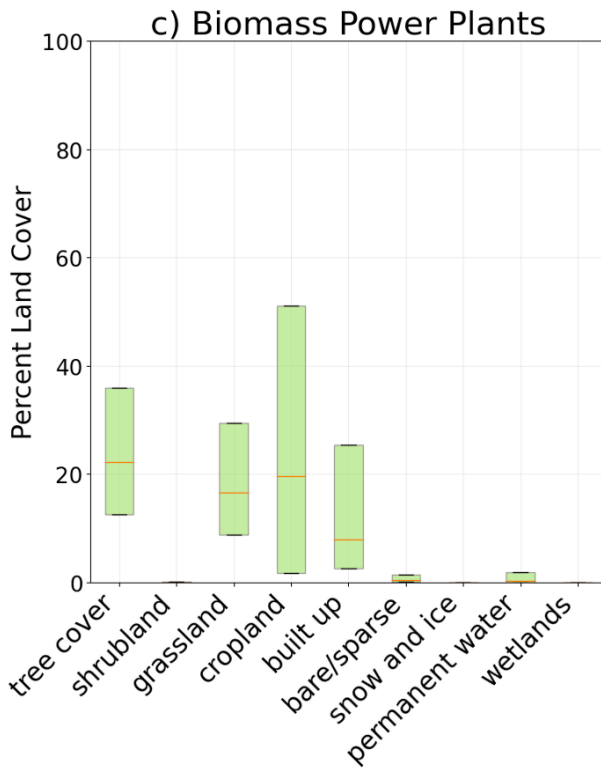
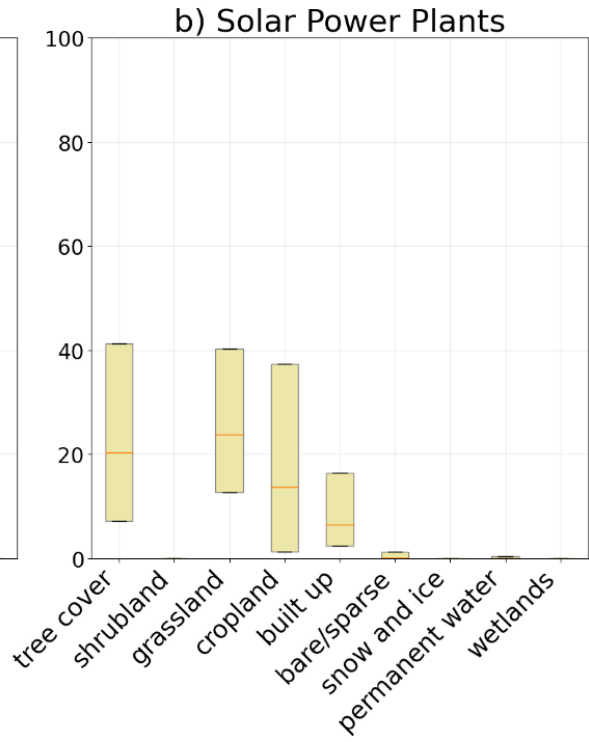
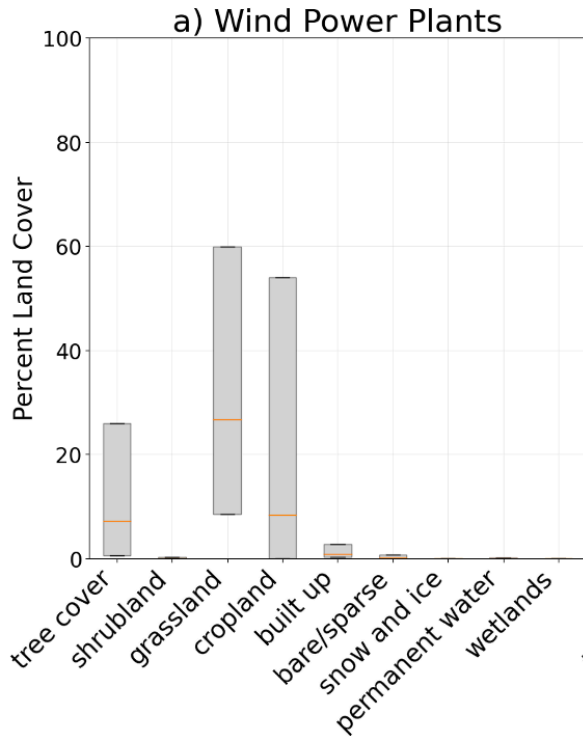
the landscapes that each type of energy has been developed on. Note that in Figure 8, the orange line which represents the average percent coverage of each land type in the region surrounding a power plant will not necessarily sum to 100%. This is because each land type represents a separate category.

Across all resources, the most prevalent land types are tree cover, grassland, and cropland, with considerably smaller values for other categories. As seen in Figure 8b and 8c, solar and biomass plants are surrounded by a similar land distribution of ~25% tree cover, ~20% grassland, with biomass appearing near a higher mean of cropland at 27% opposed to the 18% mean value for solar power plants. The findings for solar are in agreement with Hernandez et al. (2015) who found that 28% of solar installations in California, USA are located in croplands and pastures. Both solar and biomass have a relatively small box height, meaning the amount of tree cover and grassland near the power plants doesn't vary by more than 15% from the mean. This means that both solar and biomass are placed in relatively consistent environmental conditions, with less variation. Geothermal (7c), and hydro (7e) power plants have distinct land patterns as well. On average, 44% of the 5km surrounding geothermal plants is tree cover, although this value varies significantly, ranging from 2% to 76% within the dataset. All other land types surrounding geothermal plants are less consistently prevalent, with the second highest being grassland, sitting around 18%, followed by cropland at around 3%. Hydro sites are frequently surrounded by tree cover as well, with a mean of 59% of land within 5km. Following the same rank proportion as geothermal, the next most frequent land type for hydro power plants is grassland with a mean value of 17%, and then cropland with a mean value of 2%.

The greater range of land types around geothermal and hydro is surprising; because both hydro power and geothermal are more limited geographically due to the need for accessible, fast-moving water and specific geological conditions, it would be logical to assume there would be a narrower range of landscape configurations for which these power plants are feasible. This counter-intuitive result is

potentially due to most of the viable locations for geothermal and hydro energy production having already been developed, whereas other renewable energy resources such as solar or biomass are not limited in placement the same way. Since nearly all easily available regions for energy such as hydro has already been implemented, there would be a higher range of land types observed, which is demonstrated in my findings in Figure 8.

Finally, wind power (seen in Figure 8a) has the highest range and most unique land distributions, with grassland leading with a mean value of 26% of the land within 5km of power plants, but ranging from 12-64% within the dataset. Following grassland is cropland, with a mean value of 12% and ranging from 0-50%, and forest, with a mean value of 11% and ranging from 3-30%.



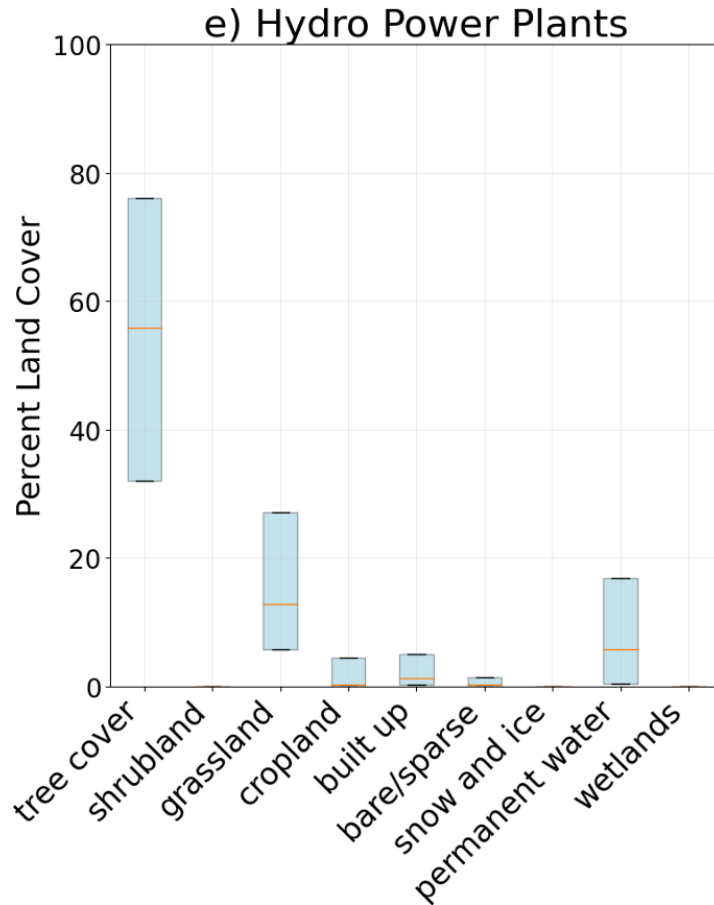


Figure 8: Distribution of percent land cover within 5km of biomass, geothermal, hydro, solar, and wind power plants. The orange line represents the mean value, with the height of each box plot capturing the interquartile range. The area below the line in each box represents the 25th percentile (also called Q1), the area above the line represents the 75th percentile (Q3), the value below which 75% of the data falls.

In terms of trends across all renewable power plants, tree cover is the most common land type surrounding biomass, geothermal, and hydro power plants. Grassland is the most common land type surrounding wind and solar power. This is likely due to solar and wind performing better when placed in an unobstructed area where solar radiation and wind gusts are stronger and more consistent, however bare/sparse vegetation and shrubland provide similar opportunities for these factors and would provide fewer ecosystem trade-offs but were rarely (if ever) observed. A clear trend seen across all power plant types in Figure 8 is the lack of surrounding land that is built-up or bare. For many of these, much of the

small (typically <3%) portion of the surrounding region that is considered built is the area of the power plant itself. Similar patterns are visible at the 1 and 10km range, with the most prevalent land cover type maintaining throughout the radius of nearby land examined as seen in Table 5.

*Table 5: Most prevalent land type within 10km of renewable energy power plants by resource*

<b>Renewable Energy Resource</b>	<b>Prevalent Land Type</b>
Biomass	Cropland
Wind	Grassland
Geothermal	Tree Cover
Solar	Grassland <1km, Tree cover 1-10km
Hydro	Tree Cover

The lack of renewable energy development in built or bare areas is concerning from an ecosystem and biodiversity perspective; the dominating land surrounding renewable energy plants is consistently trees and grassland, with very little energy produced in developed/ bare areas. The preference for ecosystem-rich environments is not necessary to produce energy and is instead largely a result of policy and land planning choices. Renewable energy has been well documented to be successfully generated in urban and built environments. Other scholars have focused on methods for making use of already developed or ecologically bare sites such as solar urban planning, the practice of implementing solar energy into the built environment (Amado & Poggi, 2014), or agrivoltaics where crops and solar are rotated to maximize land use and recovery (Moore et al., 2022). Very little energy in my findings is produced in developed/built areas. Most renewable energy is being produced in ecosystem-rich areas right now, and this trend is likely to continue if we don't shift the perspective of energy development to integrate ecosystem considerations.

### 3.4.2 Ecosystem Services

Applying the land results to the commonly associated ecosystem services found in Table 4, the count occurrence of ecosystem services associated with each land type surrounding every power plant was summed, seen in Figure 9. This plot provides a visual representation of the ecosystem services that the environment around power plants is likely providing. The two most prevalent categories near power plants are supporting and regulating. These are simultaneously the most nuanced to measure the health of, and when impacted negatively, have a trickle-down effect on provisioning and cultural services (Costanza et al., 1997). This suggests that the environmental and ecological impacts of renewable energy power plants may be more subtle to measure, and longer term, a future research direction which may be important in impact assessment in the coming years.

The most recurring ecosystem services nearby the power plants shown in Figure 9 were carbon storage, and food and drink. The contents in Figure 9 when replotted for each individual energy resource type (solar, hydro, etc.) were visually nearly indiscernible, with only slight variations. From the results in Figure 8, this is somewhat expected; while the order of prevalence varied slightly, 3 land types (tree cover, grassland, cropland) clearly dominate the geography around all resource types. With minimal differences between, the renewable energy power plant with the highest amount of ecosystem services within 10km is Hydro power, which agrees with the modelled results in Aziz (2023).

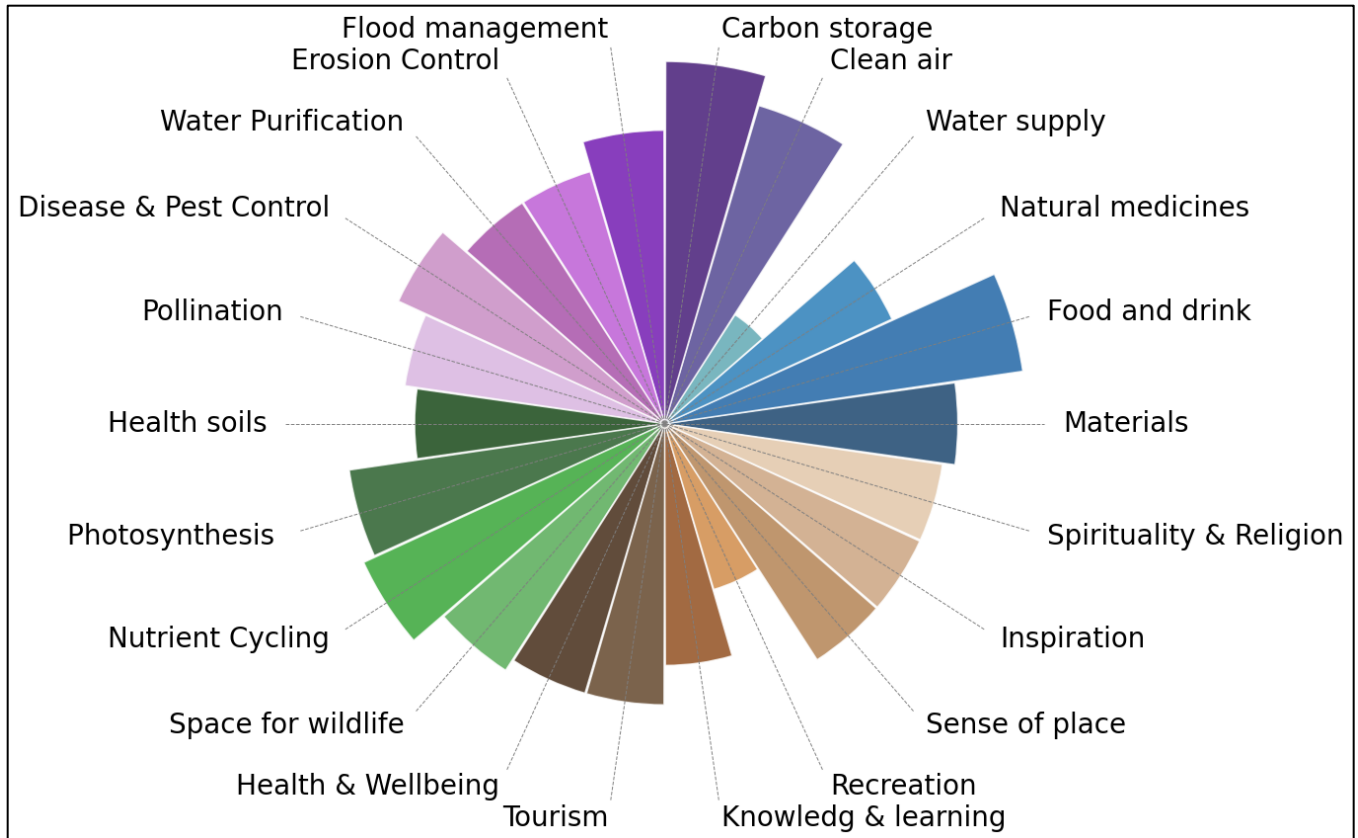


Figure 9: Qualitative visualization of the number of times each ecosystem service associated with a land type occurs across the entire renewable energy power plant dataset. The purple hues represent regulating services, the green hues represent supporting services, the brown cultural services, and the blue provisioning services.

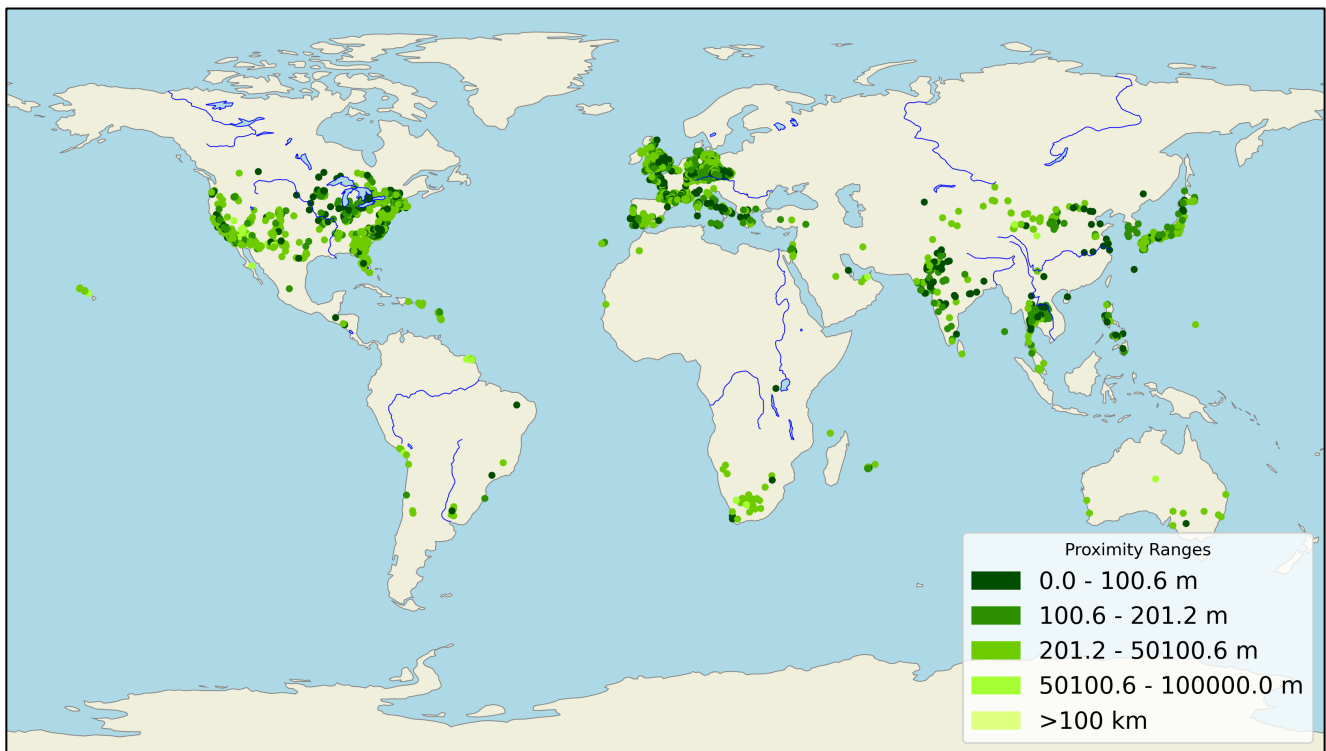
From my review of the literature, I found the three critical environments that typically provide the highest abundance of ecosystem services to be tree cover, wetlands, and permanent water bodies. To better understand the portion of land near renewable energy power plants that are critical in providing these services was calculated for each energy site and summed. I find that 16% of wind power plants, 20% of solar power plants, 73% of hydro power plants, 45% of geothermal power plants, and 16% of biomass power plants exist where over half of the surrounding area is a critical land type for ecosystem services. The implications of this are two-fold; the first being the risk of ecosystem services trade-offs, and the second being robust, wide-scale evidence of the co-existence of renewable energy projects within critical ecosystems.

Across energy types, 7273 power plants (39% of the entire dataset) had more than half of the land nearby as a critical ecosystem. Dai et al. (2024b) found that projects developed in areas with little human modification have a much lower land efficiency and result in higher land transformation than projects in areas with high human modification. Because energy systems are constructed, maintained, and do not operate in isolation, the ongoing use of renewable energy in proximity to these ecosystems will result in interactions and possible negative impacts of the services they provide.

Despite the concerns around ecosystem trade-offs, the fact that these energy systems are currently in proximity to valuable ecosystems may actually be in support of previous literature focused on synergies seen in Lamhamedi & de Vries (2022). Clearly, these environments are still existing next to functioning power plants, meaning that the benefits of both are not mutually exclusive within the nearby region of a renewable energy plant. Unlike fossil fuel or coal extraction sites, the land in proximity of solar or wind farms can still have biodiversity and provide valuable ecosystem services. In particular, the high portion of nearby land that remains as tree cover or grassland supports the theories in previous literature that renewable energy and ecosystem services can co-exist. Scholars such as Hanes et al. (2017) and Hernandez et al. (2019) have proposed a techno-ecological synergy framework for facilitating power plants with mutually beneficial relationships between technological and ecological systems. My findings provide empirical data in support of this type of framework, indicating that co-benefits already feasible in practice, and could be greatly increased if renewable energy - ecology synergies were prioritized in the engineering of power plants.

### 3.4.3 Agriculture

Turning now to the implications on agriculture, Figure 10 shows all renewable energy power plants within World Resources Institute Database, with each location depicted as a dot whose color corresponds to its distance to the nearest agricultural land. Figure 10 shows a significant portion of the power plants in the database are in close proximity to agricultural land.



*Figure 10 Proximity of all renewable energy power plants contained within the database to designated agricultural land.*

Table 6 shows the mean and median distances seen in Figure 10 categorized by resource type. Across all resources there is a high median proximity of agriculture to currently existing renewable energy resources, with Biomass the closest at only 200 m, and hydro power the furthest at ~647m. Because biomass is generated by growing and burning vegetation, the close proximity to cropland is

somewhat expected. Wind power is also commonly placed in or around cropland, as the wind turbines themselves occupy very little growing space, and the wide-open fields are conducive for wind power production.

*Table 6: median and mean distance to agricultural land by renewable energy resource type, as well as the distances at which 25 and 75% of the power plants is less than*

<b>Resources</b>	<b>Median distance to cropland (m)</b>	<b>Mean distance to cropland (m)</b>	<b>25<sup>th</sup> Percentile (m)</b>	<b>75<sup>th</sup> Percentile (m)</b>
Biomass	200	1487+/- 10074	30	384
Wind	201	3616 +/- 16464	30	1061
Geothermal	494	8170 +/- 25305	162	2083
Solar	201	1487+/- 10074	95	480
Hydro	647	9325 +/- 27167	247	1991

While this may initially appear to confirm the concerns around agriculture and renewable energy competing, it is important to note that at this stage, agriculture is not the current dominant land type near any renewable energy resource type. This indicates that agriculture is regularly nearby renewable energy, but not necessarily in competition yet, per say, as there are other land types in proximity as well.

The high degree of spatial overlap raises important considerations regarding potential interactions between renewable energy infrastructure and agricultural systems, especially considering they are both expanding currently to meet increasing demands. This proximity is likely to lead to both direct and indirect impacts; because they are both expanding, their growth could result in competition if proper land planning is not done. However, similar to the results for ecosystem services, this result also opens possibilities for encouraging synergistic land use strategies, such as shared infrastructure (Amado & Poggi, 2014) as potential techniques to minimize conflict in the coming years.

### 3.5 Conclusion

This study examined the current land and associated ecosystem services surrounding existing renewable energy power plants globally. Because land-energy interactions have been identified as important in protecting ecosystem services, understanding the impacts that these energy systems have is critical in informing decision-makers on how and where they should be implemented. To meet my research objectives, I made use of a global power plant database created by the World Resources Institute. I then overlaid the European Space Agency's (ESA) WorldCover global land classification map to identify the types of land cover in proximity to currently existing renewable energy projects and conducted a literature review to determine ecosystem services attributed to each land type in previous work, as well as their comparative importance to other land types for providing ecosystem services. As research into ecosystem service and renewable energy interactions are not well defined at this time, my findings aimed to describe the range of interactions rather than confirm a hypothesis.

Mapping the land distribution for solar, hydro, geothermal, wind, and biomass power plants, I found that tree cover, grassland, and cropland dominate the nearby environment, with solar and biomass located the most consistently, and geothermal, wind, and hydro showing larger variations. On average, less than 3% of the land in proximity to power plants was bare, and 4% was the built environment. These findings provide robust data on the current geographic choices for renewable energy development, and highlight that while urban renewable energy production is possible, land planning which prioritizes power plants be constructed in urban, developed or bare areas is not occurring in practice. The high portion of nearby land that provides ecosystem services means there is likely to be interactions particularly with supporting and regulating services.

Using the cropland within the geographic map, I found that all renewable power plants have a mean distance of less than 1km away from agriculture. This result confirms that agriculture and renewable energy are currently favoring the same geography in practice, and as both renewable energy and agriculture expand in the coming years, land planning may be necessary to ensure these do not compete.

These findings, both on ecosystem services and land composition, support the small but growing body of literature which emphasizes the need for land planning during the energy transition, both from an ecological and social lens. As Owens (1992) eloquently stated; “If land use planning is intended to influence the evolution of spatial structure, it must be legitimate for planners to be concerned with energy supply, demand and conservation”. My findings provide robust, global evidence that there is currently high co-location between renewable energy sites and land that provides valuable ecosystem services, and my results support the sentiment found in Amado & Poggi (2014), Hoffacker et al. (2017), Moore et al. (2022), Owens & Cowell (2002), Owens, (1992), and Poggi et al. (2018); the field of land planning must adopt the knowledge growing within the land-energy nexus field in order to minimize future environmental trade-offs during the energy transition.

The environmental impacts of renewable energy development have important implications for policymakers and industry leaders. As my literature review indicated, research into the environmental impacts of renewable energy is new and fragmented across resources, disciplines, and geographic focus. Without comprehensive understanding or regulation of renewable energy development, the energy transition risks repeating several of the pitfalls of the fossil fuel industry, choosing locations for energy production that have an unnecessarily large impact on both the people nearby and the environment it sits on (Rand & Hoen, 2017). Mobilizing the current understanding of the socio-ecological impacts of renewable energy development when choosing power plant locations is critical.

From my findings, some suggested future research directions include:

- Incorporating longitudinal land cover data to identify changes in land cover that occur with the development of different renewable energy power plants to understand their direct impact on land cover.
- Combining the large-scale land cover assessment methods found here with life-cycle assessments for the energy projects in order to determine the environmental impacts beyond the power plant sites themselves.
- Further exploration using qualitative methods to include social data on ecosystem services, perhaps from case studies.

A sustainable energy future depends on maximizing the benefits of renewable energy while addressing their environmental challenges. My findings emphasize the need for a balanced approach that prioritizes both clean energy expansion and environmental responsibility. *When* the renewable energy transition happens has been answered; it is unequivocally now. But in our race to avoid the disastrous impacts of fossil fuels, it is critical we also ask *where* the renewable energy transition goes.

## 4. A Comparison of Power Plants and Renewable Energy Clusters: Geographic and ecosystem implications for decentralized energy systems

### 4.1 Introduction

Fossil fuel use has resulted in an increase in greenhouse gases in the atmosphere, causing an unprecedented warming of the climate, resulting in extreme weather, rising sea levels and loss of biodiversity, necessitating a transition to low-carbon energy systems. (Akhmat et al., 2014). By transitioning away from fossil fuels to low-carbon systems, the environment and climate can be protected.

In Chapter 3, I discussed the geographic factors of utilizing renewable energy. However, there are other challenges in addition to these factors, one of which being that renewable energy resources face limitations to generating reliable power (power that can withstand instability or uncontrolled events) (Hoicka et al., 2025; Muruganantham et al., 2017).

Resource types such as wave, wind, and solar power require specific weather conditions for energy to be generated (e.g. regular solar radiation). As a result, a single-technology energy system using these resources struggle to provide consistent, reliable power. Cumulatively, land requirements, energy resources that are dependent on climate conditions, and unevenly distributed growth in energy demand make the low-carbon energy transition a spatially variable process (Bridge et al., 2013; Poggi et al., 2018; Sliz-Szkliniarz, 2013). Wind and solar can be placed where there is daylight and a wind current, avoiding the location challenges that sources like hydro and geothermal face. However, they are

directly dependent on weather, meaning that power is only generated when there are favorable climate conditions. Combustible fuels (gas, oil, biofuel) can be stored in their “raw” state, but renewable resource such as hydro, solar, and wind are immediately converted to electricity which then requires storage techniques such as batteries. Single-resource renewable energy systems in particular face significant difficulties with providing reliable power.

The complex factors of an energy transition has led to a unique diffusion of technological innovations, acknowledged in literature as early as 2000 (Jacobsson & Johnson, 2000), including energy systems that use a portfolio of multiple energy types rather than relying on just one (van der Kroon et al., 2013). In some cases, the use of multiple resources can create complementarity, which refers to using a variety of different variable renewable energies at the same time to smooth outpower production and increase the stability of an energy system, where a household or grid can rely on one energy source when another is not available (e.g. making use of a generator when there is decreased solar power during peak demand) (Hoicka et al., 2021, 2025). This technique has been described as clustering.

In simplest terms, clusters can be described as an agglomeration of related innovations, objects, or organizations in geographic proximity which benefit from co-location and collaboration. Clustering has begun to appear within the modelling and implementation of different renewable energy systems (Bekirsky et al., 2022; Hoicka et al., 2025). Clustering and co-locating multiple types of energy technology is a possible method of addressing the challenges with location, power density, and reliability. (Lowitzsch et al., 2020) describe renewable energy clusters as “the complementarity of different energy sources, flexibility, interconnectivity of different actors and bidirectionality of energy flows” working to provide reliable electricity.

A crucial aspect of the energy transition will be addressing the challenge of integrating highly variable energy sources such as solar and wind power (Hoicka et al., 2025). On the demand side, social change, cross-commodity sharing, and prosumership (a prospective consumer who is involved in the design, manufacture, or development of a product or service) can also contribute to creating a more reliable energy system. Because renewable energy clusters by-definition theoretically include a mosaic of actors, institutions, and technologies, their design could assist in achieving a balance of available and variable sources. As complementarity and diversity in terms of energy portfolios have been expressed as essential for successful energy sovereignty in rural and remote communities (Leonhardt et al., 2023), renewable energy clusters are potentially well-positioned to address many of the justice challenges that renewable energy transitions face, as well as some of the challenges that fossil fuels systems have failed to solve.

Decentralized energy systems such as renewable energy clusters also present a potential opportunity to address current injustices within the fossil fuel industry. Beyond environmental concerns, there are systematic inequalities and injustices within current fossil fuel energy system, and the low-carbon energy transition presents an opportunity to disrupt them (Levenda et al., 2021; Wilson, 2018), although this result is not guaranteed (Temper et al., 2020). Despite the potential that clustering renewable energy technologies has for improving reliability of single-energy technology systems, there is no current understanding of how they compare ecologically.

Because land-energy interactions have been identified as important in protecting ecosystem services, understanding the impacts that these energy systems have is critical in informing decision-makers on how and where they should be implemented. Scholars in the land-energy nexus field such as Aziz, (2023), Dai et al. (2024b), and Hernandez et al. (2014) have consistently recommended that future

work be focused on expanding both the geographic scope of ecosystem-energy interactions as well as including renewable energy projects that use multiple resources. Because land-energy interactions have been identified as important in protecting ecosystem services, understanding the impacts that these energy systems have is critical in informing decision-makers on how and where they should be implemented. A broader perspective that considers the land implications of both single-technology power plants, and more recently emerging clustered energy systems is needed. Here, I seek to compare the impacts that power plants have with renewable energy clusters.

As Hoicka et al. (2025) stated:

During a climate emergency, the risks of disruptions to social ecological systems are increasing with greenhouse gas emissions. Shifting our understanding of how a renewable energy transition occurs as landscape change, quite literally on the ground in practice, as it interacts with communities, justice, governance and ecosystems, can support the replication of renewable energy infrastructures and acceleration of renewable energy uptake. (p14)

This chapter seeks to answer the question: *To what extent does clustering renewable energy change the impact that renewable energy systems can have on ecosystem services?* To address this, I compare the geography and ecosystem interactions of single technology renewable energy power plants with projects that cluster multiple renewable resources. Because of the theoretically posited ability for renewable energy clusters to provide place-based, reliable power, I hypothesize that the environmental

impacts are lessened, and they emerge in a wider range of geographic circumstances, emerging more based upon local demand rather than land convenience as seen in Chapter 3 with major power plants.

As renewable energy production increases, providing policymakers with accurate on-the-ground knowledge of how clusters operate in practice will become critical to facilitating a low-carbon transition. By identifying broader trends in how and where renewable energy clusters are interacting with other vital ecosystem services, we can contextualize their role in the energy transition and support policymakers and global leaders in creating pathways of access for communities to implement these systems.

## 4.2 Methods

To compare the types of land that renewable energy clusters and single-technology renewable energy power plants are on, I analyzed satellite-derived land cover classification land from the European Space Agency, a growing global database of renewable energy clusters created by the ReSET CoLab, and the World Resources Institute Global Power Plant Database. Due to the difference in size and scope of each energy dataset, I ran a series of statistical tests to confirm their environments could be compared and then applied the buffer zone and ecosystem assessment methodology seen in Chapter 3 to the renewable energy clusters database.

### 4.2.1 Clusters Database

Since 2023, I have contributed to the development of a dataset that has been under development by researchers in the RE-Imagining Social Energy Transitions (RESET) CoLab under the direction of Canadian Research Chair Dr. Christina Hoicka to identify renewable energy clusters globally. The dataset framework has been defined drawing from Hoicka et al. (2025) and utilizes a mixed methods data-driven approach to identify existing cases of renewable energy cluster projects around the world, gathering information from reports, peer-reviewed articles, media, and databases. For each cluster found, its operational date, general location, actor, and resource information were documented, relying on targeted searches for supplemental information if needed. Within this dataset, there are many clusters that had different types of features, including the use of prosumership, flexibility, and fossil fuels alongside renewable energy technology.

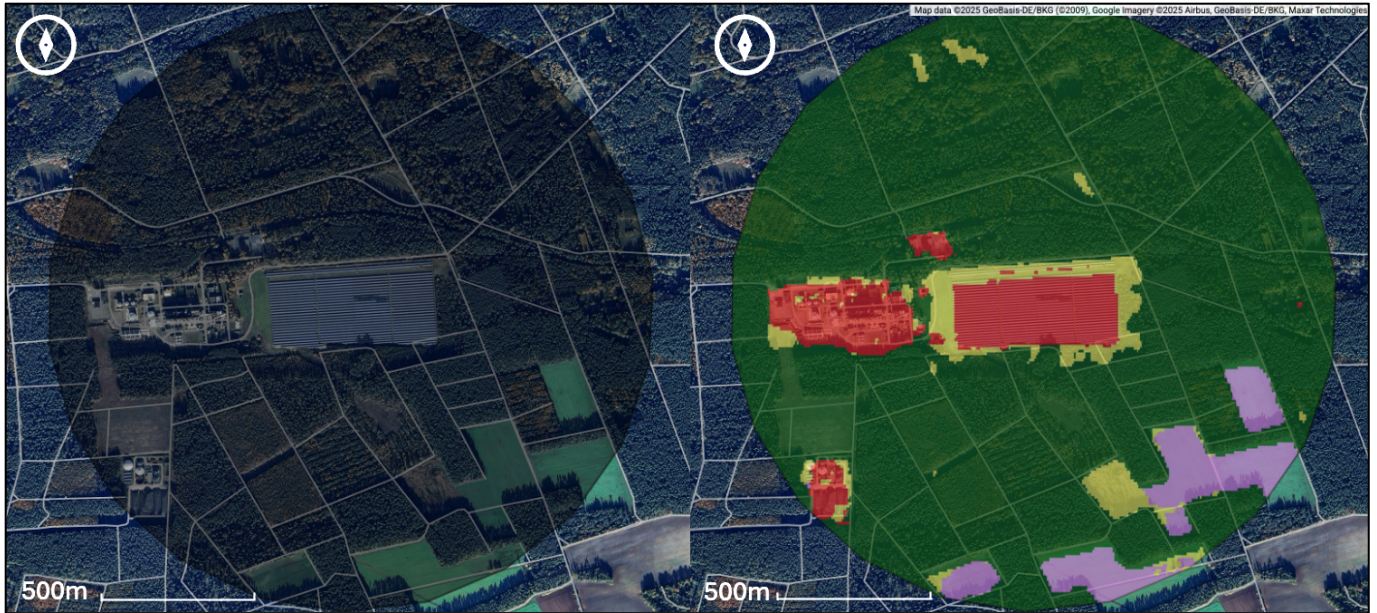
I made use of this dataset by adding spatiality, identifying the specific locations of each cluster and converting the dataset from its current CSV format into a geospatial dataset, which required all power plants be geolocated. I used similar techniques to geolocate the renewable energy clusters as seen in Byers et al. (2018) via the Pandas Python package (McKinney, 2010). This required significant effort because most geolocation information is not directly available from the original data sources. During the coding process, as much geographic information provided in the source was documented as possible when available (Country, jurisdiction, region, latitude and longitude). In most cases, the city or town scale information was included, but not the coordinates. From there, targeted web searches using the energy types, capacities, year established and location information were conducted to find the exact coordinates, relying heavily on online sources. Finally, renewable energy clusters that had no web

information on their coordinates were manually located via searching the region in Google Earth Explorer satellite imagery (Gorelick et al., 2017).

Because the clusters identified within the current database are discrete places connected to longitude and latitude, a spatial file format was required for my research purposes. To use for geospatial purposes, I wrote a software package in Python that allows user input of the clusters CSV file to create an updateable GeoJSON as output, adding each cluster as “POINT” vector geometry in the geospatial file, with each variable added as an attribute of that vector.

#### 4.2.2 Ecosystem Service Assessment

To assess the potential ecosystem service interactions with renewable energy clusters, I identified the land cover types surrounding each renewable energy cluster by using the previously described European Space Agency’s World Cover V200 dataset (see Figure 11) (ESA, 2022) and by repeating the same spatial methodology used on the power plant database in Chapter 3.



*Figure 11: Maps generated showing the location of a renewable energy cluster contained in the ReSET CoLab's renewable energy cluster database, with a 1km buffer surrounding it. The left map is the Google Earth satellite background map, the right is the ESA land cover database. Retrieved from Google Earth Engine Code Editor (Gorelick et al., 2017)*

I then applied my previously completed literature review which assessed the ecosystem services of each land type as seen in Chapter 3) to the land cover distribution for each renewable energy cluster to identify the ecosystem services with the highest risk of impact.

### 4.2.3 Analysis

In order to compare results found in Chapter 3 with my findings of ecosystem service interactions for renewable energy clusters, both datasets required statistical comparison, which I completed using Python packages SciPy version 1.10.1 (Virtanen et al., 2020) and NumPy version 1.24.4 (Harris et al., 2020). The World Resources Institute Global Power Plant Database (Byers et al., 2018) contains approximately 30,000 power plants (18,695), with capacities up to 22,500 MW. In contrast, the renewable energy clusters database contains 511 sites with capacities only up to 3000 MW. The difference in capacities is important because the scale of infrastructure between a 100kW wind

turbine compared to a 10MW wind farm could impact the way an energy site interacts with the nearby environment. The difference in number of data points is important because the size of your sample can artificially influence a given p-value if not adjusted for. Due to the substantial difference in size and scale, statistical analysis was required to determine if and how I can compare the results between the two datasets.

To determine which statistical analysis to run, I used a Shapiro-Wilk test to assess if the data is normally distributed (Wheeler et al., 2013). The mean capacity,  $\mu$ , for renewable energy clusters is 28.60, with a larger standard deviation,  $\sigma$ , of +/-163.20 MW. A Shapiro-Wilk test  $p < 0.0001$ , confirms what the large standard deviation already indicates: that the data is not normally distributed. For the global power plants database,  $\mu = 73.60$  with  $\sigma +/- 352.86$ , and a Shapiro-Wilk test value of 0.1542 and  $p < 0.0001$ . This value means that the null hypothesis of the Shapiro-Wilk test can be rejected, and the capacity of the energy projects in this database is also not normally distributed, meaning I cannot use parametric statistical methods based on normality assumptions.

Because the datasets are not normally distributed, I utilized a Mann Whitney-U test to determine if the datasets can be compared, which is a non-parametric test used to compare two independent groups to determine if one group tends to have larger values than the other (Sheskin, 2020). To address the differences in sample size between the two datasets, I conducted the Mann-Whitney-U test on a random subset of the power plant database equal in size to the renewable energy clusters database 10,000 times, a statistical technique known as bootstrapping (Davison & Hinkley, 1997). Because the statistical analysis with both full datasets showed their size may have impact on the comparability to their results, I limited the power plant database to contain only power plants that had equal to or less capacity than the maximum value in the clusters database (3000 MW), and ran 10,000 sub-samples, seen in Figure 12:

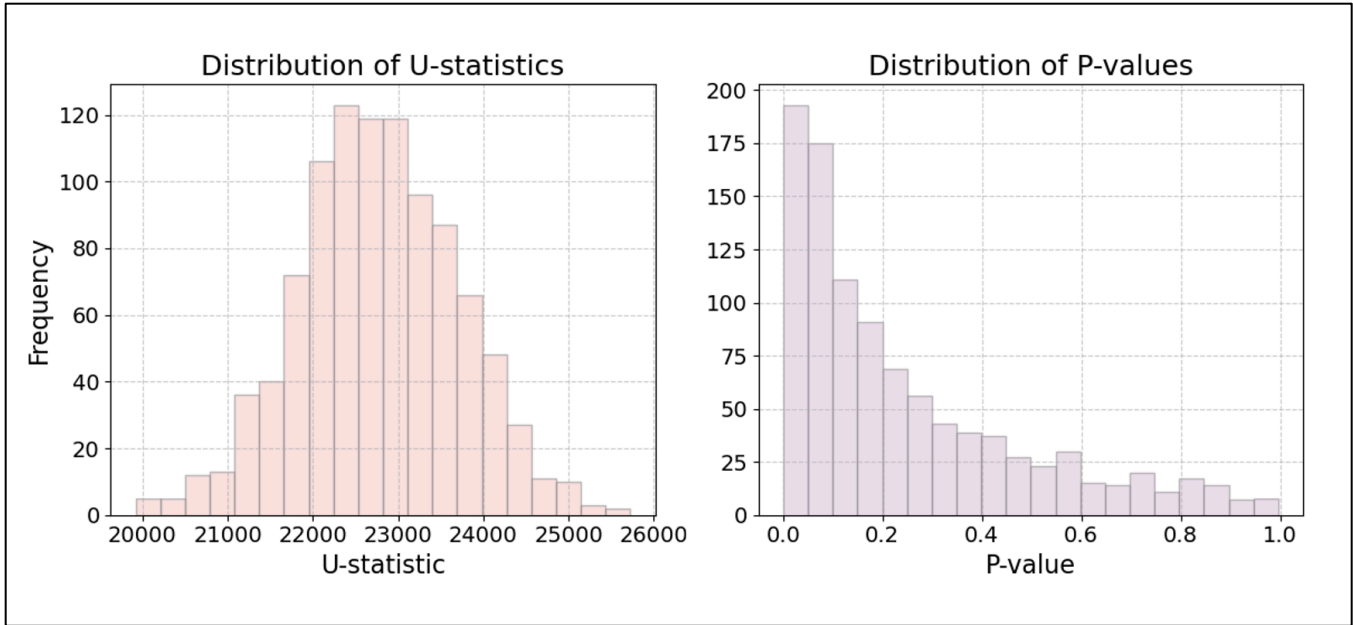


Figure 12: Distribution of U statistics and p values of Man-Whitney U test conducted 10,000 times on randomly selected 511 power plants and the renewable energy clusters database.

From this analysis, I found a value of  $p < 0.5$  (mean  $p = 0.26$ , see Figure 12). However, if the p-value from the Mann Whitney-U test is small, but effect size is small, the difference is likely to be meaningful in practice, in which case a comparison is still appropriate (Agathokleous, 2022). In order to check this, I ran a Common Language Effect Size test, which shows the probability that a random value from Group 1 is larger than a random value from Group 2, and a Cliff's Delta test which measures the strength of difference between two distributions (Agathokleous, 2022). The measured Common Language Effect Size between the two samples is 0.467, meaning there is ~47% chance that a randomly selected observation from the power plant database is greater than a randomly selected observation from the clusters database, which is within an appropriate range for the two datasets to be considered comparable (for  $0.4 < x < 0.6$ ) (Guskey, 2019). Finally, the Cliffs Delta test yields a value of  $\Delta = -0.076$ . For  $\Delta < 0.147$  (Meissel & Yao, 2024), the difference is considered small between groups as their values overlap significantly.

As a result, by limiting the power plant database to projects with capacity <3000 MW (the maximum measured capacity of a cluster), the two datasets are similar enough for their interactions with ecosystem services to be compared. To compare the results of the renewable energy clusters and power plant datasets, I generated a multi-dimensional spider plot for the land types of each and compared the density of energy sites vs distance to agriculture using the Python Matplotlib package version 3.7.1 (Hunter, 2007).

### 4.3 Results & Discussion

Building on my findings from Chapter 3, the results presented offer a comparative analysis between the original dataset and a second, independent dataset. The comparison is structured in three parts. First, land distribution in proximity to various power plant types is examined across both datasets, highlighting notable differences in spatial patterns. Next, the dominant ecosystem services associated with each land type are identified and compared, with attention to how differences between dataset locations leads to fewer ecosystem services near renewable energy clusters. Finally, the proximity of power plants to agricultural land is assessed across both datasets to explore how differing land cover representations affect conclusions about the interaction between energy infrastructure and surrounding land use. This comparison provides insight into the robustness and variability of spatial patterns and ecosystem relationships across data sources.

### 4.3.1 Land Cover Distribution

The visualization of the types of land in proximity to renewable energy clusters can be seen in Figure 14. While there is still a high occurrence of tree cover and grassland, there is substantially more built-up and bare environment present than seen in the results for the single technology power plants in Chapter 3.

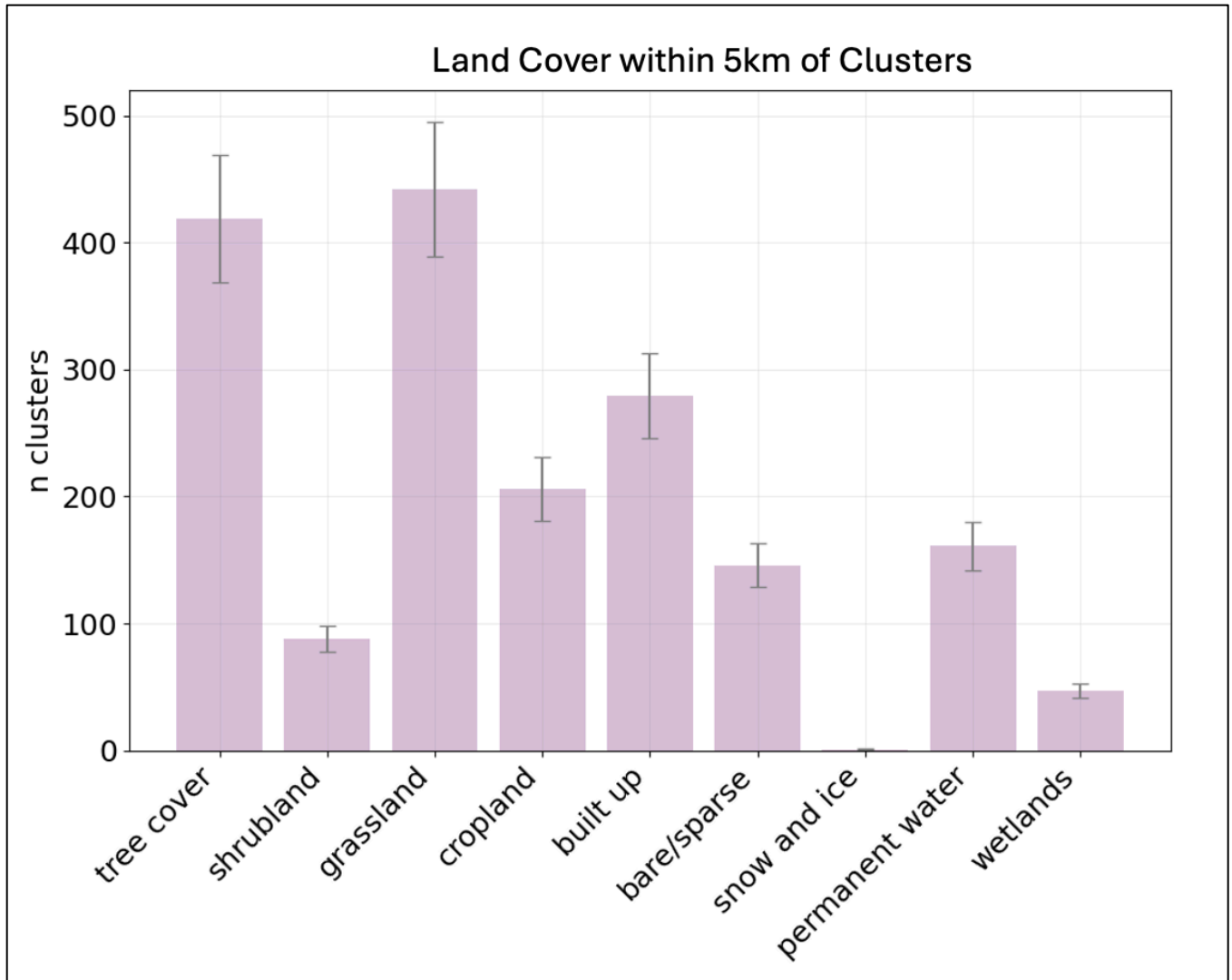


Figure 13: Binned count occurrence of different land types in the 1km surrounding renewable energy clusters

The rank proportion percent-wise within 5km of clusters is: tree cover, built-up, grassland, cropland, bare/sparse, shrubland, permanent water, wetlands, and snow and ice. This differs from all single-technology power plants, which consistently had tree cover, grassland, and cropland as the most prevalent nearby land cover types.

A weighted visualization of the distribution of land types can be seen in Figure 14 for power plants (a) and renewable energy clusters (b). Figure 14a shows that in general, power plants have a larger impact on grassland cropland and tree cover. This can be seen especially for wind plants in Figure 14a, which are substantially further into the grassland region of the spider plot. This means that a large portion of land surrounding wind power plants is grassland. 14b shows a much tighter layering of energy types, all with overlapping and similar shapes. This is in part because each cluster is represented multiple times, once for each energy type it contains. However, using the white center point as a reference, the clusters are visibly consistently surrounded by a higher degree of land that is bare, built, or sparse in vegetation in comparison to the power plants seen in 14a. Resources such as geothermal, and hydro present in similar shapes across both 14a and 14b, indicating that there is consistency in where they are placed. This result is not surprising and supports the validity of my findings, as both resources require specific environmental contributions that impact the land cover (hydro requires running water, and geothermal requires a geothermal vein which cause specific climates nearby). Overall, the land cover impact of power plants seen in Figure 14a is over a greater variety of land types and more focused in land types that have higher ecosystem services such as grassland, tree cover, and cropland than renewable energy clusters.

The finding in Figure 14 agree with findings from Aziz (2023) which state renewable energy sites that use hydropower have the largest environmental impact, both for renewable energy clusters and power plants that have hydro power (blue in Figure 14a and 14b)

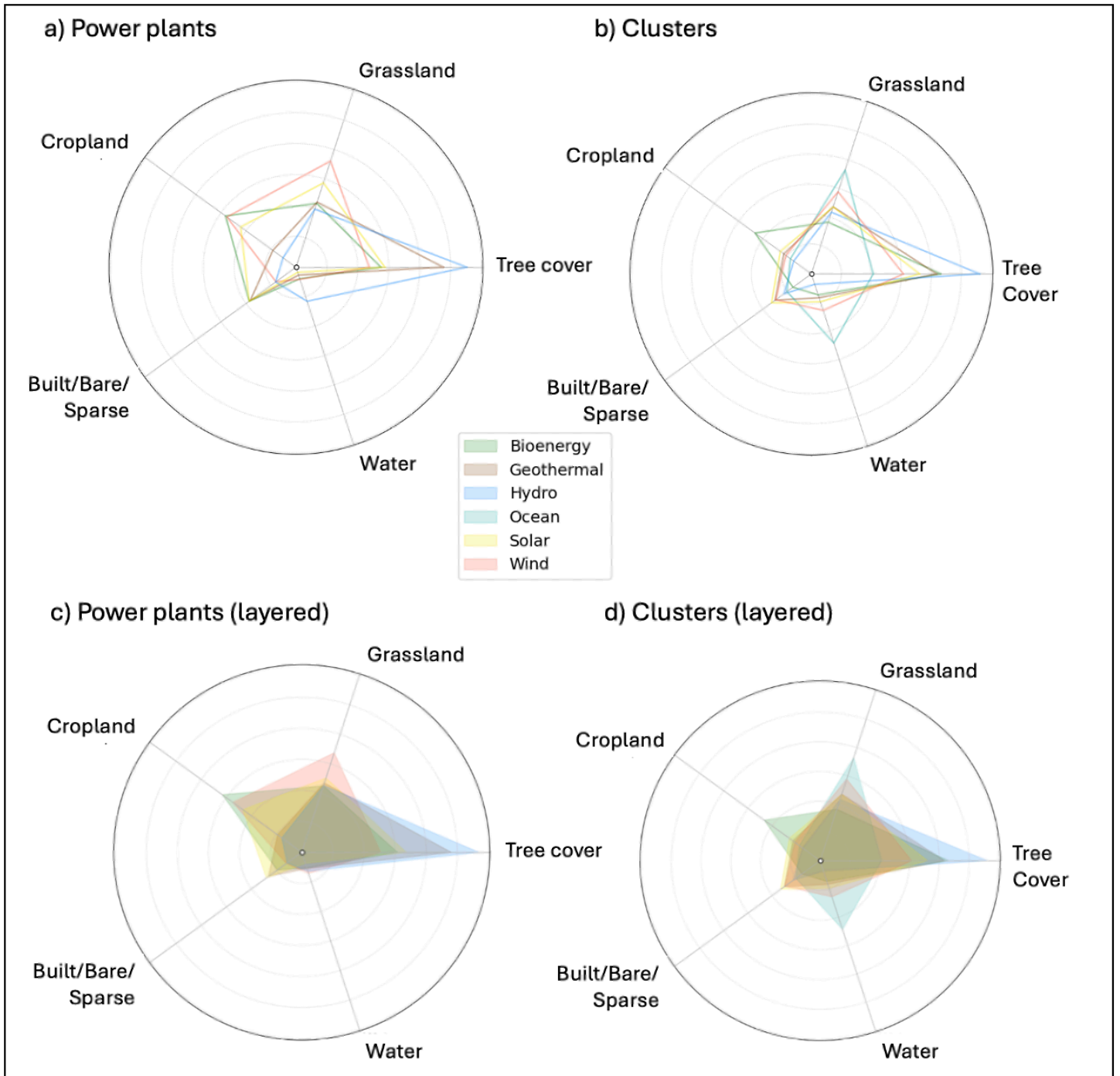


Figure 14: Spider plot depicting the fractional weighting of land cover near renewable energy power plants (a,c) and shared renewable energy clusters (b,d). Each type of energy is represented by a geometric shape determined by the average land composition within 5 km of the energy site, with the area the shape takes up on each axis indicating the prevalence of its corresponding land type. The white point in the center represents 0% coverage, and the largest ring in (a,c) and (b,d) represent 50% coverage.

### 4.3.2 Ecosystem Services

Figure 15 shows ecosystem services within 5 km of different energy sites (a) power plants, and (b) renewable energy clusters, averaged across each respective data set. In Figure 15a, the average ecosystem services surrounding power plants is unevenly distributed, with a much higher number of food and drink, carbon storage, and nutrient cycling services in particular. On average, food and drink services are identified 2.5 times per power plant which means that two to three ecosystems nearby typically provide food and drink. This aligns with the high prevalence of forested area and grassland in the data set.

For renewable energy clusters in Figure 15b, we see a much more even spread of ecosystem services across the average energy site as well as lower values than seen for power plants. This is likely due to the higher portion of bare land or built environment near renewable energy clusters, which do not provide ecosystem services. The only ecosystem service which appears on average more than twice near renewable energy clusters is food and drink, which is not only the most common ecosystem service across land types but is also prevalent for the land types near cluster sites seen in Figure 14. This supports findings from Dai et al. (2024b) who found that projects developed in areas with little human modification have a much lower land efficiency and result in higher land transformation than those in areas with high human modification, resulting in higher risk of trade-offs with ecosystem services.

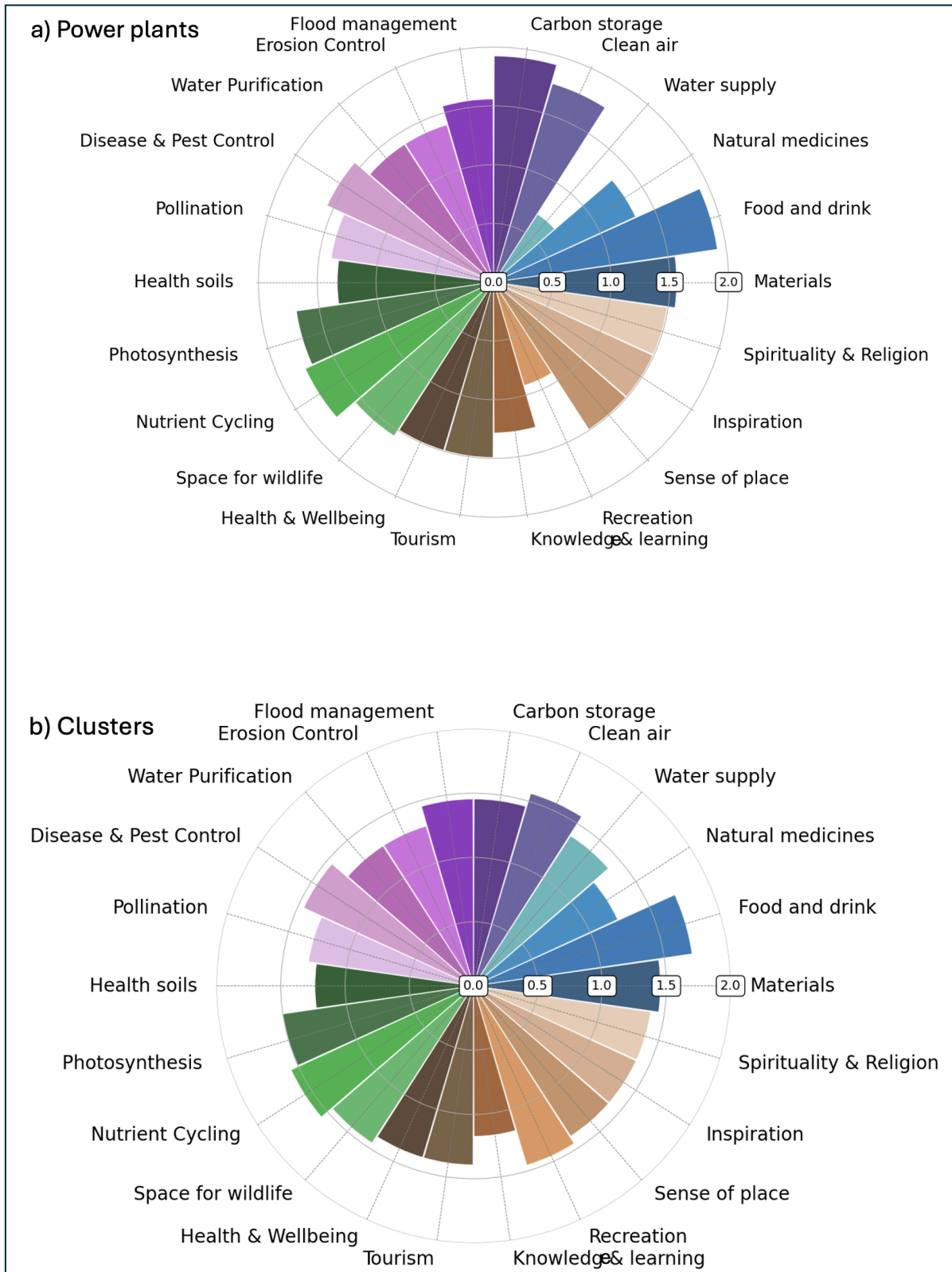


Figure 15: Qualitative visualization of the number of times each ecosystem service associated with a land type occurs across the entire renewable energy power plant dataset. The purple hues represent regulating services, the green hues represent supporting services, the brown cultural services, and the blue provisioning services.

### 4.3.3 Agriculture

Figure 16 shows the density of energy sites by distance to agriculture for both renewable energy clusters and power plants, with renewable energy clusters further and more varied in distance from cropland on average. The height of Figure 17 shows that power plants are typically in a much narrower range of distances to agriculture than clusters which seemed to be placed in a greater variety of distances.

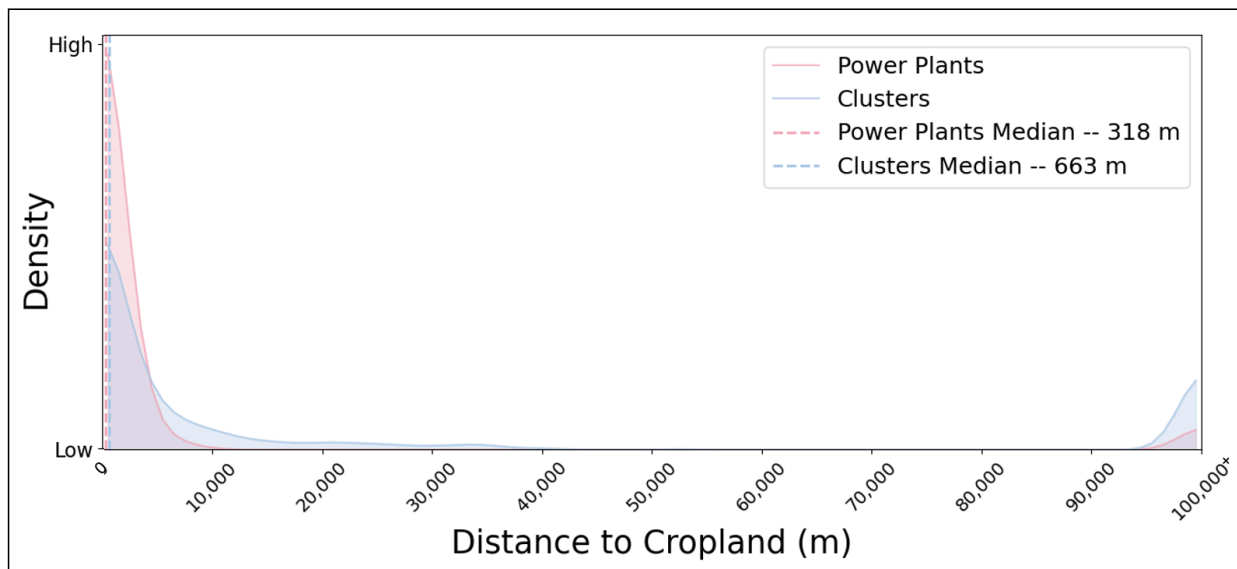


Figure 16: Smoothed histogram plot of the density vs distance to agriculture for both power plants (pink) and renewable energy clusters (blue).

The mean distance to cropland for renewable energy clusters is 15913 m and the median 663 m. This is notably smaller than the case for power plants which as seen in Chapter 2 have a mean distance of 5053 and a median distance of 318 m (see Table 6 for a breakdown by resource type). Hoffacker et al. (2017) argues that sustainable land management in the future hinges on how energy, agriculture, and water resources are managed within landscapes. The authors

encourage solar energy development on “nonconventional” surfaces over competing with viable agricultural land, arguing that this approach could alleviate competition for land amongst farmers, raise property values, enhance air quality, and generate clean energy for and in local communities. My findings show that the concerns around competition with agriculture stated in Hoffacker et al. (2017) as well as Hernandez et al. (2019) and Pilogallo et al. (2019) may not apply, at least to the same degree, for renewable energy clusters. While my findings are exploratory, they do support Hoffacker et al.’s argument in support of nonconventional energy installations which are more typical for renewable energy clusters, and have resulted in these systems being located near fewer critical ecosystems.

#### 4.4. Conclusion

In this chapter, I examined the extent that clustering renewable energy changes the impact that renewable energy systems can have on ecosystem services. Because land-energy interactions have been identified as important in protecting ecosystem services, understanding the ecological impacts of renewable energy clusters compare to those of single-technology renewable energy power plants is critical in informing decision-makers on what to consider when selecting the location and configurations of energy sites

To meet my research objectives, I made use of a global power plant database created by the World Resources Institute and overlaid the ESA WorldCover global land classification map to identify the types of land cover in proximity to current renewable energy clusters. I then ran a series of statistical tests to confirm the renewable energy clusters database and power plant

database were similar enough to be analyzed together, and once I found they were, compared the results for renewable energy clusters to my findings in Chapter 2 for single-technology power plants.

Comparing the land distribution near renewable energy clusters to single resource power plants, I found that renewable energy clusters are more frequently in proximity to regions that do not provide ecosystem services such as bare or built environments, than power plants. These findings provide empirical data on the current geographic choices for renewable energy development and show there are differences in how renewable energy clusters and single resource power plants are interacting with the nearby environment. My results highlight that while urban renewable energy production is possible, land planning which prioritizes power plants be constructed in urban, developed, or bare areas is likely occurring more for the construction of renewable energy clusters than other renewable energy sites. Additionally, renewable energy clusters are occurring at a greater distance to agriculture than other renewable energy sites, meaning the agricultural concerns of renewable energy development seen in previous literature (Hoffacker et al., 2017; Pilogallo et al., 2019) as well as in Chapter 3 may not apply to the future development of renewable energy clusters, however at this stage given the newness of knowledge on renewable energy clusters and the relatively small sample size (n=511), it is difficult to determine.

Hoicka et al. (2025) argues that place-based approaches to renewable energy landscapes, such as renewable energy clusters create local value, incorporate multifunctionality and decentralisation, mitigate harm for ecosystems, and address justice and local resilience (Hoicka et al., 2025). My findings indicate that renewable energy clusters are currently operating in more

diverse landscapes than any one type of renewable energy power plant, supporting previous literature that theorized renewable these clusters are able to provide place-based power in a variety of circumstances (Hoicka et al., 2021).

My results support the sentiment found in Amado & Poggi (2014), Hoffacker et al. (2017), Moore et al. (2022), Owens & Cowell (2002), Owens, (1992), and Poggi et al. (2018); the field of land planning must adopt the knowledge growing within the land-energy nexus field in order to minimize future environmental trade-offs during the energy transition. Scholars such as Bridge et al. (2013) have argued that considering the spaces, places, and people that will be impacted by the renewable energy through energy geography can result in a higher chance of success of a transition that does not perpetuate systems of inequality and can clarify how a low-carbon future can be realized. I argue that while this is true, there is currently a lack of focus on the environmental aspect of the “places” of renewable energy, and the resulting consequences on the spaces and people near renewable energy development.

As Bridge et al. stated, because of the unique circumstances and needs of different locations and communities, the energy transition will be a spatially explicit process. Understanding how different types of low-carbon energy systems interact with and impact the other ways in which we enjoy and benefit from the natural environment will be critical in informing decision-makers which low-carbon energy site is the right choice for their circumstance. My findings highlight how important a balanced strategy to the energy transition that doesn't compromise the integrity of our ecosystems is needed. As renewable energy generation rapidly continues to increase, we must consider the local social and ecological context to each unique circumstance of development, rather than applying one-size-fits-all approaches.

This will mean carefully evaluating local ecosystems, community needs, and resource availability to ensure that each energy project results in as few trade-offs as possible.

## 5. Discussion and Conclusion

This chapter synthesizes the key findings from the two research papers and situates them within the broader academic and practical context. My research was guided by the overarching question: *in what ways are renewable energy systems interacting with ecosystem services?* While my results do not directly address interactions of renewable energy systems with ecosystems as in my research question), they provide a first step towards addressing this issue. From analyzing both a robust dataset of renewable energy power plants in Chapter 3 and a new, growing database of renewable energy clusters in Chapter 4, I found that renewable energy systems are interacting with spaces that provide all 22 ecosystem services. By identifying these broader trends in how and where different renewable energy systems, both single technology and clustered, are interacting with other vital ecosystem services, my findings can support policymakers and leaders in creating pathways of access for regions to implement these systems while considering land cover implications.

### 5.1 Key Findings

From my initial, exploratory research of the land cover and ecosystem services in proximity to currently existing renewable energy power plants, I found that tree cover, grassland, and cropland dominate the nearby environment; on average, less than 3% of the land in proximity to power plants was bare, and 4% was the built environment. My results also showed that renewable power plants have a median distance of less than 1km away from agriculture. This result confirmed previous research highlighting concerns that agriculture and renewable energy are currently favoring the same geographic areas (Hernandez et al., 2015; Hoffacker et

al., 2017). As both sectors continue to expand in the coming years, coordinated land planning may be necessary to prevent future competition. My findings highlight that while urban renewable energy production is possible, land planning which prioritizes power plants be constructed in urban, developed or bare areas is not occurring broadly in practice.

Following my exploratory research on single-technology power plants, I replicated my methodology on renewable energy clusters and conducted a statistical comparison of the land cover between datasets. Through a Cliffs Delta and Common Language Effect Size test I confirmed that the two datasets could be compared, and found that renewable energy clusters occurred more frequently in proximity to built or bare environments, and were placed further away on average from agriculture, with a median distance of 663 m for renewable energy clusters in comparison to the median distance of 318 m for power plants. My findings showed that the concerns around competition with agriculture stated in Hoffacker et al. (2017) as well as Hernandez et al. (2019) and Pilogallo et al. (2019) may not apply to the same degree for renewable energy clusters. While my findings are exploratory, they do support Hoffacker et al.'s argument in support of nonconventional energy installations which are more typical for renewable energy clusters and have resulted in power plants located near fewer critical ecosystems.

The high portion of nearby land that provides ecosystem services means there is likely to be interactions, particularly with supporting and regulating services. My results confirm findings from Hernandez et al. (2014) who stated the fields of energy transitions and ecosystem services are not integrated. While previous scholars have stated that using bare and built-up areas for energy production is feasible, my findings show that these types of land

don't account for as significant a portion of development as potentially theorized by other scholars, implying that current geographic siting may prioritize ease of development over minimizing environmental impact. The scope of my findings provides data to further challenge the social assumption that renewables are "green" by default; they still can impact the environment. My findings provide robust, global evidence that there is currently high co-location between renewable energy sites and land that provides valuable ecosystem services, and my results support the sentiment found in Amado & Poggi (2014), Hoffacker et al. (2017), Moore et al. (2022), Owens & Cowell (2002), Owens, (1992), and Poggi et al. (2018); the field of land planning must adopt the knowledge growing within the land-energy nexus field in order to minimize future environmental trade-offs during the energy transition

Beyond ecological impacts, the land use patterns reveal important intersections with other systems that rely on the same geographies, most notably, ecosystem service provision and agricultural production. The overlapping regions found in my results for both power plants and renewable energy clusters - although somewhat to a lesser degree - raises the question of how renewable energy can coexist with other land uses in a way that maximizes benefits and minimizes harm.

Proximity to high-functioning ecosystems presents a dual reality: renewable energy projects may both threaten and benefit from the services these ecosystems provide (Hastik et al., 2015). My initial findings for power plant shows a high co-location with ecosystems rich in regulating/supporting services, particularly carbon storage and biodiversity. The high portion of nearby land that provides ecosystem services means there is likely to be interactions, especially with supporting and regulating services. This presents a subtle but significant potential risk of

ecological degradation from the cumulative, long-term pressure of an energy project installation. Despite the concerns around ecosystem trade-offs, the fact that both clustered and single-technology energy systems exist in proximity to valuable ecosystems may actually be in support of previous literature focused on synergies seen in Lamhamedi & de Vries (2022). Clearly, these environments still exist next to functioning power plants; therefore the ongoing existence of these ecosystems near power plants suggests co-benefit potential. For example, wind farms placed in grassland areas can both reduce the demand for fossil fuel energy and prevent the grassland from being developed, all while the wind farm benefits from unobstructed air flow provide by the geography of the grassland.

The consistent proximity of renewable energy infrastructure to agricultural land as shown by my results agrees with previous identified overlap patterns and echoes previous scholar's concerns of future implications. Currently, there is high geographic overlap between energy projects and agriculture (while less so for renewable energy clusters, the proximity is still high). This high overlap indicates the increasing popularity of co-location models such as agrivoltaics or shared land tenure; however it also reinforces the potential risk of future tension as both sector's scale, particularly in densely populated or food-insecure areas, where airable land used for energy projects could impact food availability. Similar to ecosystem services concerns, this finding is of importance to multi-functional landscapes that serve energy, food, and ecological goals. My research findings agree with both Jordaan et al. (2021), who recommends that future work look at how land may be used more efficiently by energy developments, and Jones et al. (2015), who call for using a landscape approach to predict and plan for the cumulative effects of development.

## 5.2 Implications

Beyond empirical findings, my research also offers theoretical contributions to novel directions in the fields of energy geography and land-energy nexus research. The small but growing body of literature emphasizing the need for land planning during the energy transition, both from ecological and social lenses, is reinforced by the differences in how single-technology power plants and renewable energy clusters present geographically. This finding potentially connects to an underlying research agenda I have not explicitly focused on in my results. Previous research has shown that renewable energy projects are more likely to succeed when there is a perceived fair due process, making justice concerns not only ethically important but also practically effective in reducing “not in my backyard” resistance to energy development (Devine-Wright, 2011; Rand & Hoen, 2017). My findings provide further evidence that this dynamic may already be operating in practice; renewable energy clusters, by definition, involve a range of actors, including communities, local governments, cooperatives, and households. While not universally participatory, many of these governance models offer greater opportunity for the kind of procedural justice Rand and Hoen describe (Rand & Hoen, 2017). As a result, renewable energy clusters in the dataset frequently appear in already built environments, on rooftops or within community spaces, embedding energy systems into daily life rather than displacing existing land uses. Findings from Dai et al. (2024) further support this approach, showing that projects developed in areas with low human modification tend to have lower land efficiency and cause greater landscape transformation, increasing risks to ecosystem services. By this logic, addressing “not in my backyard”-ism through inclusive planning and localized ownership not only increases the likelihood of project completion but also may, at times, reduce its environmental trade-offs.

Many of the identified underlying challenges that arise from my findings around choices of where to put energy projects can be connected to the explanatory theory of carbon lock-in. Much of the current infrastructure for electricity may create barriers to implementing more integrated energy production, which could ultimately be resulting in higher environmental impacts. This is a manifestation of infrastructural lock-in, which involves the physical structures that indirectly or directly shape the energy supply (Seto et al., 2016). For example, city bylaws can have preventative regulation for utility to install rooftop solar (CADSolar, 2024). The lack of policy currently prioritizing that urban planning incorporate low-carbon energy considerations, seen as early as Owens (1992), is still prevalent and could be attributed in part to institutional lock-in. Finally, “not in my backyard”-ism resistance to the placement of renewable energy power plants in visually disruptive areas connects to the social lock-in of how we perceive and interact with power plants under a carbon-dominant energy system. While the energy projects I analyzed were all renewable, the issues preventing renewable energy from being produced are also impacting how and *where* the renewable energy sector is able to grow.

These forms of carbon lock-in not only shape where renewable energy can be developed, but also reinforce broader patterns of exclusion and inequality, highlighting the need for justice-oriented frameworks. Spatial justice in land-energy nexus positions energy and land relationships as requiring land management and regulation to prioritize fair, equal and just distribution of the benefits – and fair, equal and just costs of implementing systems. These tenets align heavily with both ecosystem service justice and energy justice literature, although there are no current direct connections with the two. Ecosystem service justice emphasizes the need for the diverse values and needs of people from ecosystems be incorporated into understanding their importance, rather

than on monetary valuation alone. Ecosystem service justice focuses on advocating for socially-inclusive decision-making related to the protection and use of ecosystem services (Berbés-Blázquez et al., 2016). Similarly, energy justice advocates for the inclusion of historically harmed communities in energy processes, including but not limited to ownership (Jenkins et al., 2016). Within the spatial justice paradigm in land energy nexus research, we see a convergence of concerns and interest between the two fields that are highly complementary, and currently not thoroughly explored together.

Scholars such as Brisbois (2019) have posited that decentralization creates the potential for new actors to become empowered and challenge current power structures, rather than reproduce the systems that exist within fossil fuel energy production. The loss of ecosystem services most likely harms those who do not consume the majority of energy produced the most (Berbés-Blázquez et al., 2016). Berbés-Blázquez et al. argue that decision-makers must account for this social context in order to avoid inequalities and injustices in who benefits from the choice of development or ecological protection. Energy justice focuses on access and procedural fairness, ecosystem service justice focuses on the other side of this development, making these two perspectives deeply intertwined.

Together, these could lead to a promising, though underdeveloped, convergence between ecosystem service justice and energy justice. Both frameworks advocate for recognizing the needs and voices of marginalized communities in decision-making, whether it be during the production of low-carbon energy, or the development of valuable ecosystems. Viewing energy development through land-based lens of justice reveals that decisions about where infrastructure is placed are not neutral; they redistribute benefits and burdens in ways that can either reinforce

or disrupt existing inequities. Consequently, the theoretical frameworks of ecosystem service justice literature and energy justice understandings, if used more closely, could help illuminate the indirect, yet impactful, ways that energy transitions affect food security, biodiversity, cultural practices, and ecological resilience.

My findings have important implications for policy, industry, and society. For policymakers, my results provide a data-driven rationale to prioritize development that focuses on siting renewable energy in already developed or bare areas, minimizing ecological trade-offs. Industry stakeholders can apply these insights into early-stage feasibility assessments, considering if a proposed project placement aligns with both technical performance and sustainability goals. Community planners and local governments may use these findings to prioritize opportunities for multi-functional land use such as agrivoltaics or rooftop solar which reduce land competition while fostering public support.

### 5.3 Limitations

This study has several limitations, some of which originate from the datasets used, and some from the assumptions made and the scope of my research focus.

The ESA Land cover dataset has a mean accuracy of ~16%, meaning that any particular 30m may be incorrectly categorized up to 16% of the time, due to cloud cover, unclear satellite imagery, or inaccurate coordinates. While this is an issue at small scales, because the region examined around power plants was 1-10km, it is unlikely this error created bias the results.

In addition to the uncertainty in the land cover data, both energy datasets have their respective limitations. Uncertainty in both the World Resource Institute Power Plant Database and the growing renewable energy cluster database from the ReSET CoLab arises from relying on a large variety of data sources, some of which could have outdated or incorrect information about any particular energy site. A consideration in the Power plants database is the inconsistent coverage of resources included (for example, ~94% of estimated geothermal capacity is in the dataset in comparison to only ~17% of solar), which could have influenced the diversity of land distributions seen in Figure 8. The additional limitation on the renewable energy clusters database is the currently limited number of sites, however this is likely also part of the nature of renewable energy clusters; they are not a dominant configuration of energy production at the moment. Due to the data-driven nature of these datasets, and the level of difficulty that comes with gathering comprehensive information about energy development which remains jurisdictionally fragmented, there is a slight over-representation of North America and Europe as currently seen in the global power plants and clusters database (as seen in Figure 5). As these are currently the most robust options for global assessment of the location of energy systems, it is possible my findings are lightly biased towards the geographic context of English speaking areas, and that some land patterns seen in areas with less thoroughly reported on energy systems are underrepresented.

The omission of longitudinal data from my research was intentional as to allow for a cross-sectional understanding of the current land and power plant circumstances globally, consequently, my research does not encapsulate the *changes* to the land near power plants before and during construction; it only provides snapshot information on what the nearby environment

looks like after. Additionally, confounding factors were not considered. One example of this would be other development occurring as a result of the power plant construction, such as towns that grow due to economic growth associated with a power plant construction.

## 5.4 Future Research

As the goal of this research was to produce broad scale understanding of current trends and patterns in the land that surrounds power plants, these types of specific context for energy sites are outside of the scope of this study, but would be beneficial for future work to provide complimentary information as to the land interactions of the projects. Future work could build on these findings by incorporating more localized assessments of ecosystem services to better interpret the patterns within my results. While this study provides a broad spatial overview, a more detailed understanding of the specific services provided by each environment would require evaluating the ecological and social value of local landscapes. Adopting regionally tailored valuation methods, such as those used by Jordaan et al. (2021), would allow for more precise estimates of ecosystem service trade-offs and strengthen the relevance of land-energy planning at local and national scales.

Addressing the complexities of incorporating local assessments will also likely require a more integrated theoretical framework. While examining land-energy nexus literature, I found that epistemological differences across disciplines influenced which landscapes are prioritized.

I have previously identified a challenge within the land-energy nexus research area that energy geographers and land planners and ecosystem service researchers prioritize different

landscapes in research surrounding the energy transition. Specifically, land-energy research by energy geographers and land planners typically focuses on urban and agricultural impacts, while ecosystem service researcher focuses on water systems and forest impacts, due the epistemological differences between the disciplines. Ecosystem services takes a socio-ecological approach, and energy geography typically takes a socio-economic or socio-technical approach. As a result, the framework for land-energy nexus research remains somewhat fragmented. A possible future direction for this field could lie in blending these frameworks, rather than using just one, by understanding energy transitions through a socio-ecological-technical lens.

Socio-ecological-technological systems (SETS) theory is a framework which aims to incorporate all three considerations when analyzing sustainability challenges, including the energy transition (McPhearson et al., 2022). Including social, technological, and ecological may aid in identifying barriers to and opportunities for sustainability transitions. Very little research has been conducted on this framework could be applied to the field of energy transitions, and those who have not used direct SETS framing (Razzaghi Asl, 2022). Given my observed gap in current knowledge further exploration of a combined framework such as SETS could hold merit for future research endeavors.

My research presented in this thesis collectively provides a foundation for the aforementioned possible future directions by contributing to a nuanced understanding of the land-energy nexus and its broader significance in energy transition research. The need for an energy transition is not up for discussion; it is essential for social and environmental wellbeing across the world. Rather than challenging this need, increased knowledge on how this transition is occurring in real-time, and how that is impacting the other ecosystem services is critical to

having an informed, holistic energy transition that focuses on maximizing synergies and minimizing trade-offs with the environment. By highlighting where renewable energy is most often placed and the land cover and ecosystem services that are implicated in that placement, my findings contribute geographically robust insight to ongoing discussions about trade-offs of development, and highlight future directions in justice and planning in the energy transition. The question is no longer when the energy transition occurs, but where it goes. It is my hope that my findings can point towards a more holistic framework for where renewable energy projects go, and how they interact with the environments and communities around them.

## 6. Appendices

### Appendix A

*Table A.1: List of ecosystem services that each land type typically provides according to previous scholarship, delineated by ecosystem service type. A full description of each land cover type can be found in Table 3.*

<b>Land Cover</b>	<b>Provisioning ES</b>	<b>Regulating ES</b>	<b>Cultural ES</b>	<b>Supporting ES</b>
Tree Cover	Water, Materials, food and drink, natural medicines (Martínez Pastur et al., 2018)	Clean air, carbon storage, flood management, erosion control, water purification, disease and natural pest control, pollination (Martínez Pastur et al., 2018)	Physical health and mental wellbeing, tourism, knowledge and learning, recreation, sense of place, inspiration, spiritual and religion connection (Kreye et al., 2022; Martínez Pastur et al., 2018)	Healthy soils, photosynthesis, nutrient cycling, space for wildlife (Martínez Pastur et al., 2018)
Shrubland	Materials, food and drink (Brunson, 2014; Havstad et al., 2007)	Clean air, carbon storage, flood management, erosion control, water purification, disease and natural pest control, pollination (Daryanto et al., 2019; Guarino et al., 2020; Havstad et al., 2007)	Knowledge and learning, recreation (Havstad et al., 2007)	Nutrient cycling, space for wildlife (Brunson, 2014; Havstad et al., 2007)
Grassland	Materials, natural medicines, food and drink (Bengtsson et al., 2019; Richter et al., 2021)	Clean air, carbon storage, flood management, erosion control, water purification, disease and natural pest control, pollination (Bengtsson et al., 2019; Guarino et al., 2020)	Physical and mental wellbeing, tourism, recreation, sense of place, spiritual and religious connections (Bengtsson et al., 2019)	Healthy soils, photosynthesis, nutrient cycling, space for wildlife (Bengtsson et al., 2019; Richter et al., 2021)

Cropland	Food and drink (Hu et al., 2023)	Clean air, carbon storage (Hu et al., 2023)	Tourism, knowledge and learning (Peng et al., 2023; Plieninger et al., 2013)	Nutrient cycling, photosynthesis (Hu et al., 2023; Peng et al., 2023)
Built				
Bare/sparse vegetation/ moss and lichen				
Snow and ice	Materials, food and drink (Su et al., 2019)	Carbon storage, flood management, disease and natural pest control (Knoll et al., 2019; Steiner et al., 2021; Su et al., 2019)	Physical health and mental wellbeing, tourism, knowledge and learning, recreation, sense of place, inspiration, spiritual and religion connection (Knoll et al., 2019; Steiner et al., 2021)	Space for wildlife (Knoll et al., 2019; Steiner et al., 2021)
Permanent water bodies	Materials, food and drink, natural medicines, Water (Biggs et al., 2017; Chowdhury & Behera, 2021; Doherty et al., 2014)	Clean air, carbon storage, flood management, erosion control, water purification, disease and natural pest control, pollination (Biggs et al., 2017)	Physical health and mental wellbeing, tourism, knowledge and learning, recreation, sense of place, inspiration, spiritual and religion connection (Doherty et al., 2014)	Healthy soils, photosynthesis, nutrient cycling, space for wildlife (Biggs et al., 2017)
Herbaceous wetland/mangroves	Water, Materials, food and drink, natural medicines (X. Xu et al., 2020; Zedler & Kercher, 2005)	Clean air, carbon storage, flood management, erosion control, water purification, disease and natural pest control, pollination (X. Xu et al., 2020; Zedler & Kercher, 2005)	Physical health and mental wellbeing, tourism, knowledge and learning, recreation, sense of place, inspiration, spiritual and religion connection (Mitsch et al., 2015; Xu et al., 2020)	Healthy soils, photosynthesis, nutrient cycling, space for wildlife (Mitsch et al., 2015; Xu et al., 2020)

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