A Natural Fit

Renewable energy and sustainable land management

IISD REPORT

International Institute for Sustainable Development

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Executive Summary

Renewable energy technologies—solar, wind, bioenergy, hydropower, and geothermal—interact with land systems in complex ways, influencing land health and productivity, the provision of ecosystem services, and local socio-economic outcomes.

To avoid catastrophic climate change impacts, the world must rapidly transition away from fossil fuels toward renewable energy sources. The share of renewable energy in the power mix is likely to grow rapidly in the short term as countries strive to fulfil their emission reduction commitments and the cost of renewable energy technologies continues to decline, including those associated with installation, transmission, and storage.

The expected shift to solar, wind, and other renewables could lead to a significant increase in land-use intensity to generate electricity when compared to fossil fuels. This expanding environmental footprint is comprised not only of the direct land take for renewable energy farms and plants, but also the infrastructure required (e.g., access roads, transmission lines, power substations), which can have an adverse effect on ecological connectivity and the delivery of ecosystem services.

Renewable energy technologies rely heavily on the extraction and processing of critical minerals, which further increases their land footprint. To minimise potential impacts, the responsible extraction and procurement of lithium, cobalt, copper, and rare earth elements must recognise the legitimate land rights of local communities and minimise the risks to human health and the environment.

How can we transition to renewable energy systems—which are vital for limiting global warming—without compromising the health of the land, the functioning of ecosystems, and the livelihoods of local people?

Dual-land-use systems that combine energy generation and other productive uses can unlock synergies to achieve food security, biodiversity conservation, land restoration, and climate change mitigation. The LDN response hierarchy offers a practical framework for implementing integrated approaches that provide multiple benefits through national commitments to scale up the conservation, sustainable management, and restoration of land resources.

- **Countries can avoid land degradation** by siting renewable energy systems on land or freshwater systems that have already been degraded or modified by human activities, such as abandoned agricultural land, buildings and infrastructure, canals, and reservoirs. For example, solar, wind, and bioenergy farms on low-impact sites can be explicitly designed to reduce the reliance on wood and charcoal for fuel, thereby avoiding further deforestation and land degradation.

- **Countries can reduce land degradation** by designing and implementing dual-use approaches, such as agrivoltaics, ecovoltaics, wind farms on rangelands, micro-hydropower, and sustainable bioenergy. For example, integrating renewable energy with sustainable land, water, and grazing management practices (e.g., regenerative agriculture, agroforestry, and silvopastoralism) can increase food production, enhance drought resilience, conserve biodiversity, and reduce post-harvest losses.
- **Countries can reverse land degradation** by the targeted siting of solar and wind farms or producing bioenergy by harvesting invasive species or cultivating feedstock on marginal or degraded land. For example, solar systems can support land restoration through shading or wind protection, providing clean energy while promoting soil health and vegetation growth under the solar panels.

Combining renewable energy development and sustainable land, water, and grazing management can also support multiple socio-economic and development objectives. For example, dual-use systems can provide clean energy alternatives to the millions of people who still lack access to electricity and rely on traditional biomass for cooking. Improved access to low-cost energy at the farm and community levels provides critical support for sustainable water management in agriculture, zero-emission farm machinery, and food processing and storage that can reduce food loss, improve supply chain integration, and enhance the resilience of communities.

In order to be equitable and effective, dual-land-use systems require an enabling environment that includes policy and sector coordination, governance and regulatory frameworks, finance and incentive mechanisms, and capacity building and stakeholder engagement.

Policy and sectoral coordination can include the

- establishment of public and private sector coordination and planning mechanisms,
- integration of Productive Use of Renewable Energy (PURE) solutions into national electrification plans and sector-specific development programmes, and
- adoption of integrated land-energy planning and budgeting frameworks for coherent implementation.

Governance and regulatory frameworks are needed to

- enforce land-use and energy sector planning and legislation,
- promote quality and performance standards for renewable energy installations (e.g., certification), and

- safeguard access and benefit sharing, as well as the legitimate land and resource rights of local communities.

Finance and incentive mechanisms can be employed to

- direct financial assistance for the startup costs of renewable energy installations,
- introduce tax and tariff exemptions for renewable energy entrepreneurs, and
- leverage environmentally responsible biodiversity and carbon credit instruments.

Capacity building and stakeholder engagement involve

- training and empowering local communities to operate renewable energy installations,
- strengthening community tenure rights and access to resources, and
- promoting community-based business models and sustainable value chains.

As a result of their inherent scalability, renewable energy systems can be adapted to diverse contexts and integrated with other productive land uses. This creates new opportunities to design systems and management practices that avoid, reduce, and reverse land degradation while contributing to multiple sustainability objectives. Integrated land-use planning and integrated land management (ILM) play an important role in unlocking synergies between renewable energy and sustainable land management while also contributing to national environmental and development goals.

The adoption of renewable energy technologies is closely linked to the effective implementation of the three Rio Conventions (UN Framework Convention on Climate Change, Convention on Biological Diversity, and UN Convention to Combat Desertification), offering numerous entry points for scaling up projects and programmes that integrate renewable energy and sustainable land management.

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Abbreviations and Acronyms

AI	artificial intelligence
BECCS	bioenergy with carbon capture and storage
CBD	Convention on Biological Diversity
CO_2	carbon dioxide
CSP	concentrated solar power
FPV	floating photovoltaic systems
GHG	greenhouse gas
GIS	geographic information system
IEA	International Energy Agency
ILM	Integrated Landscape Management
IPCC	Intergovernmental Panel on Climate Change
ILUP	integrated land-use planning
IRENA	International Renewable Energy Agency
LDN	land degradation neutrality
LER	land-equivalent ratio
LUIE	land-use intensity of energy
NBSAP	National Biodiversity Strategy and Action Plan
NDC	nationally determined contribution
PURE	Productive Uses of Renewable Energy
PV	photovoltaic
SDG	Sustainable Development Goals
SLM	sustainable land management
SWP	solar-powered water pumps
UNCCD	United Nations Convention to Combat Desertification
UNFCCC	United Nations Framework Convention on Climate Change

1.0 Introduction

As the world transitions to renewable energy to achieve its climate goals, attention must be given to the land-energy nexus. Renewable energy technologies—solar, wind, bioenergy, hydropower, and geothermal—interact with land systems in complex ways, influencing land integrity, ecosystem services, and socio-economic outcomes. How can we transition rapidly to renewable energy systems, which are vital for limiting global warming, without undermining land health, ecosystem functions, and the rights and livelihoods of people depending on these lands? This primer explores challenges and opportunities associated with the transition to renewable energy and examines approaches to ensure that the expansion of renewable energy installations supports sustainable land management (SLM) and sustainable land-use systems, improves local livelihoods, and drives progress toward the objectives of the Rio Conventions and Sustainable Development Goals (SDGs).

The world is set to decarbonise rapidly. To avoid catastrophic climate change impacts, the world must rapidly transition away from fossil fuels toward renewable energy sources. The Intergovernmental Panel on Climate Change (IPCC) highlights that climate mitigation options, including solar and wind power, are becoming increasingly cost effective and accepted by the public.[1] The global clean energy transition is gathering speed. In 2024, renewables accounted for 29.9% of global electricity generation, 46% of total installed power capacity, and over 90% of newly added capacity.[2] Solar power increased by a record 29%, continuing the trend of doubling global solar capacity every 3 years.[3] The expansion of renewable energy will further accelerate as key sectors like industry and transport electrify to reduce their greenhouse gas emissions and increase the share of electricity in total energy consumption from 25% in 2023 to 55% in 2050 to achieve the target of the Paris Agreement on Climate Change to limit global warming to 1.5 °C above pre-industrial levels.[4]

Renewable energy sources are key to power development. The rapid expansion of renewable energy is fuelled by a continuing decline in costs. The average levelised cost of electricity, a measure of the lifetime cost per unit of energy produced, for solar power, for example, has declined by approximately 85%–90% since 2010, making it one of the cheapest sources of electricity in many locations by 2024.[5] At the same time, the cost of enabling technologies like battery storage and grid management technology is also decreasing, opening opportunities for integrated renewable systems that combine intermittent solar and wind energy with stable renewable sources like geothermal and bioenergy. The scalability of these systems makes them a potentially viable solution to connect the 666 million people who still lack access to electricity to the grid and provide clean alternatives to the 2.1 billion people who still rely on traditional biomass for cooking.[6]

On average, renewable energies require more land than fossil fuels. Some renewable energy systems, including solar and wind power, have higher land-use intensity of energy (LUIE) (a measure of the land footprint required to produce 1 terawatt-hour of electricity per year [ha/TWh/y]) than fossil-fuelled generation. The higher land footprint has raised concerns that the prospect of a rapid clean energy transition could have adverse impacts on land quality and compete with other land uses, such as food production, biodiversity conservation, carbon sequestration, and livelihoods.[7] Based on real-world estimates, solar power requires twice the amount of land compared to coal-fired electricity. Wind power can require up to 12 times more land than coal. However, these estimates include the need for spacing components such as solar panels and wind turbines. In most cases, the land between these components remains available for other uses. The underground impacts of activities related to geothermal, natural gas, and coal mining, which can disturb hydrological cycles and deep soil structure, are excluded.[8]

Renewable energies interact with land in complex ways. LUIE is only one element shaping the relationship between renewable energy and land use. Renewable energy and land interact in multiple, complex ways that can create both negative and positive impacts on land quality and other land uses (Chapter 2). Because of their scalability, renewable energy systems can be adapted to diverse conditions and needs and integrated with other land uses. This opens opportunities to design systems and management approaches that avoid land degradation and contribute to objectives, including land regeneration, biodiversity conservation, climate action, and people's well-being.

Integrating renewable energies with land degradation neutrality (LDN) enhances synergies between multiple international frameworks. The adoption of renewable energy technologies has linkages with each of the three Rio Conventions, and each of these agreements provides entry points for pursuing projects that integrate energy and land priorities. The most direct influence is their contribution to reduced reliance on fossil fuels and the implications for achieving the objectives under the UN Framework Convention on Climate Change (UNFCCC) and its Paris Agreement on climate change. The adoption of renewable energy can serve multiple purposes, including indirectly easing pressure on natural landscapes; supporting biodiversity conservation and the Convention on Biological Diversity (CBD); empowering the local, remote, off-grid communities with electricity; and developing the capacity to adopt smart, SLM that supports UN Convention to Combat Desertification (UNCCD) objectives.

Article 8.1 of the UNCCD specifically calls for parties to coordinate activities under the UNCCD and UNFCCC, CBD, and other agreements to maximise benefits from activities under each agreement while avoiding duplication of effort.[9] In 2024, the UNCCD Conference of the Parties adopted a decision encouraging parties to "leverage synergies at the national level in the planning and implementation processes of the three Rio Conventions through integrated actions and approaches."[10] In addition, aligning renewable energy expansion and SLM for LDN can contribute to several SDGs, including SDG 1 (no poverty), SDG 7 (affordable and clean energy), SDG 13 (climate action), and SDG 15 (life on land). The approaches discussed in this report show that solutions can address multiple SDGs simultaneously by advancing energy access, improving livelihoods, restoring land, and empowering marginalised groups.

LDN can be an entry point for integrated implementation. The overarching goal of LDN is to maintain or enhance land-based natural capital and its associated ecosystem services. The Scientific Conceptual Framework for Land Degradation Neutrality, developed by UNCCD's Science-Policy Interface, establishes a dual-pronged approach: measures to avoid or reduce land degradation are combined with efforts to reverse existing degradation, ensuring that losses are balanced by gains to achieve a "no net loss" position of healthy and productive land.[11,12] LDN can provide a useful lens and a benchmark to evaluate the impacts of renewable energy projects and discover opportunities for integration.

Box 1. Land degradation neutrality

The UNCCD's LDN goals, also reflected in SDG target 15.3, describes a situation in which the amount and quality of land resources necessary to support ecosystem functions and enhance food security remain stable or increase within specified temporal scales and ecosystems. LDN can be achieved by enhancing land-based natural capital to ensure no net loss through a dual-pronged approach. This involves integrated land-use planning (ILUP) to keep land use in balance and prevent/reduce degradation alongside measures to restore degraded land that balance anticipated losses with equivalent gains.[13]

This primer explores opportunities at the renewable energy–land nexus. Against this background, this report scans the recent scientific and grey literature on interactions between renewable energy and land alongside integrated approaches that consider these interactions to create multiple benefits for the climate, land, biodiversity, and people.

- Chapter 2 describes the land footprint of different renewable energy sources, identifies how each source interacts with land, and reviews the potential negative and positive impacts that can arise from these interactions.
- Chapter 3 explores strategies to reduce land demand for renewable energy and design systems and approaches that minimise land degradation and enhance benefits for land, biodiversity, climate, and people.
- Chapter 4 discusses governance and finance aspects that can provide entry points for decision makers to support the development of integrated approaches.

2.0 The Renewable Energy–Land Management Nexus

All types of energy generation require site-specific installations and transmission infrastructure that have a land footprint. However, on average, renewable energy sources require more land per unit of energy generated than fossil fuels. The direct and indirect land footprint of energy includes the surface that is covered with physical elements, such as solar panels, wind turbines, batteries, access roads, and transmission lines; land occupied by upstream activities such as mining and the production of fuel and raw materials for components; and land occupied by waste from decommissioned solar panels, wind turbine blades, and batteries. The siting and spacing of renewable energy infrastructure can affect land quality, impact biodiversity and ecosystems, interact with climate change impacts, and affect communities in positive and negative ways. These complex interactions between renewable energy and land offer opportunities to design approaches in collaboration with stakeholders that minimise negative impacts and enhance benefits.

This chapter reviews current estimates of the direct and indirect land footprint of renewable energy sources, followed by a discussion of the complex interactions between renewable energy generation and land quality, biodiversity, climate, and people.

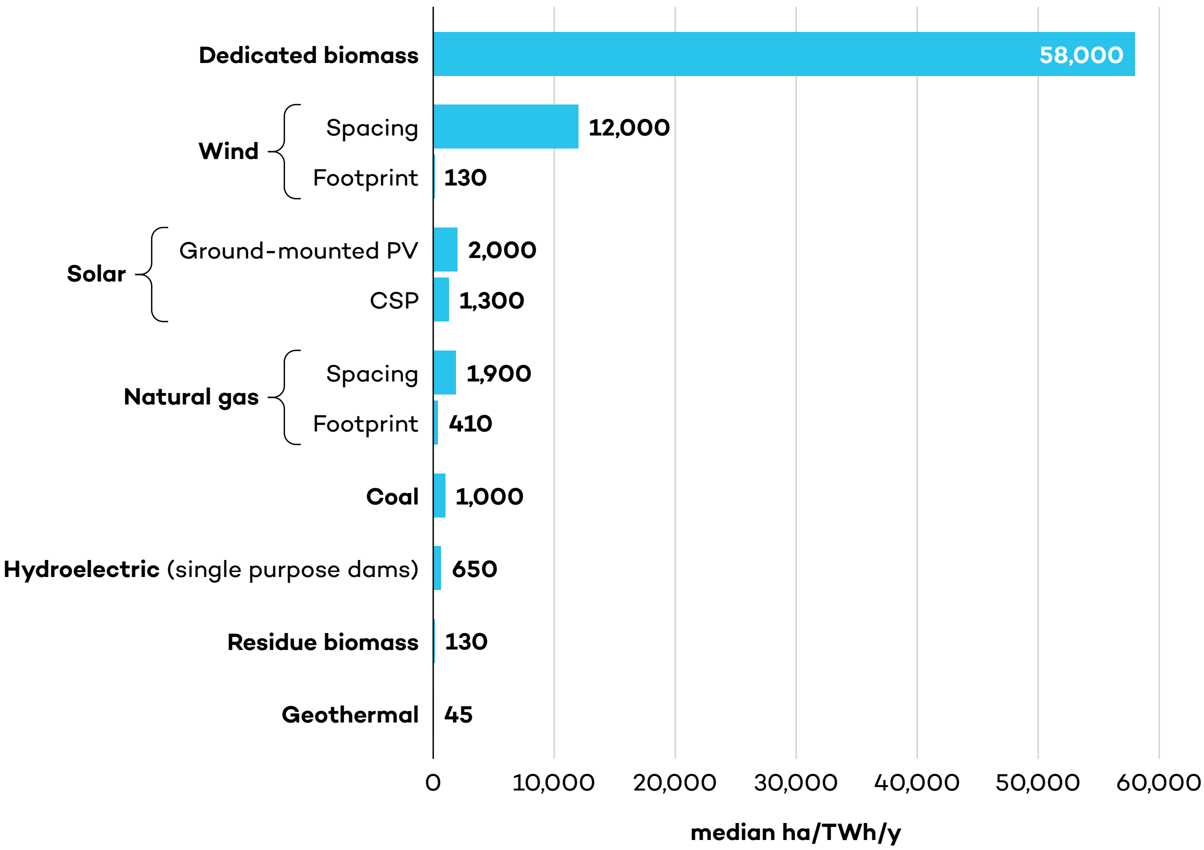
2.1 Recognising Land-Use Intensities and Managing Trade-Offs

The global energy system currently has an estimated land footprint of 0.4% of ice-free land, a relatively small portion compared to agriculture, for example, which occupies 30%–38%.[14] The decarbonisation of the energy system could lead to a significant increase in land demand for electricity generation, driven by the relatively higher land footprint of renewable energy sources, the need to electrify key sectors including industry and transport, and growing demand for energy, which is expected to more than double by 2050.[15]

Understanding LUIE for various energy sources in different contexts is crucial to ensure that the expansion of renewable energy generation does not jeopardise LDN or other goals for sustainable development. LUIE measures the amount of land occupied by energy-producing facilities, infrastructure, and related upstream and downstream activities in relation to the amount of usable electricity generated over a certain time. It offers a standardised, energy-based comparison between different technologies by accounting for the full life-cycle land requirements. Upstream activities include the production of fuel, mining for raw materials, and the production of energy generation components, such as turbines and solar panels. Downstream activities include decommissioning generation facilities and waste management. This report uses ha/TWh/y to measure the LUIE.

Estimating LUIE values is challenging, as the land footprint of energy systems varies with energy type, technology, location, climate, facility design, and the sourcing of upstream materials. Most estimates to date have used a mix of modelling and real-world data to estimate the LUIE. Lovering et al. (2022)[16] conducted one of the first studies of LUIE using exclusively real-world data across all major electricity sources. Their estimate includes the direct footprint of energy-generating facilities like power plants, solar panels, or wind turbines, including access roads and ancillary structures. For combustion-based generation, LUIE measures also include land used for fuel production (coal, gas, oil, or biomass). However, their analysis does not include land required for mining and the production of renewable energy components or the land impacts of decommissioning and waste management.

Figure 1. LUIE for selected energy sources



Source: Compiled by the authors based on data from Lovering et al., 2022.[17]

Table 1 shows the median and mean LUIE values for selected renewable energy and fossil fuel-based systems. It shows that in real-world scenarios, the direct land footprint of onshore wind energy is lower than that of gas- and coal-fired electricity. However, it is 10 times higher when the spacing of wind turbines is considered. The direct footprint of ground-mounted solar panels is twice that of coal-fired electricity and comparable to the LUIE of natural gas-fired electricity when real-world spacing of onshore gas wells is considered. The land footprint of electricity generated with residue biomass is lower than that of both coal- and gas-fired electricity, whereas dedicated biomass crops for electricity generation have the highest LUIE by far.

Table 1. LUIE for selected electricity sources

	LUIE median (ha/TWh/y)	LUIE mean (ha/TWh/y)
Geothermal	45	140
Wind (footprint)	130	170
Residue biomass	130	150
Natural gas (footprint)	410	410
Hydroelectric (single-purpose dams)	650	15,000
Coal	1,000	1,100
Solar (CSP)	1,300	2,000
Natural gas (spacing)	1,900	1,900
Ground-mounted PV	2,000	2,100
Wind (spacing)	12,000	15,000
Dedicated biomass	58,000	160,000

Sources: Compiled from Lovering et al., 2022.[18]

The comparison between mean and median values shows there are variances for most energy types, underlining that LUIE is highly specific to location, available technology, and supply-demand relations that determine capacity utilisation. On hydroelectric dams, for example, Lovering et al. (2022) note that wide variances exist among dams in mountains, dams in flat areas, and run-of-river hydroelectric systems.[19] Dams with secondary purposes, such as irrigation water management, were excluded from this study.

LUIE only measures quantitative land footprints; it ignores both the quality of the land occupied by energy facilities and, more importantly, impacts on the land adjacent to and between energy facilities and ancillary infrastructure. This land can be affected by energy generation activities, but whether the impact contributes to land degradation or SLM depends on how renewable energy activities interact with other land uses. The remainder of this chapter examines issues related to the alignment and management of land uses for energy generation activities. It looks more closely at how renewable energy generation interacts with surrounding land and affects other land-related issues, including biodiversity, climate, and people.

Box 2. Sustainable land management

SLM involves the use of land resources, including soils, water, animals, and plants, to produce goods that meet changing human needs while simultaneously ensuring the long-term productive potential of these resources and maintaining environmental functions. SLM practices, such as judicious use of chemical inputs or agroforestry, can maintain land-based natural capital by avoiding or reducing degradation.[20]

2.2 Renewable Energy for People, Nature, and the Climate

Geothermal, solar, wind, hydropower, and biomass each offer opportunities and challenges regarding the renewable energy–land nexus, as reviewed below.

Geothermal Energy

Geothermal energy harnesses the heat stored beneath the Earth's surface. It has the lowest LUIE among renewable energy sources, with 45 ha/TWh/y (Table 1); however, geothermal extraction is not yet very common, contributing around 1% of renewable electricity generation in 2024.[21] While many countries have high geothermal potential, only a few countries, including the United States, Iceland, Kenya, and Morocco, have made notable efforts to include geothermal energy in their electricity mix.[22] While geothermal energy extraction has a minimal land footprint, it can use significant amounts of water, produce contaminated wastewater, and cause seismic activity due to drilling and high-pressure extraction.[23] New technologies like enhanced geothermal systems and closed-loop geothermal systems enable economically viable extraction at scale in more areas and could become a significant source of baseload renewable energy in the near future.[24,25]

Solar Energy

Solar energy is harnessed through thermal collectors (for heating) or photovoltaic (PV) and concentrated solar power (CSP) systems (for electricity). On average, PV solar installations with more than 20 MW of capacity use around 2 ha of land to generate 1 GWh of electricity per year (Table 1). The direct land footprint varies between the sites chosen and with the design of solar arrays. Rooftop solar systems, for example, have no direct land impact. Large-scale solar installations in agricultural regions, on the other hand, can compete with prime agricultural land. This competition can be avoided by siting solar installations on brownfields or land degraded by previous activities or abandoned agricultural land. PV panels can also be combined with other renewable energy systems, such as wind turbines, to reduce intermittence, thereby lowering the need for installed capacity and reducing competition for land.[26]

Competition for land can be further reduced by co-locating solar panels with agriculture (agrivoltaics) or designing systems that support natural plant growth to maintain ecosystem functions (ecovoltaics). These approaches use the shade provided by PV panels to improve water retention and favour plant growth. In some cases, PV panels provide wind breaks to support regeneration efforts on adjacent land. These benefits can balance the direct land footprint by supporting the regeneration of the surrounding land. Ecologically sensitive siting avoids habitat fragmentation and impacts on wildlife that can result from the construction of solar arrays and ancillary infrastructure, such as access roads and transmission lines.[27]

PV solar farms can also alter the local climate. Large and densely spaced solar arrays can create a heat island effect, whereas more widely spaced panels can have a cooling effect through the shade provided and by reducing water evaporation. In cold regions, dark solar panels impact the albedo effect of snow cover, increasing local air temperature, which can cause premature snow melt in the spring. A study of 116 solar farms around the world showed that, while impacts are heterogeneous and depend on local conditions and seasonal variations, solar farms reduce the albedo effect, and in most cases, have a cooling effect on surrounding temperatures. The study also found that vegetation tends to decrease in areas surrounding solar farms.[28] A study using satellite data found that while the reduced albedo of solar farms is noticeable, their warming effect is smaller than previously thought, and a farm's lifetime impact can be offset by the clean solar energy produced within a year.[29] Recommended strategies to offset some of the reduced albedo effect of solar farms include maintaining healthy, short grass, using reflective materials like white gravel as ground cover or reflective membranes, and choosing naturally reflective soils for installation.[30]

Box 3. Managing solar waste

Solar panels have a life span of 20–30 years, which means a rapidly growing number of first-generation solar power plants will be decommissioned in the next few years. The International Renewable Energy Agency (IRENA) projects that cumulative waste from solar PV projects will increase from 0.2 Mt in 2021 to 4 Mt in 2030 and continue growing to 200 Mt in 2050.[31] Disposing of solar panels in landfills not only increases life-cycle LUIE for solar energy but can also cause environmental problems like toxic chemical leaching. Panels also contain valuable critical minerals and metals, the demand for which is expected to increase rapidly during the global clean energy transition (see Box 2). Technologies for recycling solar panels are evolving rapidly, but commercial applications are still low volume and face both logistical challenges and underdeveloped markets for recovered materials.[32] Technology development is broadening the scope of panel types and materials that can be recovered.[33] Countries are also adopting PV-specific waste management regulations, such as the EU's Waste from Electrical and Electronic Equipment Directive.[34] Some researchers suggest exploring end-of-life management options beyond recycling, such as repairing and refurbishing used panels and improving panel design to reduce non-recyclable components; however, many of these strategies face similar challenges as recycling strategies.[35]

Wind Power

Wind power converts the energy of wind into electricity using turbines. Wind energy has a relatively small direct land footprint with a LUIE of 130 ha/TWh/y (Table 1) and low greenhouse gas (GHG) intensity compared to fossil electricity. Although wind farms can cover large areas when spacing is considered (LUIE = 12,000 ha/TWh/y), the direct footprint of turbines and infrastructure requires less than 10% of the land within a farm's boundaries, leaving the remaining land available for other uses, like agriculture or grazing.[36] Offshore wind farms have no direct terrestrial land footprint but do affect marine ecosystems.

Like PV solar, the construction of wind farms can fragment ecosystems and reduce habitats for wildlife or alter ecosystem dynamics. Wind turbines can also cause collision fatalities for birds and bats. The presence and operation of facilities can displace wildlife from their habitats due to noise, human activity, and alteration of the landscape.[37] Careful siting to avoid migratory routes and sensitive habitats, along with technological solutions like AI-powered turbine shutdown systems, can mitigate these impacts.[38] Zoning strategies are often used to steer development away from sensitive areas, and regulations like minimum distances to settlements are used to address noise pollution.[39]

Hydropower

Hydropower uses the flow of water to generate electricity. The primary impact of hydropower is the inundation of land for reservoirs behind dams, permanently removing it from other uses, such as agriculture or forestry. The land-use intensity of hydropower varies with dam height, reservoir size, topography, and design. Large, single-purpose dams have lower LUIE than run-of-river and small-scale hydro systems, even though the latter typically have smaller reservoirs.[40] Small and micro hydro systems are often combined with dams built for irrigation water retention, water management, or other purposes that influence reservoir size and water management. Their impact on land can be balanced by the positive impacts of using electricity and water to improve irrigation and water management in surrounding areas (see Section 3.4).

Dams disrupt natural water flow patterns and can create sudden flow changes affecting downstream ecosystems, erosion, and sediment deposition patterns. They also present barriers for fish and other species. Technical solutions like fish ladders and ecologically informed operational practices like minimum flows and gradual changes in flow patterns can address some of these impacts; however, their performance in real life is poor in many settings. One reason is the lack of ecological and hydrological knowledge or the omission of such knowledge in site-specific design. A particular concern is the lack of knowledge on the passage needs of fish species other than cold-water salmonoids.[41,42]

Bioenergy

Bioenergy uses organic material to produce biofuels or generate heat or electricity. In 2024, bioenergy accounted for 632 TWh, or roughly 7% of global renewable electricity production. Bioenergy sources constitute 14% of renewable electricity generation in Central America and the Caribbean, 12% in Europe, 7% in South America and Asia, and less than 1% in Africa.[43] Renewable fuels from bioenergy sources, including solid biomass, liquid biofuels, and biogases, account for 95% of global demand for renewable fuels by industry, buildings, and transport in 2024, with the remaining 5% contributed by green hydrogen. On an energy basis, the total supply of renewable fuels exceeded wind and solar PV generation in 2024.[44] Bioenergy also accounts for more than 90% of renewable commercial heat generation, which is concentrated in Europe.[45]

In addition, 2.1 billion people, roughly one quarter of the global population, used solid biomass for cooking in 2025. Of the 660 million without access to electricity, many also relied on biomass for heating and other energy needs.[46] Traditional biomass use is often associated with negative impacts, such as deforestation, water scarcity, air pollution, and resulting health issues. Unsustainable wood harvesting can lead to a cycle of energy poverty and land degradation. The use of dried manure for cooking instead of fertiliser also deprives the soil of nutrients.[47]

Feedstocks for modern bioenergy use for liquid fuels and electricity generation include dedicated energy crops (e.g., sugarcane, corn, oil palm, perennial grasses, short-rotation coppice), agricultural and forestry residues, and organic wastes.[48] The LUIE for bioenergy varies with the type of energy generated, the type of feedstock, and how feedstock is produced or sourced. The LUIE of waste biomass is low, as no additional land is used. The LUIE of dedicated biomass varies between 30,510 and 107,900 ha/TWh/y according to estimates developed by King et al. (2023),[49] using data from different regions (Table 2).

Table 2. Estimates of LUIE for different bioenergy feedstocks and technologies

Feedstock and energy type	LUIE (ha/TWh/y)
Bioenergy crops to electricity	37,500
Forest biomass to electricity	107,900
Forest biomass to heat	32,370
Bioenergy crops to biofuel	30,510

Source: King et al., 2023.[50]

To date, electricity is mainly generated using biogas produced from waste materials.[51] The use of dedicated biomass for power has been proposed as part of bioenergy with carbon capture and storage (BECCS) strategies that envisage capturing and permanently storing carbon released in the combustion of biomass[52] (see Box 6). Electricity generated from dedicated biomass crops has the highest median LUIE among renewable energy sources. There is, however, great variance depending on crop types, land conditions, and climate. If grown on brownfields or degraded land, biomass crops can improve soil quality and support land restoration. If bioenergy is generated using residues and waste, the LUIE is low and can reach zero, as residues are by-products of other activities like agriculture or forestry.

Land competition for agriculture would be a particular concern for using dedicated biomass crops for electricity generation. The "food versus fuel" debate highlights the conflict where land used to grow energy crops could otherwise be used for food production.[53] This is especially true for first-generation biofuels from food crops like corn, sugarcane, and palm oil. In Europe alone, 9.6 million ha were converted for biofuel production by 2020.

Strategies like using agricultural residues, cultivating biomass on degraded land, or integrating bioenergy with food production (e.g., agroforestry) can mitigate this competition. Agroforestry involves combining trees with crops/livestock and intercropping, which can improve resource efficiency, enhance soil health, and diversify farmer income.[54] However, poorly managed bioenergy plantations, especially monocultures, can lead to soil erosion, nutrient depletion, water pollution through fertiliser runoff, and soil compaction. Conversely, perennial bioenergy crops and agroforestry systems can help reverse land degradation by improving soil structure, increasing soil organic carbon, and reducing erosion.

Regarding climate change interactions, there is a significant concern that biofuel production can lead to direct and indirect land-use changes that offset or even negate the GHG benefits of replacing fossil fuels.[55] Estimating emissions from indirect land-use changes is complicated by uncertainties, and more research is needed to assess the conditions under which biofuel use leads to net emission reductions.[56] On the other hand, renewable energy projects could restore degraded land and sequester carbon in soils and vegetation, particularly when perennial biomass crops are grown, contributing positively to climate goals. Moreover, integrated and inclusive land-use planning under a resilience framework like the one provided by LDN can help ensure project development is optimised to safeguard against the social and environmental risks that come with scaling up land-based solutions like bioenergy.[57]

Storage, Infrastructure, and Mining

Like fossil fuel-based power systems, renewable energy systems require infrastructure for conversion, transmission, distribution, and storage, all of which have land footprints. Utility-scale systems with higher shares of decentralised and intermittent renewables like wind and solar typically need more infrastructure because they are located further away from consumption centres, leading to a greater land impact than centralised systems relying on continuous supply from power plants. The expansion of renewable energy requires a corresponding expansion of transmission lines, substations, and access roads, all of which occupy land and can fragment landscapes. The impact of access roads increases if renewable energy installations are sited in remote areas when new roads provide access to previously inaccessible land, thus enabling other activities that can have negative land impacts.

Energy storage, particularly batteries and pumped hydro, is crucial for stability in grids with high shares of variable renewables like wind and solar. Pumped hydro storage involves reservoirs and has a land footprint like conventional hydropower, while large-scale battery storage facilities also occupy some land. The production of renewable energy technologies and batteries requires critical minerals like lithium, cobalt, copper, and rare earth elements, the extraction, transport, and processing of which have their own land footprints and environmental impacts. Mining, for example, can cause deforestation, soil erosion, and water pollution.[58]

Box 4. Mining critical minerals

Renewable energy generation relies heavily on critical minerals for the manufacturing of components such as solar panels, generators, batteries, and motors for electric vehicles. In the International Energy Agency's (IEA's) Net Zero Emissions scenario, global demand for key minerals like copper, cobalt, lithium, nickel, graphite, and rare earth elements is expected to almost triple by 2030.[59] Mining for these minerals has significant environmental and social impacts, including habitat destruction and fragmentation, soil erosion, air pollution, carbon dioxide (CO_2) emissions, water consumption, and pollution. Many of these minerals are sourced from poor countries where weak labour standards can lead to exploitative and dangerous conditions for workers, sometimes referred to as "modern slavery."[60] Mining can displace communities and violate Indigenous human and cultural rights.[61]

To support the responsible mining of critical minerals, the UN Secretary-General's Working Group on Transforming the Extractive Industries for Sustainable Development released a set of guiding principles and actionable recommendations. Guiding principles include human rights, planetary integrity, justice and equity, responsible and fair investments, benefit sharing, transparency and accountability, and multilateral cooperation. The actionable recommendations focus on institutions and initiatives such as a high-level expert group on benefit sharing, value addition, economic diversification, or a global transparency and accountability framework that aims to ensure coordinated action across the UN and its member states to implement the Guiding Principles.[62]

The IEA has established tools to track global demand for critical minerals[63] and national policies governing the sourcing, use, and recycling of critical minerals.[64] A key strategy to reduce the impacts of critical minerals mining will be recycling and moving toward circular supply chains. The IEA,[65] the International Institute for Sustainable Development's Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development,[66] and other researchers[67] are developing strategies and policy recommendations for critical mineral recycling and circularity.

Impacts on People

The large land requirements of many renewable energy projects often lead to conflicts with local communities, especially when people's land tenure is insecure or Indigenous rights are not respected. Conflicts frequently arise over the process of land acquisition, with communities alleging a lack of fair compensation, inadequate consultation, and displacement from land they depend on for their livelihoods. For example, in Mexico's Isthmus of Tehuantepec, wind energy development has led to prolonged conflicts with Indigenous communities over land rights and consultation processes.[68] A recent global study found that renewable energy is a dominant driver of development pressure on Indigenous Peoples' lands, showing that challenges to Indigenous Peoples' rights, lack of representation, and insufficient human, social, and institutional capital are the main factors determining land conversion risk.[69]

A key source of conflict is the failure to ensure Free, Prior, and Informed Consent from Indigenous and local communities. Many communities feel that consultation processes are merely a formality to validate projects rather than genuine engagement. Conflicts also emerge when the economic benefits of projects are not shared equitably, and local communities bear the environmental and social costs without receiving adequate compensation or access to the energy generated.[70] Inadequately planned projects can also violate cultural rights and affect the physical and socio-economic well-being of communities.[71]

Large-scale renewable energy projects, particularly hydropower, can lead to the physical displacement of communities. In 2000, a report of the World Commission on Dams documented the socio-economic problems due to dam development projects. It found that 40 million–80 million people were displaced, and it has proven challenging to resettle them properly.[72] Scudder (2011) estimates that 80 million people were displaced in the last century because of dams.[73] Moran et al. (2018) caution that the surge in large dam projects in megabiodiverse river basins such as the Amazon, the Congo and the Mekong could lead to much more serious socio-economic and environmental damages.[74] This involuntary resettlement often leads to social disruption, loss of livelihood, and the destruction of cultural heritage, particularly for Indigenous Peoples.[75] Renewable energy installations, especially wind farms and large solar arrays, can significantly alter the aesthetic and cultural value of landscapes, leading to opposition from local communities. The visual intrusion of tall wind turbines or expansive solar farms can be seen as a degradation of scenic landscapes, leading to "NIMBY" (Not in My Back Yard) opposition.[76] This is often linked to a community's sense of place and attachment to its local environment. Projects can threaten sites of cultural or spiritual significance, particularly for Indigenous communities whose identity is closely tied to the land. Finally, wind turbines can cause noise and shadow flicker, which can be a nuisance for nearby residents and affect their quality of life.

Positive impacts of renewable energy on people include enhanced energy access, new business opportunities, and a healthier environment if renewable sources replace combustion-based energy systems. In off-grid or underserved communities, energy access enables many additional positive impacts, some of which are discussed in Section 3.3. Table 3 summarises the interactions between solar, wind, hydropower, and bioenergy operations and land, climate, biodiversity, and people. The table provides only a snapshot of some of the most important linkages that shape the complex relationships that characterise the renewable energy–land nexus. The interactions do not occur in isolation but affect complex systems of existing relationships and land uses. Each system is different and characterised by specific risks that can be mitigated and opportunities that can be realised when renewable energy projects are localised.

Table 3. Overview of renewable energy–land connections

Impact Area	Solar[77]	Wind[78,79,80]	Hydropower[81]	Bioenergy crop production[82,83,84]	Storage, infrastructure, and mining[85]
Land resources					
Land demand[86]	No impact when sited on rooftops or over infrastructure; on land, LUIE = 2,000 ha/TWh/y.	LUIE up to 15,000 ha/TWh/y, but more than 90% of land is available for other purposes.	LUIE varies strongly with topography and size. Reservoirs occupy land but can enable floating solar.	Residue biomass has low to no impact. Dedicated biomass LUIE can exceed 100,000 ha/TWh/y.	Transport and transmission infrastructure, construction sites, mining and processing facilities contribute to LUIE.
Land quality	Construction or inadequate siting on productive land can cause land degradation. Properly sited panels for agrivoltaic or ecovoltaic applications improve land quality, such as through reduced evaporation (shade) and wind erosion. Panels can reduce photosynthetic efficiency for plants that thrive in direct sunshine.	Land degradation can occur during construction.	Altered flow patterns can affect downstream erosion and sediment deposit patterns.	Intensive production can degrade land through erosion, nutrient depletion, compaction, etc. Sustainable production can support land restoration on marginal land.	Infrastructure can pollute adjacent soils and provide access for secondary land conversion.

Impact Area	Solar[77]	Wind[78,79,80]	Hydropower[81]	Bioenergy crop production[82,83,84]	Storage, infrastructure, and mining[85]
Climate					
Emissions from land-use change	Land degradation from construction or operation can release soil carbon.	Land degradation from construction or operation can release soil carbon.	Flooding of vegetation leads to methane release.	Land conversion releases soil carbon. Sustainable production on degraded land can sequester carbon.	Land degradation from construction, operation, or secondary land conversion can release soil carbon.
Resilience	Horizontal panels provide shade and shelter that reduces heat stress under the panels; however, their dark surface absorbs solar energy, causing longwave radiation and sensible heat flux, jointly causing heat islands. Vertical panels can protect against wind.		Reservoirs can manage seasonal fluctuations and provide a buffer during floods and droughts.	Land cover improves water retention and prevents erosion.	Partially degraded land is vulnerable to further degradation during extreme weather events.
Local climate	Large PV arrays can create heat islands. Spaced panels can provide shade.	Wind turbines affect air mixing patterns that can affect local temperature.	Large reservoirs can affect local temperature and humidity.	Vegetation changes alter heat adsorption and evapotranspiration. Biofuel combustion releases short-lived climate pollutants.	Large built-up areas can create a heat island effect.

Impact Area	Solar[77]	Wind[78,79,80]	Hydropower[81]	Bioenergy crop production[82,83,84]	Storage, infrastructure, and mining[85]
Biodiversity					
Habitats and ecological connectivity	Solar arrays can contribute to fragmentation, but can also be designed to support specific habitats.	Habitat destruction can occur during construction.	Dams disrupt riverine habitats. Reservoirs can create or expand aquatic habitats at the expense of terrestrial ecosystems.	Land conversion for biofuel crops can destroy habitats. Siting of plantations and access roads can increase fragmentation.	Access and transmission infrastructure can cause fragmentation. Secondary land conversion can degrade habitats.
Wildlife	Ecological traps: polarised reflected light attracts some aquatic insects, birds, and bats. This can be mitigated with surface coating.[87] Panels provide shelter in grasslands.	Birds and bats can collide with wind turbines, especially near migratory routes.	Dams can disrupt aquatic populations. Reservoirs can create new aquatic habitats.	Operations create noise and light pollution. Monocultures reduce biodiversity and food/fodder for animals, including pollinators.	Roads and transmission corridors can provide access for predators and illegal hunting.
Pollution and ecosystem functions	Panel production can release toxic chemicals. Decommissioned panels are hard to recycle, producing long-lived waste.[88,89]	Wind turbines create noise and visual impacts. Decommissioned blades are hard to recycle, producing long-lived waste.	Altered flow patterns can affect water quality.	Intensive production uses agrochemicals. Biofuel processing and combustion create air pollution.	Pollution risks from spills and accidents.

Impact Area	Solar[77]	Wind[78,79,80]	Hydropower[81]	Bioenergy crop production[82,83,84]	Storage, infrastructure, and mining[85]
People					
Land conflict	Land acquisition can violate land rights and create conflicts over benefit sharing. Community-led development can improve land management and increase land productivity.				
Displacement	Energy production on productive land can lead to economic displacement. Large-scale land acquisition and land flooding for new reservoirs can physically displace local communities.				
Energy access	Microgrids can provide access in off-grid communities.	Microgrids can provide access in off-grid communities.	Integrating hydro with other renewables can improve grid stability.	Biomass can provide baseload power and stabilise hybrid grids.	Storage can stabilise grids with a high degree of intermittent generation.
Economic opportunities	Diversification of farmer incomes Job creation for construction and maintenance Electricity access opens new opportunities				
Food security	In agrivoltaic applications, shade and wind protection improve the resilience of food production to climate stress.	n/a	Reservoirs can enable irrigation for higher and more resilient yields. Reservoirs can be used for aquaculture.	Biomass production can compete with agricultural land use.	n/a

Source: See endnotes in table.

3.0 Powering Sustainable Land Management With Renewable Energy

Energy and land are connected in multiple complex ways. The relatively higher land footprint per unit of energy generated and the need to space out renewable energy installations like wind turbines create risks, as well as opportunities, for land. The risks include increasing competition for land and accelerating land degradation when the expansion of renewable energy generation is driven solely by energy-related objectives. However, the overall impact of the renewable energy transition on land does not have to be negative. As the previous chapter has shown, many interactions between renewable energy and land can impact land in both negative and positive ways. The opportunity lies thus in identifying potential negative and positive impacts and strategically designing mutually supportive land-use systems. This section outlines key strategies, approaches, and opportunities that can reduce land demand and support SLM.

3.1 Avoiding Land Degradation

These strategies focus on co-locating renewable energy installations with existing infrastructure, such as buildings or roads, rail and other transport infrastructure, or with other land uses, such as agriculture, to maximise land-use efficiency.

Integration with Buildings and Other Infrastructure

The simplest method to reduce land demand for renewable energy is to place renewable energy installations on land that is already occupied by buildings or infrastructure. Solar panels can be installed on roofs, over streets and parking lots, between train rails, and even in public spaces in need of shading. These locations are close to energy consumption sites and can often benefit from existing transmission infrastructure. Estimates of the potential for rooftop solar vary with the methods applied and assumptions made. A 2021 study estimated the global technical potential for rooftop solar at 27,000 TWh/y, with 10,000 TWh/y that could be economically viable after accounting for factors like building orientation, shading, structural capacity and local electricity costs.[90] (Global electricity demand in 2024 was 30,856 TWh.[91]) Another study estimates that potential reductions in CO_2 emissions from rooftop solar could reduce global temperatures by 0.05°C–0.13°C by 2050.[92]

Siting on Degraded Land

Concentrated solar plants, PV solar, and wind turbines can be built on abandoned or contaminated land like former mines, closed landfills, retired industrial plants, or abandoned farmland. This practice reclaims unproductive land for new economic income streams, which often reduces public opposition to large-scale renewable energy development. Wind and solar energy development can also be combined with decontamination and restoration practices. Marginal and lightly contaminated land that is unsuitable for food production can also be used for biomass production. This option is considered in Section 3.2.

In the United States, an analysis identified nearly 2 million ha of federally owned degraded lands (brownfields, closed landfills, and abandoned mines) where solar and wind power could collectively generate 114 TWh/y of electricity without any net land take.[93] Using a wider definition of marginal land as areas with inherent disadvantages or lands that have been marginalised by natural and/or artificial forces, another study identified 86,5 million ha of marginal lands that could theoretically be used to generate up to 11,200 TWh/y from PV solar, CSP, and wind power.[94] Similarly, in China, the amount of land considered degraded far exceeds the projected land demand for solar installations.[95] These estimates should be treated with caution, however, as they do not consider other constraints or potential environmental impacts of using degraded land for renewable energy generation.

Siting on Water

Floating photovoltaic systems (FPV) are another strategy to reduce land demand for renewable energy. FPV systems are up to 15% more efficient due to water cooling. They reduce water evaporation and can, under certain conditions, improve water ecosystems.[96] In shallow waters, on the other hand, panels can promote the growth of cyanobacteria, which can deteriorate water quality.[97] Other potential environmental impacts include the alteration of water bodies and impacts on water temperature, noise production, and the leaching of chemicals into water bodies.[98] Siting solar panels on hydroelectric reservoirs or water storage ponds further increases land-use efficiency and provides electricity for irrigation infrastructure and water management. Installing FPVs on 30% of global water reservoirs could generate approximately 9,500 TWh/y of electricity and render many communities self-sufficient in energy.[99] Another study that included reservoirs and other water bodies estimates generation of up to 14,906 TWh/y, noting that FPVs could contribute a considerable fraction to the energy demand and decarbonising strategies of many countries.[100]

Hybrid Renewable Energy Systems

Combining several renewable energy sources and energy storage into a single interconnected grid creates a more efficient and more reliable power supply, reducing the overall LUIE of the system. Integrating intermittent wind and solar generation with more stable hydropower or biomass-fuelled generation, for example, can provide a continuous electricity supply in remote and off-grid regions.[101] A study from South Africa, for example, showed that hybrid systems improve efficiency and reliability while also reducing GHG emissions and fostering local economic development.[102] Hybrid systems are complex, and their establishment and management require careful, system-level integration, policy support, public engagement, and cross-sectoral collaboration.[103]

Dual Land Use

Dual land use refers to the co-location of different productive uses on the same piece of land, such as placing wind turbines on fields or pastures, allowing most of the agricultural land use to continue with relatively small impact. Approaches that integrate solar panels with agriculture (agrivoltaics), using the land between solar panels as pasture (rangevoltaics), or combining solar panels with efforts to restore or conserve nature (ecovoltaics) are becoming increasingly popular. These designs not only increase land-use efficiency as the combined output of the activities per unit of land is higher than each activity alone, but they also produce co-benefits through shading and other impacts that can improve soil quality (discussed in more detail in Section 3). Using solar panels to provide shade for livestock, for example, improves the well-being and productivity of wool sheep and lambs raised for meat consumption in tropical countries.[104] In a model-based pre-feasibility study, Dupraz et al. estimated that agrivoltaic systems could achieve a land-equivalent ratio (LER), a quantitative measure of combined food and energy yield per unit of land, of between 1.35 and 1.7.[105] A recent systematic review of agrivoltaics research states that LER is highly site specific, noting that only a few studies have attempted to determine real-world LER values. However, the review found multiple examples of economic productivity, which can be an indication of increased land productivity.

The total annual revenue of agrivoltaic systems exceeded that of agriculture-only systems by a factor of 4 to 15 for different production systems. The authors note that agrivoltaics could significantly reduce the amount of land required to reach net-zero emissions targets when focusing on opportunities where the shade from solar panels benefits crop production. It should be noted, however, that research on agrivoltaics is highly concentrated in industrialised countries, China, and India. More research from other regions reflecting diverse ecosystems and agricultural production systems is needed to better understand how agrivoltaics projects impact food production and how they can be optimised in underrepresented regions.[106]

3.2 Reducing and Reversing Land Degradation

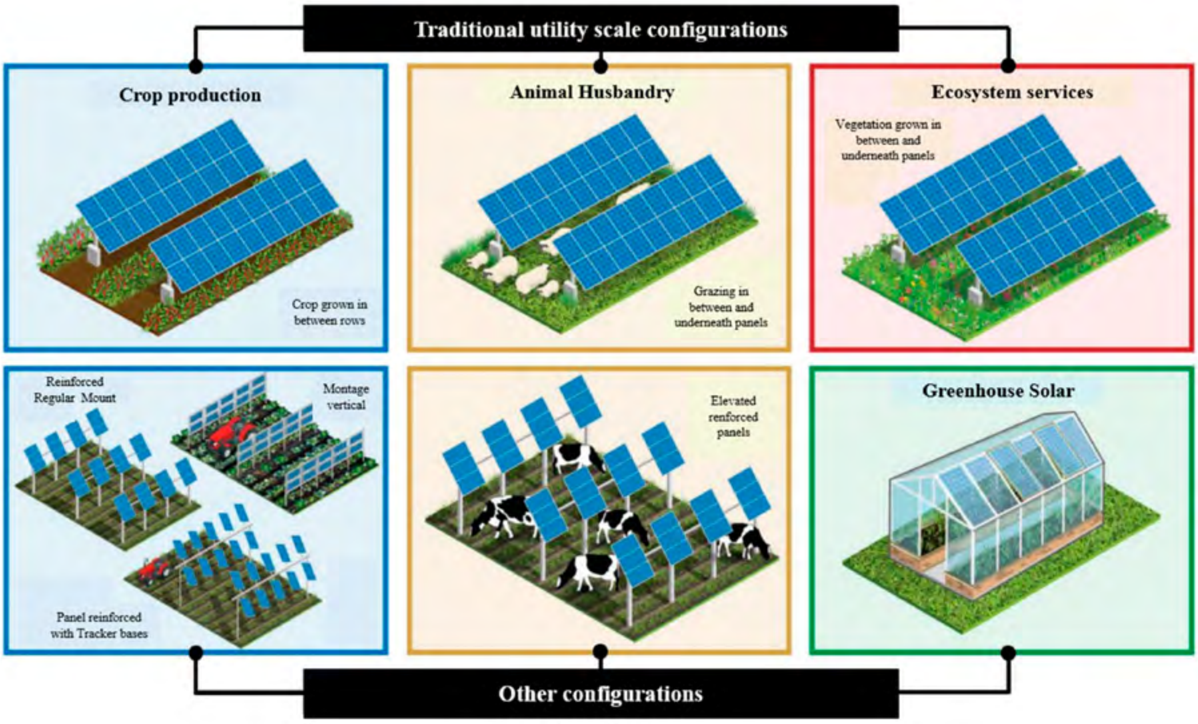
The strategies in the previous section were discussed with a focus on reducing land demand, even though several approaches also affect land quality. This section looks at strategies that aim to intentionally create mutually supportive land-use systems, where the siting, design, and operation of renewable energy infrastructure avoid adverse impacts on land quality and other land uses and maximise positive contributions. The most common examples are agrivoltaics and ecovoltaics, where solar panel arrays are designed to provide shade for plants and animals, provide wind breaks, and support water management. The third approach discussed in this section—modernising bioenergy—focuses on the role of biomass for local energy supply.

Agrivoltaics

Agrivoltaics is the co-location and co-management of PV solar energy facilities with agricultural production. The installation of solar panels can be optimised for different forms of agricultural or agroforestry production, such as crop cultivation, livestock grazing, the creation of pollinator habitats, or the cultivation of fruit trees. Agrivoltaics can improve land-use efficiency, reduce energy input costs, and create new income streams for landowners, such as sales to the grid.[107] Research shows agrivoltaic systems can improve the efficiency of water use by 20%–47% and reduce air and soil temperatures by 1°C –4°C.[108] By combining farming and solar energy on the same land, agrivoltaics can boost total agricultural productivity. Studies suggest that this approach can deliver 1.35 to 1.7 times more output than using separate plots for each activity.[109]

Solar panels on fields provide shade, reducing evapotranspiration and heat stress for crops. This reduces water consumption, can increase output for certain types of crops, and can make farming more resilient to heat, drought, and other climate-related impacts. The panels can also shade livestock and even serve as windbreaks in areas prone to desertification, land degradation, and sand and dust storms.[110] In some regions with seasonal rainfall, panels have been equipped with gutters to capture and store excess rainfall water for irrigation later. A review of studies in African countries finds that applying a water–energy–food nexus lens to designing agrivoltaic systems can deliver "symbiotic" benefits in regions facing the complex challenges of achieving high PV development targets under land and water constraints.[111]

Figure 2. Agrivoltaic system designs



Source: Sarr et al., 2023.[112]

Like other PV solar systems, agrivoltaic systems are highly scalable and can be used with other components, such as battery storage, to establish microgrids. This enables deployment in small, off-grid communities where access to cheap, clean electricity can unlock further opportunities to improve land management, such as irrigation or reduced food waste (see Section 3.3). On the other end of the spectrum, large, utility-scale agrivoltaic projects could make significant contributions to the decarbonisation of energy systems and improve the management of land and water resources while enhancing the resilience of food and energy systems.

Researchers and engineers are exploring opportunities to produce green hydrogen with agrivoltaics systems. Green hydrogen could provide a zero-emission fuel for agricultural machinery and reduce the emissions and fossil fuel dependence of fertiliser production.[113,114] Initial applications are likely limited to large-scale systems in areas with existing infrastructure for hydrogen transport, storage, and processing.[115] Unlocking this potential requires research for a better understanding of the impacts of agrivoltaics on energy, plant, and animal production; impacts on biodiversity across a wide range of environments; soil types and plant species; improved knowledge on how technological development can improve agrivoltaics benefits; and a better understanding of landowners, farmers, and other key stakeholders' constraints to the wider adoption of agrivoltaics.[116]

Case Study 1. Using agrivoltaics to reverse land degradation in China

The CHINT-Jiangshan Solar Park in Jiangshan city, Zhejiang Province, China is a privately-owned, commercial-scale 200 MW grid-connected PV power plant covering 4.2 square kilometres on agricultural land that was degraded due to severe soil erosion.

The shading created by the solar panels and the plants resulted in a microclimate that increased soil water storage, mitigating soil erosion and increasing soil fertility. The project used a multi-layer planting approach, including a combination of shade-tolerant plants, mostly Chinese herbs with high economic value, and sun-loving species, such as vegetables and kiwifruit, to maximise economic output. The shaded vegetation improved ground cover from 1% on the previously degraded soil to 90% after installation.

The project is expected to prevent emissions of about 4.5 million tonnes of CO_2 over its 25-year operational period. It has supported local economic development by creating employment for 120 to 150 local people and benefiting nearly 1,000 farmers. The power generated (an expected total of 4.9 billion kWh) can meet the annual electricity demand of 100,000 households in Jiangshan City.

The authors note that professional cultivation technicians were hired to develop the agricultural management plan and determine solar panel height and spacing. This case demonstrates the importance of technical expertise for the design of successful agrivoltaic systems. The authors also note that, in China, agrivoltaic systems avoid administrative hurdles that complicate land acquisition for single-use PV solar systems.[117]

While some crops, like brassicas or leafy greens and root crops, have demonstrated increased yields when paired with agrivoltaics, crops requiring elevated levels of sunlight, like wheat, corn, and rice, produce mixed results. Site-specific testing and selection of appropriate crops is essential for successful agrivoltaic implementation.[118] Further research is needed to assess the impact of agrivoltaics under various climate and soil conditions.[119] Research on the impact on livestock is more limited, but preliminary studies show that sheep and cattle benefit from reduced heat load in hot climates, which reduces the amount of energy animals spend on thermoregulation. One study found that the avoided carbon emissions from solar panels used to provide shade for dairy cows can offset the enteric methane emissions released.[120]

A related concern is the impact of utility-scale renewable energy projects on pastoral lands. While many pastoral lands have ideal conditions for both solar and wind energy generation, cases have been documented where the top-down implementation of renewable energy projects has ignored the human and land rights of pastoral communities, leading to land conflict and negative impacts on communities and their livestock. A study commissioned by the Heinrich Böll Foundation finds that in cases where solar farms have been built without participation and the Free, Prior, and Informed Consent of local communities, pastoralists lost access to pasture and felt that their land and cultural rights had been violated. In cases where consultations were conducted before siting and where wind turbines were the primary renewable energy installation, pastoralists retained full access to land and reached benefit-sharing agreements with energy companies.[121] Noting that successful projects share inclusive and participatory designs, the authors recommend, among other actions, that policy-makers should prioritise open discussions with informed civil society, especially local communities in project areas, to design projects for a mutually beneficial green transition.

Case Study 2. Advancing land efficiency through agrivoltaics in Mali and The Gambia[122]

The APV-MaGa project, implemented in Mali and The Gambia and coordinated by the United Nations University (UNU-VIE) in Bonn, Germany, demonstrates the innovative integration of solar energy generation, agricultural cultivation, and efficient water management on the same land. This "triple-land-use" model showcases how agrivoltaic systems can significantly improve land-use efficiency, boost effective water use, and increase farmers' incomes while promoting environmental conservation.

In The Gambia, the project operates across three pilot sites, each reflecting a unique business model and highlighting the adaptability of agrivoltaic systems to varying socio-economic conditions.

The Fass Community Women's Garden represents a community-led approach empowering over 350 women engaged in vegetable farming. The Afri-Farm site demonstrates private sector engagement, testing commercial models that link renewable energy to market-oriented agriculture. The University of The Gambia site supports academic research, innovation, and student training, contributing to knowledge generation in the water–energy–food nexus. Together, these sites illustrate a holistic, multisectoral approach to sustainable energy and land use.

Located near the village entrance and just 200 metres from the main highway, the Fass Women's Garden is off-grid, with limited access to solar power. The existing 4,000-litre borehole falls short of meeting the garden's irrigation demands, especially during peak sunlight hours when water pumping is constrained. Irrigation is labour intensive and manually conducted using watering cans, with little access to formal water management tools. Energy access constraints also limit opportunities for food processing and preservation, resulting in 15%–20% post-harvest losses each season.

The introduction of an agrivoltaic system at Fass aims to provide clean, reliable power for irrigation and processing and open new economic pathways for women through the productive use of energy, reduced post-harvest losses, and improved water availability. After collaborative consultations, the project scaled down the originally planned 60 kWp system to a more sustainable 20 kWp installation. The savings were reinvested to expand the irrigated area (now 0.71 ha) and support income-generating activities such as groundnut processing and water pumping—directly enhancing livelihoods, food security, and climate resilience.

Notably, in The Gambia, the systems were installed and commissioned by female technicians, challenging traditional gender roles and creating local employment in both energy and agriculture. The project also provided hands-on training in system operation, maintenance, and basic repairs, building technical capacity within the community and reducing reliance on external support.

From design to implementation, APV-MaGa places community participation at the centre. Co-design workshops unite farmers, local organisations, village leaders, and universities to tailor systems to local needs, considering crop types, energy use, water access, and gender roles. Participatory site selection ensures systems are installed where they offer the most value and are welcomed by the community. Shared ownership and sustainability are fostered by involving communities throughout the project life cycle.

Key insights from these cases include that community engagement is essential for long-term success; tailored, context-specific solutions outperform one-size-fits-all approaches; avoiding top-down planning prevents project failure and resource waste; and renewable energy and land-use strategies must be co-developed with communities to ensure relevance, ownership, and lasting impact.

Agrivoltaics is the fastest-growing type of dual-land-use renewable energy installation, with installed capacity growing from 5 MWp in 2012 to 14 GWp in 2021. Key challenges that currently prevent wider adoption include the high upfront cost, which partly depends on the need to adapt panel size and height to prevailing crop types and grazing behaviour.[123] From a producer's perspective, key barriers include uncertainty regarding long-term land productivity, uncertainty over market potential, the need for just compensation, and the need to build in flexibility to adapt to future changes in production.[124]

Ecovoltaics

Ecovoltaics incorporates ecological principles into the design and management of solar arrays to achieve a "nature-positive" approach to PV energy generation, as it protects biodiversity and enhances ecosystem services. The key principles of ecovoltaics include the co-prioritisation of energy generation and ecological functions and balancing energy and conservation perspectives during planning and design, rather than subjugating nature and wildlife to the disruptions and restrictions imposed by PV panel design.[125] Ecovoltaic system design aims to create or protect natural habitats with native vegetation, thus contributing to biodiversity conservation.[126] While ecovoltaic systems can be implemented in various ecosystems, they are especially promising in semi-arid grasslands, where most large-scale applications have been implemented to date.[127]

In practice, this means the design of solar arrays can reduce energy output potential to optimise plant growth and other biodiversity outcomes. In many arid and semi-arid ecosystems, for example, plant growth is limited by water stress, especially during the hottest hours of the day. Ecovoltaics prioritises plant growth in the morning by orienting panels to maximise photosynthetic activity, whereas in the afternoon, panels are oriented for maximum energy generation while shading plants to reduce water stress and evaporation. Ecovoltaics can thus support more diverse and resilient ecosystems. While the temporal prioritisation of plant growth reduces panel efficiency, it allows for increased panel density, which can increase land-use efficiency.[128]

Panels can also be sited to create structurally diverse ecosystems with shaded and unshaded areas, creating microclimates that support greater biodiversity. Ecovoltaics approaches are best suited for solar energy generation on semi-arid grasslands and marginal lands, where the focus on ecosystem functions can support biodiversity habitat conservation, carbon sequestration, and other ecosystem services. Ecovoltaics principles can also reduce the environmental impact of agrivoltaic systems by incorporating ecological understanding for better biodiversity conservation and improved resilience.[129] Ecovoltaics can be understood as multi-functional cooperation between energy, social, and ecological land use. To realise this opportunity, regulatory and legal systems must address barriers to cooperation that exist in large-scale solar regulatory frameworks.[130]

Both agrivoltaic and ecovoltaic approaches underline the importance of incorporating site-specific knowledge in the design of solar PV facilities. Successful projects (see Case Study 1 above) intentionally include technical and scientific experts in the development and management of solar energy projects. Another aspect is detailed biophysical monitoring to ensure that the desired ecosystem benefits are realised and enable adaptive management and continuous learning. While agrivoltaic approaches are well established, ecovoltaics is a new concept requiring additional research. In time, ecovoltaics can inform a second generation of agrivoltaics projects that balance energy and food production with biodiversity conservation and carbon sequestration or other ecosystem services.[131]

PV Cooling of Greenhouses

Solar panels can also be installed on greenhouses for cooling to support food production in harsh climates and reduce competition for land.[132] In the Sahel region, conventional greenhouse technology generates an unfavourable microclimate. PV panels can reduce temperature, relative humidity, and solar irradiance to enable crop production.[133]

Box 5. The role of information technology

Advanced data, Internet of Things technologies, and artificial intelligence (AI) enable new approaches to advance renewable energy expansion, develop efficient and stable microgrids, connect people in remote areas, and make new tools and technologies accessible.

AI can facilitate the integration of renewable energy sources with electrical grids by optimising energy distribution, forecasting supply and demand, and reducing energy waste through predictive analytics. This can stabilise rural microgrids to realise the economic development benefits of energy access.[134]

In microgrids, where agricultural operations may create peak loads, demand forecasting can also optimise the scheduling of energy-intensive processes. India, Kenya, and other countries are starting to use these technologies to introduce smart irrigation systems that use real-time data to optimise irrigation timing with grid load and save water.[135]

Internet of Things technologies and remote sensing also improve the performance of Productive Uses of Renewable Energy (PURE) technologies. For example, in combination with satellite data and remote sensing data, AI can support site selection for renewable energy installations, allowing communities and renewable energy developers to consider degradation risks and the value of land for agriculture and ecosystem services when siting new renewable energy installations (see Case Study 5).

Connected devices enable pay-as-you-go business models as service providers that can shut down devices remotely at the end of a payment period or when payment is delayed. Sensors can also detect malfunctions in connected irrigation and cooling systems, enabling real-time alerts to producers and timely maintenance of devices.[136]

The LDN framework and response hierarchy lend themselves to the application of assessment tools using geospatial and other forms of data. These include the Global Agro-ecological Zoning Tool and the Land-Potential Knowledge System (LandPKS). The latter uses crowd-sourced community data and geospatial data together.[137] Monitoring is especially crucial, as regular checks of the status of land cover, soil organic carbon, net primary productivity, and overall land health can support long-term planning for renewable energy installations.

India is using geographic information system (GIS) data and mapping to not only identify areas for renewable energy expansion, but also to optimise existing infrastructure by improving grid efficiency and enhancing transmission lines.[138]

Onshore Wind Farms

Onshore wind farms, like PV solar, can be co-located with agriculture and other productive uses or conservation areas to significantly reduce LUIE. Wind turbines have a small land footprint that leaves 90% of the land available for agriculture or pasture, rendering co-location a strategic approach.[139] Wind turbines have a low direct impact on the vegetation below, which means they neither enhance nor restrict plant growth. While wind farms can be a hazard to birds and bats, and the need for access roads and transmission lines can contribute to habitat fragmentation, many of these impacts can be mitigated through careful planning and management.[140] Wind turbines combined with solar PV reduce intermittency in energy supply and generate higher economic benefits and employment opportunities.[141]

Key barriers to the expansion of co-located wind farms include local opposition due to their aesthetic impact on the landscape and the audible noise generated. These impacts can restrict the use of wind farms in the vicinity of settlements and may lead to complicated permitting processes.[142] Research on community-driven wind farm development and siting has shown that local opposition can be overcome through transparent and accountable benefit-sharing agreements involving all communities affected by the audio-visual impacts of wind farms.[143] As wind generation technology evolves rapidly in both smaller-scale and larger-scale installations, these will need to be tailored to optimise the choice of wind installation for local conditions and to respond to community needs.

Bioenergy

Modern bioenergy technologies use biomass feedstocks to generate heat, electricity, or fuels, such as biogas, bio-methanol, and biodiesel. Some processes create nutrient-rich residues that can be used as fertiliser. Biomass processing technologies, such as gasification or anaerobic digestion, generate fuels that are more efficient, less polluting, and can replace traditional, unsustainable biomass sourcing practices, such as fuelwood harvesting, and reduce impacts on natural forests and degraded land.[144] Under certain conditions, for example, where large quantities of biomass residue are available, modern uses of bioenergy can be part of a sustainable energy mix that enables new types of businesses and encourages local innovation (see Case Study 3). Transitioning from traditional biomass use toward renewable energy sources like wind, solar, and hydro can create multiple benefits for local communities, including improved energy access, better health, and reduced land degradation and deforestation. This transition must involve local stakeholders, ensure access to alternatives is affordable, and safeguard livelihoods tied to biomass supply chains to guarantee that solutions are culturally appropriate and do not exacerbate social or gender inequalities.

The use of invasive species for bioenergy production is another pathway for addressing the growing demand for renewable energy and the restoration of degraded land and ecosystems.[145,146] For example, in South Africa, invasive species, which cover 10% of the land surface area, degrade ecosystems, disrupt biodiversity, increase fire severity, and use up to 6% of freshwater resources. Stewards of Nature/Coega Biomass Centre's pilot project converted the invasive species biomass into pellets, estimating the "average amount of water savings per tonne of biomass between 70-80 m^3 and 105-125 m^3 per tonne of pellets."[147] Namibia is building a biomass power plant that will be powered by encroacher bush to support the restoration of degraded land;[148] meanwhile, several countries are producing biochar from invasive species to support land restoration and climate change mitigation.[149]

Box 6. Bioenergy with carbon capture and storage

BECCS describes the use of biomass for heat or electricity generation, combined with the capture and permanent storage of the CO_2 released. Since plants absorb CO_2 as they grow, BECCS results in negative emissions if the stored amount of carbon exceeds emissions created during the production, transport, and processing of the bioenergy feedstock. However, the efficiency of the process and its potential contribution to a net-zero transition are still subject to debate, as carbon capture is energy intensive and permanent storage requires infrastructure and adequate geological formations for sequestration.[150] The large-scale deployment of BECCS to balance the carbon budget of the fossil fuel energy sector would require devoting significant land area to biomass production. King et al. (2023) estimate that BECCS would require 247.5 million ha of land if it could be deployed rapidly. Under a delayed deployment scenario, the land required for BECCs could triple.[151]

Certain bioenergy crops can be cultivated on already-degraded land, reducing competition for fertile agricultural land to generate energy. The use of perennial crops like grasses and short-rotation coppice (woodlands with fast-growing tree species) can support the regeneration of degraded land. Similarly, agroforestry approaches that integrate biomass production with sustainable forest management can restore degraded forests.[152]

Case Study 3. Rice straw management in Asia

Using rice straw for bioenergy conversion is a crucial strategy for renewable energy generation and sustainable residue management, particularly across Asia, which accounts for more than 90% of global rice production. Traditional residue management methods release significant amounts of GHGs. Open-field burning in India, for example, emits 197.65 million tonnes of CO_2 equivalent annually. Incorporation into flooded fields releases between 3,500 and 4,500 kg CO_2 equivalent of methane (CH_4) per hectare.[153]

Rice straw is converted into various energy forms (heat, steam, methanol, biogas, biochar) through thermochemical pathways (combustion, gasification, pyrolysis) and biological pathways (fermentation, anaerobic digestion). Bioenergy conversion mitigates emissions and reduces reliance on fossil fuels. Since it uses agricultural residue, it creates no additional demand for land. Anaerobic digestion produces a compost-like digestate that can be used as organic fertiliser. Pyrolytic gasification produces biochar, which enhances microbial activity and the water-holding capacity of soils. Bioconversion initiatives also foster rural development by creating employment and offering additional income streams for farmers, such as selling biomass or generating carbon credits.[154]

Challenges revolve around high implementation and labour costs caused by the low density and bulky nature of rice straw. Overcoming these challenges requires strategies such as spatial planning (GIS) to site processing facilities so that the transport of bulky biomass is minimised, but convenient access is provided to densified products such as wood pellets and briquettes. Smallholder farmers require training and incentives to make the switch from traditional practices to modern biomass fuels.[155] As the following examples show, rice straw conversion can be undertaken at various scales adapted to local needs and conditions.

In Assam, **India**, GIS data were used to develop an optimised supply chain network among 90 villages for bio-methanol production and use. The project mitigates GHG emissions and air pollution from open-field burning and avoids the loss of soil nutrients associated with combustion. The carbon footprint of the bioethanol produced is also significantly lower than that of non-renewable fuels.[156]

In **Thailand**, a recent study compared three utilisation strategies: biomass fuel pellets, high-tech biochar, and low-tech biochar. The study showed that high-tech biochar produced with modern, industrial-scale equipment and advanced engineering creates negative emissions when used as a soil additive, typically mixed with fertiliser. Biochar stably sequesters carbon and improves soil organic chemistry, which reduces nitrogen dioxide (NO_2) emissions, another potent GHG.[157]

In Laguna province, **Philippines**, researchers surveyed farming households to identify preferred business models for the conversion of rice straw into biogas. Farmers favoured business models that offered broader socio-economic benefits beyond energy access. The most supported model created opportunities for diversifying agricultural activities and generating additional income through mushroom cultivation using the digestate. Farmers also valued digestate organic fertiliser to replace mineral fertilisers.[158]

3.3 Leveraging Productive Uses of Renewable Energy

Improved access to low-cost energy at the farm and community levels provides critical support for sustainable water management in agriculture, zero-emissions farm machinery, and food processing and storage that can reduce food loss and improve supply chain integration. PURE, also referred to as Productive Uses Leveraging Solar Energy (PULSE), involves deploying renewable energy resources, primarily off-grid and mini-grid solar, to enhance income generation, farm productivity, and rural welfare through agricultural, commercial, and industrial activities.[159]

Water Management

Water management: Solar water pumping and irrigation technologies are recognised as proven technologies that are ready to scale.[160] In many semi-arid and arid regions, solar-powered drip irrigation can enhance food security by conserving water and improving power reliability. When replacing diesel-powered pumps, renewable energy-powered alternatives reduce GHG emissions and exposure to unreliable fuel supplies and fluctuating prices.[161] Solar PV technology is becoming more affordable. Over the past 15 years, the global cost of solar energy has decreased rapidly. The average levelised cost of electricity, a measure of the lifetime cost per unit of energy produced, for solar power has decreased by almost 90%, from USD 0.417/kWh in 2010 to USD 0.043/kWh in 2024.[162] Solar panels have become more affordable. In 2019, the payback time for investing in a small water pump was estimated to be 1.5 years for a pump that can be expected to last 10–20 years.[163]

The introduction of reliable, affordable energy, such as solar-powered irrigation, should be combined with water-conservation techniques like drip irrigation and policies that incentivise SLM to avoid overexploitation of groundwater sources. Policy design must consider cross-sectoral impacts on water and land use and incentivise efficient resource use, such as agrivoltaic systems or maximising the use of degraded arable land.[164]

Case Study 4. Solar irrigation in India, Kenya[165] and Egypt[166]

Solar energy solutions, particularly solar-powered water pumps (SWPs) and agrivoltaics, are driving significant improvements in water management, SLM, and community livelihoods across Kenya, India, and Egypt, directly impacting climate resilience and biodiversity.

In India, the government subsidises the replacement of diesel-powered water pumps with solar-powered irrigation systems. The use of solar pumping has boosted farmers' annual incomes by 50% or more compared to rain-fed agriculture, while reducing life-cycle emissions by an estimated 95% to 98% compared to grid electricity or diesel-powered pumps. To prevent groundwater depletion, solar cooperatives were established to allow farmers to sell surplus energy back to the grid, providing diversified income and regulating water usage to minimise groundwater depletion.

In Kenya, the conversion from diesel to solar-powered irrigation pumps has boosted farm incomes by 158%, while avoiding pollution from combustion, such as fine particulate matter and black carbon. Solar water pumps are also enabling the reactivation of non-operable wells that have been abandoned because of unreliable fuel supply.

In Egypt, which faces significant water stress, the Sustainable Agriculture Investments and Livelihoods (SAIL) project supports smallholder farmers by providing access to capital for investing in solar-powered pumps and other climate-smart solutions. The funding primarily focuses on enhancing efficient water use on farms. This targeted investment aims to address the challenges of climate variability and growing water demand by leveraging solar energy to conserve scarce water resources.

Processing

Other PURE technologies can also be applied to milling, heating, chilling, milking, processing, and small machinery that allow farmers to boost land productivity and crop yields. While some of these applications do not match the energy output of fossil fuel-powered alternatives, they can make a significant contribution to increasing agricultural productivity in off-grid communities and areas with unreliable diesel supply.[167]

Food Loss Reduction

Access to reliable, low-cost energy can also enable the reduction of post-harvest food losses through the adoption of storage, processing, and cold chain technologies.[168] In 2021, the share of post-harvest loss was estimated at 13.2% of global food production, with the highest regional rates occurring in Western Africa (23.6%), Southern Africa (20.3%), and sub-Saharan Africa (19.9%).[169] Cooling and chilling facilities are essential for reducing post-harvest losses. Solar cold storage facilities at the farm gate can reduce post-harvest losses by 30% to 40%.[170] Solar-powered micro cold storage systems can be integrated with electric vehicles to effectively mitigate post-harvest losses during transportation. This renewable energy solution addresses the lack of decentralised cold storage infrastructure and facilitates climate-friendly logistics.

Economic Opportunities

PURE technologies create opportunities to increase household income through diversified activities and the establishment of small and medium-sized enterprises. Innovative business models can make PURE technologies affordable for smallholder farmers and livestock producers, enabling them to connect to markets and diversify their income through value-added processing and marketing activities. The Smart Energy Solutions for Africa Project, for example, supports the development of enterprises deploying innovative solar cooling technologies through a variety of business models:[171]

- **SokoFresh**,[172] Kenya, offers mobile, solar-powered cold rooms through various payment models, including rent, lease to own, and pay as you go, to make access to cooling affordable for small and medium-sized farms in Kenya.
- **Cold Hubs**,[173] Nigeria, combines solar-powered refrigerated warehouses and ice-point facilities with refrigerated transportation services, sustainable packaging, and streamlined supply chain management to support the distribution of locally grown produce to regional markets.

- **Koolboks**,[174] Nigeria, provides off-grid solar freezers for rent that can keep produce fresh for several days even in the absence of sunlight. The freezers enable smallholders, local butchers, food processors, and restaurants to keep food products cold and safe for sale at local markets. The company's cooling-as-a-service model eliminates the barrier of high upfront costs, making cooling solutions affordable.
- **SunCulture**,[175] Kenya, distributes solar water pumps and integrated solar drip irrigation systems through upfront or pay-as-you-grow purchase plans that include consultation, installation, training, and support.

These examples show that PURE technologies provide economic opportunities to smallholder farmers in off-grid communities and can be deployed through a variety of viable business models adapted to local needs and financial capacity. While it is generally accepted that increasing agricultural efficiency and reducing post-harvest losses can reduce land demand, there is little research on how these benefits can be maximised and what policies are most effective in delivering benefits from reduced food loss.[176]

Case Study 5. Energy Access Explorer

Developed by the World Resources Institute, the Energy Access Explorer is software designated as a "digital public good" that streamlines data sharing and management for the purpose of expanding clean energy access. With the power of data and this analytical tool, energy planners, clean energy enterprises, investors, and development organisations can identify key geospatial parameters of unserved and underserved populations, like crucial demographic data, often from a variety of different data sources.[177] This allows them to understand high-priority areas in need of energy service expansion by comparing spatial data on unmet demand with energy supply. This method has been successfully used in Nepal to expand energy access by answering the question of where energy is needed.[178]

The tool has proven especially useful for understanding the end users of energy, from residential households to institutions, businesses, and other uses.[179] This can be useful in the design of fit-for-purpose solutions to energy needs, especially in rural or underserved regions. The Energy Access Explorer can also incorporate data on land use and soil conditions and identify where renewable energy projects can have the most significant impact. By following LDN principles to protect, maintain, restore, and enhance the land resource base, governments, developers, and other stakeholders can determine where an energy project would meet energy goals, people's goals, and sustainability goals.

Some governments use the information acquired with this tool and implement the findings into their national strategies, like energy, digital transformation, or development plans. Barriers to this tool include jurisdictions that lack political commitment and infrastructure for open, collaborative approaches to data or poor relationships across data providers, meaning there is a need to establish trust between data providers and project administrators.

This chapter has outlined integrated approaches to renewable energy development and SLM that directly or indirectly contribute to LDN, biodiversity, climate, and socio-economic objectives. The literature reviewed for this primer shows that, in many cases, significant positive contributions to several or all these objectives are possible if projects are carefully designed. While the scope of this primer is insufficient to quantify the contributions that can be expected or comprehensively evaluate the weight of the evidence for each impact, it does allow for an initial assessment of the type of evidence available. Table 4 summarises what type of evidence was available for each approach and how each approach contributes to the stated objectives based on the evidence presented in the sources.

Table 4. Strategies to avoid land degradation and support land restoration

Approach and evidence assessed	Avoided land degradation	Reduced land degradation and restoration	Co-benefits for climate, biodiversity, and people	Evidence and knowledge gaps
Siting solar and wind energy on buildings and infrastructure: Evidence includes case studies from industrialised countries and global assessments of potential.	No direct footprint.	n/a	Can provide shading in public spaces. Economic opportunities.	Global assessments of potential must be "ground truthed" for different regions. Wind energy technology for siting on buildings is still emerging.
Siting solar and wind energy on marginal and degraded lands: Evidence includes spatial analyses and large-scale integrated assessment models, mostly from the United States, the European Union, and India.	Avoids additional land degradation.	Wind can be combined with land restoration. Solar can be designed to support restoration (see ecovoltaics).	Avoids detrimental ecological impacts on pristine or productive land and provides opportunities for ecosystem restoration, especially in highly degraded areas. Reduces risk of indirect land-use change emissions and creates opportunity for sequestration.	Gaps include assessments from other regions, including factors determining viability and guidance for policies and regulations.
Siting on water: Evidence includes case studies from industrialised countries and global assessments of potential.	No direct footprint.	n/a	Mixed impacts on aquatic ecosystems.	Global assessments of potential must be "ground truthed." More research on environmental impacts is needed.

Approach and evidence assessed	Avoided land degradation	Reduced land degradation and restoration	Co-benefits for climate, biodiversity, and people	Evidence and knowledge gaps
Agrivoltaics: Evidence is supported by numerous case studies and field experiments across diverse climatic regions using controlled comparisons, techno-economic modelling, and systematic reviews.	Reduces competition for productive land. Increases land-use efficiency.	Reduces negative impacts of agriculture, improves water retention and soil fertility. Can be designed to support restoration.	Can be designed to enhance native vegetation growth and provide pollinator habitats. Acts as a climate-smart strategy to mitigate heat/drought stress, conserving water and enhancing water-use efficiency. Energy access can displace fossil fuel use.	Gaps include research with a wider number of crops in various conditions and guidance policy development, as well as locally specific, participatory design.
Ecovoltaics: Mostly based on foundational ecological theory, modelling, and pilot projects in developed countries.	Can be designed to reclaim and restore degraded land.	Prevents degradation. Can be designed to support restoration.	Intentionally designed to enhance ecosystems (e.g., water quality, pollination, habitat) using native perennial vegetation and regenerative practices.	Research gaps include long-term studies on ecological impacts and cost-benefit analyses in different contexts.
Modern bioenergy: Evidence includes life-cycle analyses, economic modelling, and multicriteria analyses of pilot and implementation projects.	No to low impact on productive land.	Improves agricultural soil fertility through biofertilisers and potentially biochar.	Reduces/eliminates environmental impacts of certain traditional biomass uses (nutrient depletion, air pollution, GHG emissions).	Gaps include research on socio-economic impacts.

Approach and evidence assessed	Avoided land degradation	Reduced land degradation and restoration	Co-benefits for climate, biodiversity, and people	Evidence and knowledge gaps
PURE technologies for agricultural development: Evidence includes market assessments, regional case studies in Africa and India, and market-sizing activities to quantify opportunities for smallholder farmers.	Increases land-use efficiency.	Improves soil fertility and agricultural efficiency. Can improve management practices.	Enhances climate resilience through reliable access to water, cooling, and other services. Displaces fossil fuel use and reduces food loss. Provides fundamental energy access in remote areas, which creates jobs; specifically targets smallholder farmers, women, and youth.	The link between improved agricultural efficiency and best practices and land impacts has not been explicitly studied.

Sources: Compiled by the authors based on evidence presented in Section 3.

4.0 Policy, Governance, and Finance

The effectiveness of integrated solutions, such as agrivoltaics, ecovoltaics, modern bioenergy, strategic siting, and PURE technologies, is anchored in four interconnected pillars: policy integration and cross-sectoral coordination; regulatory frameworks and enabling environments; financial and fiscal mechanisms; and stakeholder engagement and capacity. These pillars must collectively address the complexity of the renewable energy–land nexus, while also considering linkages with water management and food security and the food–energy–land nexus to maximise synergies and manage inherent trade-offs.[180]

4.1 Fostering an Enabling Environment

Policy Integration and Cross-Sectoral Coordination

Integrated approaches demand that national planning moves beyond compartmentalised, or "siloed," policy-making, which has historically hindered the development of synergies between sectors like electricity and agriculture.[181] Effective governance requires a whole-of-government approach where ministries (of energy, agriculture, water, and finance) coordinate across multiple levels (national, subnational, and local) to deliver common solutions.[182] LDN implementation explicitly requires coherence between policies addressing separate environmental and development objectives. Parties are also expected to mainstream international commitments, such as those under the three Rio Conventions, into sector policies to achieve coherent implementation and exploit potential synergies. The success of PURE technologies, agrivoltaics, and modern bioenergy relies on inter-ministerial coordination platforms to define clear roles and responsibilities, preventing duplication and ambiguity among end users.

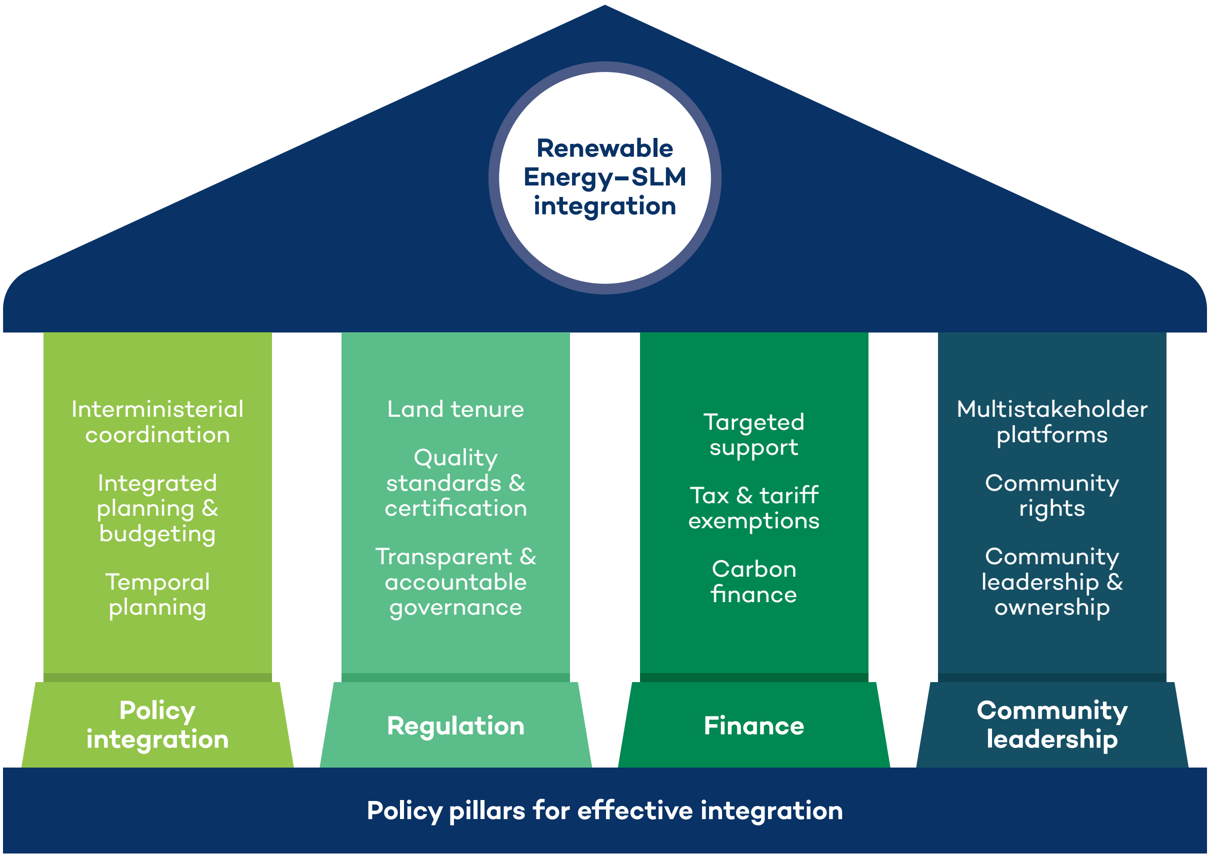
Box 7. Cross-sectoral coordination: Experiences from Uganda

In Uganda, energy needs were integrated within agriculture-led policies, which facilitated alignment with rural development priorities but created a risk of overlooking energy-specific considerations. Uganda's national irrigation policy, on the other hand, was co-developed between the ministries for agriculture and water and was aligned with Uganda's National Adaptation Plan and the National Climate Change Policy. While coordination during policy development was successful, implementation was hindered by financial constraints and institutional capacity. As the two examples show, coordination is a multifaceted challenge spanning policy development and implementation.[183]

Regulatory Frameworks and Enabling Environments

Robust regulatory frameworks provide the legal certainty, quality standards, and clear rules necessary to attract private investment and ensure the long-term sustainability of integrated multiple-land-use approaches and their benefits to communities. For agrivoltaics and strategic siting on marginal lands, regulations must be clarified to differentiate synergistic dual-use systems from conventional ground-mounted PV, which often faces opposition or is restricted on agricultural land.[184] Supportive land tenure legislation is critical to implementing the LDN framework and protecting the rights of vulnerable and marginalised land users, reinforcing responsible governance. Environmental and social risk assessments are key tools for guiding siting decisions. Ecovoltaics relies on regulatory tools, such as environmental impact assessments, to ensure biodiversity enhancement and restoration measures are an integral part of project design that are implemented upfront and promote ecological integrity.[185] For PURE technologies, unpredictable taxation policies, perverse incentive structures, and the absence of quality assurance standards hinder market growth and consumer trust. Thus, mandatory or voluntary quality assurance frameworks are needed for products like SWPs and solar refrigeration units.[186] Modern bioenergy adoption requires clear standards and guidelines for biochar production to ensure product efficacy and environmental protection.[187]

Figure 3. Policy pillars for the effective integration of renewable energy and SLM



Source: Compiled by the authors based on sources cited in endnotes #179-190.

Financial and Fiscal Mechanisms

Financial support is critical for overcoming the high upfront costs associated with innovative clean energy and agriculture solutions, especially for smallholder farmers in nascent markets. This pillar encompasses dedicated budgetary allocations, grants, subsidies, and incentives (e.g., tax/tariff exemptions) to reduce the affordability gap for PURE technologies, particularly in sub-Saharan Africa and South Asia.[188] Agrivoltaics often require financial incentives and subsidies to offset the substantial initial investment and risk, especially in the transition phase, with mechanisms like preferential feed-in tariffs proving effective. Modern bioenergy, particularly biochar generation, can be incentivised through financial support, targeted tax credits, or the establishment of carbon credit markets, acknowledging its long-term carbon sequestration benefits.[189]

Community Engagement, Leadership, and Co-Design

Stakeholder participation is crucial to ensure policy actions are context-specific, equitable, and locally sustainable. Stakeholders, especially land users, must be able to influence the design, implementation, and monitoring of interventions. This approach ensures solutions reinforce responsible and inclusive governance, particularly by protecting the land tenure rights of vulnerable and marginalised people. For modern bioenergy, a nature- and people-centric approach proved necessary in case studies, where community consultations revealed a preference for approaches offering wider livelihood benefits over simple energy access. In PURE technologies and subnational planning (e.g., in Kenya), building "bottom-up" demand through robust local participation is crucial for securing political buy-in and financial allocation for integrated projects.[190] For agrivoltaics and ecovoltaics, ensuring stakeholder engagement and using tools like community benefit agreements helps achieve strong community acceptance by addressing aesthetic and environmental concerns and managing potential conflicts and power dynamics between communities and developers.[191]

Table 5. Policy priority areas and actions

Policy priority area	Actions for national policy-makers
Policy integration	Establish formal inter-ministerial coordination bodies (e.g., ministries of energy, agriculture, water, and finance) to mainstream agrivoltaics, ecovoltaics, modern bioenergy, and PURE into cohesive national development and climate strategies.
	Integrate PURE solutions into national electrification plans and sector-specific development programmes, recognising PURE's role as a nexus element (e.g., in agriculture, health, and water programmes).
	Adopt integrated planning and budgeting frameworks that mandate financial departments to coordinate with technical ministries to ensure adequate and non-siloed budgetary allocations for integrated projects.
	Consider temporal planning to ensure that policies account for seasonal variations in energy generation, crop cycles, and water stress and respond to extreme weather events, such as droughts or floods.
Regulatory frameworks	Clarify land-use and tenure legislation to legally recognise and support the synergistic dual use of agrivoltaics and ecovoltaics on agricultural and degraded lands, distinguishing them from conventional utility PV.
	Develop and enforce quality standards and certification frameworks for PURE and modern bioenergy technologies (e.g., SWPs, solar refrigeration units, and biochar) to ensure high performance, reduce consumer risk, standardise quality, and address life-cycle and waste management.
	Reinforce responsible governance structures, including transparency and accountability mechanisms, and protect the land tenure rights of vulnerable and marginalised groups in line with LDN principles.
Financial and fiscal incentives	Implement targeted financial mechanisms (subsidies, grants, or results-based financing) to reduce the high upfront costs of agrivoltaic and PURE technologies for smallholder farmers and underserved communities.
	Introduce tax and tariff exemptions for core agrivoltaic and PURE components (e.g., PV panels, pumps, and refrigeration units) to improve affordability and encourage market growth while conducting tax harmonisation studies to maximise impact.
	Establish or leverage carbon financing instruments (e.g., carbon credits, subsidies for abatement value) to boost the financial viability of modern bioenergy projects, produce responsible biochar, and offer long-term and sustainable carbon sequestration strategies that consider the well-being and rights of communities and support multiple benefits.

Policy priority area	Actions for national policy-makers
Stakeholder engagement and capacity	Establish multistakeholder platforms through formalised national and subnational forums (e.g., new and renewable energy authorities, working groups, and alliances) that include farmer cooperatives, civil society organisations, community leaders, and local governments to ensure diverse viewpoints and inform integrated solutions.
	Strengthen community tenure and rights by implementing governance safeguards to protect the land tenure security and human rights of vulnerable and marginalised land users in line with LDN principles, especially when siting on marginal lands or implementing agrivoltaics/ecovoltaics.
	Incentivise bottom-up demand by designing mechanisms to ensure local/subnational inputs are incorporated into national policy development and budgetary allocations, encouraging politicians and planners to prioritise projects that align with locally expressed needs and co-designed solutions.
	Promote community-led models by providing dedicated support, financing, capacity building, and legal recognition to community-owned or cooperative models (e.g., energy communities) that empower citizens to participate actively in energy generation, consumption, and decision making (PURE, bioenergy). Train institutions and individuals in conflict resolution and provide access to legal support.

Source: Compiled by the authors based on sources cited in endnotes #179-190.

4.2 Operationalising Policy and Implementation Frameworks

Countries can use their LDN target-setting and planning processes under the UNCCD to balance renewable energy expansion and SLM. LDN emphasises the integration of new land uses into existing land-use planning systems. This is fundamental for effectively integrating renewable energy systems. Policy-makers can strategically include renewable systems in their voluntary LDN planning using the response hierarchy proposed in the Scientific Conceptual Framework for LDN: avoid, reduce, and reverse land degradation.[192,193]

- **Countries can avoid land degradation** by siting renewable energy systems on converted terrestrial lands or freshwater systems, such as buildings, infrastructure, canals, or reservoirs, to avoid using new land for renewable energy. Similarly, solar and wind projects can be sited on contaminated land unsuitable for agriculture. Deserts can also host large-scale wind and solar installations if they are sufficiently close to human settlements or existing grids and have sufficient water resources to support operations, and do not undermine biodiversity and ecological connectivity.
- **Countries can reduce land degradation** by designing location-specific, dual-use approaches such as agrivoltaics, ecovoltaics, PV cooling of greenhouses, wind in

pastoral lands, or by integrating bioenergy into the landscape. Land degradation can also be reduced indirectly by introducing productive uses of energy to improve land and water management, sustainably increase agricultural production, and reduce post-harvest losses to increase land-use efficiency and reduce competition for new land.

- **Countries can reverse land degradation** by producing bioenergy on suitable marginal or degraded land where feedstock cultivation can contribute to land restoration. They can also explore options to design solar systems that support land restoration through shading or wind protection.

SLM efforts that integrate LDN into the expansion of renewable energy are most effective when aligned with ILUP and integrated land management (ILM).[194] These approaches can unlock significant synergies between renewable energy and SLM while also contributing to global goals on climate change mitigation, adaptation, and biodiversity conservation. These efforts should be incorporated into the mix of policy instruments that the IPCC highlights as reducing costs and stimulating the adoption of mitigation options, including public research and development projects, funding for demonstration and pilot projects, and demand-pull instruments.[195]

- **ILUP** is the systematic assessment and allocation of land-based resources across a landscape, coordinating planning and management across multiple sectors and jurisdictions. ILUP seeks to identify the optimal combination of land uses that balances economic, social, and cultural opportunities with the need to safeguard resources for the future and maintain ecosystem services. It allows a consideration of diverse interests in the land that are increasingly recognised as key to environmental targets and to socio-economic and cultural values.
- **ILM** is a long-term collaboration among diverse stakeholders to achieve multiple objectives required from the landscape that manages ecological, social, and economic interactions. ILM aims to realise positive synergies and mitigate negative trade-offs, supporting participatory processes essential for achieving sustainability, resilience, and goals like LDN. It focuses on the development of management strategies for landscapes rather than determining how they are spatially parcelled or zoned.

National planning under the Rio Conventions provides a mechanism through which decision-makers can adopt a synergistic approach to achieve the objectives of all three. LDN planning under the UNCCD offers an entry point for these national efforts to integrate renewable energy into national planning processes for nationally determined contributions (NDCs) under the Paris Agreement on climate change and national biodiversity strategies and action plans (NBSAPs) under the Convention on Biological Diversity (CBD).

Renewable energy can be included in voluntary LDN targets, as it indirectly supports activities such as improving the efficiency of irrigation, improving stoves, and mobilising stakeholders by promoting economic viability. LDN strategies align with the UNCCD reporting cycles, which occur every 4 years. The next reporting round is in 2026.[196]

Under the UNFCCC, renewable energy is a core component of NDCs. Among the NDCs submitted in the second round, 71% include quantified renewable energy targets (e.g., solar, wind, hydro). Parties must submit NDCs every 5 years. The latest NDCs were due in February 2025.[197]

Under the CBD, renewable energy can indirectly support activities included in NBSAPs, such as reducing reliance on fossil fuel extraction, which can degrade ecosystems, and promoting renewable energy in protected areas or buffer zones to support local livelihoods. Updated NBSAPs were requested by the CBD's 16th Conference of the Parties (October–November 2024), where parties that had not yet done so were also urged to revise or update their NBSAPs as soon as possible.[198]

Countries should also consider reporting on the balancing of renewable energy and other development goals in their voluntary national reviews on SDG implementation, especially in years when the SDGs selected for in-depth review during the UN High-Level Political Forum include SDG 7 (access to clean energy), SDG 13 (climate action), or SDG 15 (life on land). Approximately 40 countries present their voluntary national reviews each year during the UN High-Level Political Forum. Countries decide when to update them, with many presenting updates at 4- or 5-year intervals.[199]

5.0 Findings and Recommendations

As the clean energy transition accelerates, decision makers face the question of how to support the decarbonisation of their electricity systems while meeting growing demand and without causing land degradation or competition for other uses, particularly agriculture. This primer has reviewed recent evidence on the complex interactions shaping the renewable energy–land nexus alongside strategies and approaches that can avoid, reduce, or reverse land degradation in the context of renewable energy expansion.

Findings on the renewable energy–land nexus:

- Knowledge on interactions between renewable energy sources and land is growing fast, providing a basis to assess the potential impacts of planned renewable energy projects and design measures to mitigate negative impacts and enhance co-benefits for the land, biodiversity, climate, and people.
- While LUIE is higher for renewable energy sources on average, real-world footprints vary with technology, design, and local conditions.
- Similarly, interactions between renewable energy components and surrounding land are highly site specific, influenced by landscapes, climate, ecosystems, and other land uses.
- Most potentially negative impacts on land quality, biodiversity, climate, and people are solvable, and co-benefits can be enhanced when design and management practices are informed by technical experts with local knowledge and led by local communities and other stakeholders.

Findings on strategies to avoid, reduce, and reverse land degradation in the context of renewable energy expansion:

- There are many approaches to avoid land conversion, reduce land degradation for renewable energy, mitigate negative impacts on adjacent land, and enhance co-benefits. This primer identifies three core strategies with multiple approaches.
- Strategies to avoid converting additional land for renewable energy include co-location with existing buildings or infrastructure, such as solar installations on rooftops, over roads and parking lots, or floating solar panels on water reservoirs and siting on degraded or marginal land like brownfields or abandoned agricultural land.
- Estimates based on remote sensing and modelling show significant global potential for these approaches, but are mostly theoretical. Countries should verify this potential with local data to consider technical, environmental, and socio-economic limitations.
- Strategies to reduce degradation caused by renewable energy projects or enhance contributions to restoration include agrivoltaics, the integration of solar panels in crop- and livestock production, where shade from solar panels reduces heat and water stress; ecovoltaics, the intentional design of nature-positive systems where solar panels support natural vegetation, wildlife, and ecosystem functioning; and the sustainable

cultivation of bioenergy crops on marginal land, where crop cover improves soil health and provides other co-benefits.

- The design of agrivoltaic, ecovoltaic, and bioenergy systems is specific to the production system and local conditions and ecosystems. Agrivoltaics do not benefit all crops, and ecovoltaics may not work everywhere. Success hinges on the appropriate incorporation of local knowledge and expertise and must serve the needs of local communities.
- Strategies to leverage PURE for water management and food security can provide substantial indirect benefits in off-grid and underserved communities. Solar pumps can improve water management and enable the sustainable intensification of production. Solar-powered processing and cooling reduce post-harvest losses and enable farmers to realise higher market values. Both uses improve land-use efficiency while energy access opens other opportunities for economic development, especially for youth and women entrepreneurs.
- Like agrivoltaics, ecovoltaics, and bioenergy, successful PURE projects are community-driven and often led by local entrepreneurs who have a clear understanding of community needs and opportunities. Local entrepreneurs also drive the development of innovative financing and ownership models, such as rent-to-own and pay-as-you-go models based on novel information technology and, increasingly, supported by AI applications.

Findings on knowledge gaps:

- Outside of the developed world, China, and India, only a few countries have conducted comprehensive spatial assessments of their renewable energy potential that include both co-location and integration strategies. Such assessments (or guidance on how to conduct them) would help countries determine the appropriate mix of renewable energy investments that maximise energy outcomes while avoiding land degradation and enhancing benefits to restoration.
- While there is a large and rapidly growing body of research in agrivoltaics, ecovoltaics, and bioenergy, most of it is focused on case studies. Systematic reviews highlight the need for synthesis and research on enabling policies, regulations, and support.
- There is little research on how the benefits of leveraging PURE can be maximised and what policies are most effective in realising land benefits from reduced food loss.[200] One reason for this research gap may be that land-use policy and planning, as well as food system planning, are not well integrated in the context of sustainable rural development.
- There is also little evidence of using ILUP and ILM to integrate renewable energy into landscape planning. Commonly used GIS-based tools for spatial planning could benefit from ILUP and ILM integration to better reflect LDN concerns and reflect the benefits of stakeholder participation and co-creation.
- An emerging field of research is the development of integrated or “hybridised” renewable energy systems that combine intermittent sources, like wind, solar, and small-scale hydro, with sources including geothermal, bioenergy, large hydro, and

storage. Hybridised systems are crucial to scale renewable energy generation within national systems. AI-supported tools are facilitating efficient and stable integration of renewable sources at different scales and could reduce barriers to connecting off-grid communities with local generation and existing mini-grids.

Recommendations for UNCCD parties:

- Understand national renewable energy potentials: Parties that have not done so should assess the areas that are realistically suitable for co-location, as well as integration strategies to inform national energy and clean transition strategies and prioritise renewable energy projects.
- Prioritise renewable energy development on transformed, degraded, or marginal land, in line with the LDN response hierarchy. In accordance with national needs and the LDN response hierarchy, countries should prioritise renewable energy development on existing transformed land and water bodies (rooftop solar and solar over infrastructure and on water reservoirs) and development on degraded and marginal lands to minimise overall land demand for renewable energy expansion. Regarding degraded and marginal lands, parties should prioritise options that support land restoration, such as ecovoltaics and sustainable energy crop production.
- Implement a national support system for agrivoltaics and related integrated approaches (rangevoltaics or solar energy on pastoral lands where appropriate), including knowledge institutions like centres of excellence, peer-learning hubs and specialised extension services, support for local and Indigenous communities, and financing mechanisms.
- Strengthen land governance to safeguard land rights and ensure equitable access and benefit sharing to ensure renewable energy investments respect the rights of Indigenous Peoples and local communities and promote inclusive benefit-sharing mechanisms.
- Promote the inclusion of renewable energy in ILUP and ILM to mitigate land competition and enhance land-use efficiency by implementing co-location strategies and ensuring participatory, effective planning involving all land users (e.g., women, youth, local communities, and Indigenous Peoples).
- Support local entrepreneurship and enhance renewable energy capacity by investing in vocational training, financial mechanisms, and infrastructure to enable local communities to engage in renewable energy value chains and develop climate-resilient livelihoods.
- Promote policy coherence across climate, land, and biodiversity policies to harmonise national policies and planning processes across climate, land, and biodiversity domains to enhance synergies in achieving global goals.
- Consider adopting a renewable energy strategy joint work programme for the Rio Conventions for countries that are also parties to the UNFCCC and CBD, recognising the cross-cutting role and implications of increased renewable energy deployment for achieving climate mitigation, biodiversity conservation, and SLM.

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