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Techno-ecological synergies of solar energy for global sustainability

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The strategic engineering of solar energy technologies—from individual rooftop modules to large solar energy power plants—can confer significant synergistic outcomes across industrial and ecological boundaries. Here, we propose techno-ecological synergy (TES), a framework for engineering mutually beneficial relationships between technological and ecological systems, as an approach to augment the sustainability of solar energy across a diverse suite of recipient environments, including land, food, water, and built-up systems. We provide a conceptual model and framework to describe 16 TESs of solar energy and characterize 20 potential techno-ecological synergistic outcomes of their use. For each solar energy TES, we also introduce metrics and illustrative assessments to demonstrate techno-ecological potential across multiple dimensions. The numerous applications of TES to solar energy technologies are unique among energy systems and represent a powerful frontier in sustainable engineering to minimize unintended consequences on nature associated with a rapid energy transition.

Solar energy generation is exponentially and globally increasing to meet energy needs, while economic barriers to its deployment are decreasing. Despite its growing penetration in the global marketplace, rarely discussed is an expansion of solar energy engineering principles beyond process and enterprise to account for both economic and ecological systems, including ecosystem goods and services[1,2].

TES is a systems-based approach to sustainable development emphasizing synergistic outcomes across technological and ecological boundaries[1]. Global sustainability challenges are inherently coupled across human and natural systems[3] and resource use on Earth exceeded regenerative capacity since approximately 1980[4]. Thus, solar energy combined with TES may prove a promising solution for avoiding unintended consequences of a rapid renewable energy transition on nature by mitigating global change-type problems[5,6]. Further, the Millennium Ecosystem Assessment, 2030 Agenda for Sustainable Development[7], and other industry-led initiatives[8] provide a robust and timely justification for sustainable technologies, particularly solar energy, to be defined as those including both the supply and demand of ecosystem services, upon which all human activities depend.

Ecosystem goods and services are needed as inputs (demand) to support the solar energy life-cycle, beginning with the sourcing of raw materials for manufacturing (Fig. 1).

When TES is applied, demand is carefully measured, including the quantity of resources withdrawn from (for example, water withdrawal and habitat loss) or materials released into (for example, CO_2 emissions and nutrient runoff) the environment. For example, systematic reviews of published life-cycle estimates demonstrate that solar technologies are more than an order of magnitude lower in greenhouse gas (GHG) emissions (16–73 $gCO_2e\,kWh^{-1}$)[9,10] than all carbon-intensive energy systems (coal and natural gas: 413–1,144 $gCO_2e\,kWh^{-1}$)[11–13] and similar to other renewable energy systems and nuclear[14].

In an open system, all industrial processes create order, thereby increasing entropy in the surrounding environment. When this entropic demand exceeds the capacity of an ecosystem to dissipate it, it manifests as industrial waste or environmental degradation (Fig. 1a)[4]. Demand imposed by solar energy development on ecosystems, especially displacive, ground-mounted solar energy power plants, can lead to environmental degradation. Displacive energy development is that which causes land-use or land-cover change and reduces the biophysical capacity or supply of ecosystem goods and services within a serviceshed. The adverse impacts of solar energy development on biodiversity, water, soil, air quality, cultural values, and land-use and land-cover change have been of increasing interest in both local-scale, power-plant-specific development decisions and at larger spatial scales for long-term planning of renewable energy landscapes (for example, the California Desert Renewable Energy Conservation Plan)[2].

When solar energy is developed with TESs, pollution and environmental degradation are avoided or minimized, reducing

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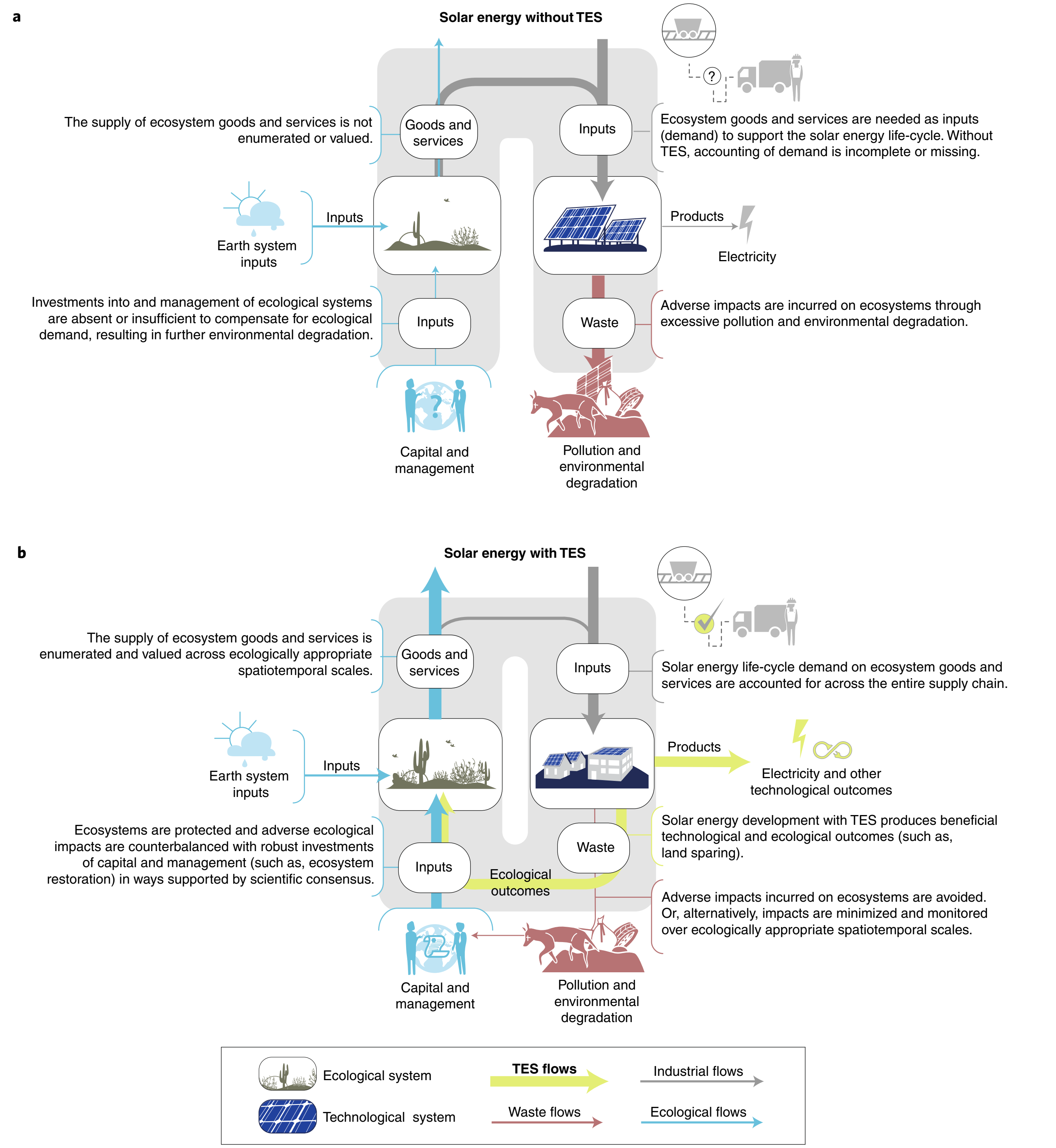

Fig. 1 | Conceptual model demonstrating how TESs of solar energy produce mutually beneficial technological and ecological synergistic outcomes that serve to mitigate global change-type challenges. a, Without TES, the solar energy development life-cycle proceeds without complete consideration of the supply and demand of ecosystem goods and services, resulting in excess environmental degradation, exacerbated by lack of inputs via capital and management. **b**, By contrast, solar energy development with TES begins with a complete accounting of the supply and demand of ecosystem goods and services across appropriate spatiotemporal scales, produces electricity and other technological outcomes while simultaneously optimizing favourable ecological outcomes, which are augmented by the investment of capital into and management of ecosystems (for example, restoration activities). Overall, solar energy with TES results in a beneficial change in the direction and magnitude of flows occurring between the 'natural system' (for example, desert and forest) and the 'technological system' (solar energy development) relative to solar energy without TES.

waste flows. Concomitantly, beneficial ecological outcomes are produced alongside technological outcomes (Fig. 1b). For example, a community-owned solar farm (Westmill Solar) in Wiltshire, UK, is notable for the presence of outplanted native grasses and herbs under and around panels to provide pollinator habitat, a positive ecological outcome[2]. Moreover, the application of TES includes the counterbalance of unavoidable adverse impacts with robust investments of capital and management in ways supported by scientific consensus and stakeholder participation across the appropriate knowledge system[15,16]. Such inputs serve to strengthen and further augment the beneficial ecological outcomes that solar energy TES produces and prevent delays in achieving renewable energy goals.

Industrial processes are also intrinsically dependent on the supply of ecosystem goods and services. Ecosystem service supply is the maximum potential of ecological function and biophysical elements in an ecosystem. For example, the sustainable generation of one megawatt hour (MWh) of solar energy at an emissions rate of 48 $gCO_2e\ kWh^{-1}$ is contingent on the supply of regulating ecosystems services to sequester approximately 48,000 gCO_2e back into the environment[14]. Despite an emphasis on enumerating GHG emissions by life-cycle analysis and related methods, a diverse suite of mass and energy flows—including nitrogen, heat, water—underpin the supply of ecosystem goods and services. For example, the washing of photovoltaic (PV) solar energy panels to reduce soiling and wetting of disturbed soils to mitigate dust is dependent on the supply of water from sources such as rivers, lakes, and aquifers within an ecosystem[17]. Enumeration of the supply of ecosystem goods and services includes an understanding of the complex feedbacks and linkages that regulate a given supply.

For all energy sources, the manner in which an energy system is sited, constructed, operated, and decommissioned can yield negative but also positive impacts on ecosystems. Thus, no individual technology or process can be sustainable, even renewable energy, without an accounting of its impact on not only the demand, but also the supply of ecosystem services at appropriate spatiotemporal scales[3]. Environmental impacts associated with energy transitions broadly can extend at time scales beyond 100 years and thus pose inter-generational ethical dilemmas that need equitable guardrails. Given its impact on environmental factors of import across spatiotemporal dimensions[3], the application of TES for solar energy development can play a powerful role in both local sustainability decisions and in the planning and realizing of decarbonization pathways for the Earth system, but these positive roles have received less attention.

TESs of solar energy framework

When applied to solar energy technologies, the outcome of TES produces both technocentric products (for example, PV module efficiency and grid reliability) as well as support for sustainable flows of ecosystem goods and services (for example, carbon sequestration and storage, water-use efficiency and habitat for species) that may mitigate global environmental change[1,18–20]. We describe ecological systems as those intersecting with spheres of the Earth system, including the anthroposphere (for example, food systems).

In this initial framework, we have identified 16 implementations of TES for solar energy technologies across four recipient systems: land, food, water, and built-up systems (Fig. 2). Recipient system in this context refers to an ecological or Earth system that predominately receives and/or supports the infrastructure associated with the solar energy TES. Together, these TESs encompass the potential for 20 unique synergistic outcomes that overlap structurally, when possible, with the environmental co-benefits of the Millennium Ecosystem Assessment[21] and ecosystem services of the Economics of Ecosystems and Biodiversity[22] initiative for valuation and value capture in decision-making. As global sustainability challenges—including air pollution, food security and water shortages—are interconnected across dimensions[3], we characterize synergistic outcomes according to: (1) space ('spatial incidence'); (2) time ('temporal incidence'); and (3) ecological organizational level (from local- to global-scale).

In the following paragraphs, we show how the build-out of TESs of solar energy provides resilience to coupled human and natural systems. Specifically, we describe 20 potential techno–ecological synergistic outcomes across 16 solar energy TESs and discuss a selection of metrics and assessment methods to measure TES flows. We argue that the categorization and characterization of their synergistic outcomes embodied within this conceptual model (Fig. 1) and framework (Fig. 2) holds promise as a powerful springboard for the integration of solar energy TESs into industry and society.

Optimizing land resources for TESs of solar energy

The diffuse and overlapping nature of land degradation and solar energy resources globally provides opportunities for land sparing in an era where land is an increasingly scarce resource[23]. Notably, we found that degraded lands in the US comprise over 800,000 km^2 (approximately twice the area of California, Table 1). Here, the most degraded sites (for example, EPA Superfund sites) could produce over 1.6 million GWh yr^{-1} of potential PV solar energy (38.6% of total US consumption of electricity in 2015)[24]. Further, if degraded lands are targeted for solar energy infrastructure in lieu of land with greater capacity for carbon sequestration (for example, shrublands and prairies), GHG and aerosol emissions associated with land-use and land-cover change will be reduced or eliminated. For example, if solar energy development leads to diminished extent of perennial plant communities, hazardous GHGs, dust emissions and soil-borne pathogens may increase[25,26]. Following TES principles, risks to human health and wildlife are quantified and even avoided completely.

Co-locating solar energy infrastructure with other renewable energy infrastructure (for example, wind turbines) is another TES. Co-location optimizes land-use efficiency (for example, MW km^{-2} for measuring installed capacity per area[27], TWh yr^{-1} for measuring generation per area[5]) and even more so when co-location happens on degraded lands (Fig. 2). Such hybrid renewable energy systems are particularly attractive if they mitigate problematic 'duck curves' or are located in remote places where grid extension and fuel are costly—improving grid reliability (a technological synergistic outcome) while reducing total life-cycle costs[28].

Degraded lands have potential to recoup, to some extent or fully, ecosystem goods and services (Table 1). Decision-support tools used to identify appropriate locations for siting renewable energy infrastructure can be designed to prioritize potential reversibility[29]. Thus, the use of degraded lands for siting solar energy can also confer positive ecological outcomes beyond those related to land sparing when habitat under, between and surrounding solar energy infrastructure is restored (that is, a win-win-win scenario with 13 potential outcomes).

Passive and active restoration activities are compatible with solar energy infrastructure and operation to support these synergistic outcomes, and are scalable across political boundaries to support governance programs seeking to incentivize such activities[30]. Ecological outcomes of this TES include biological control (for example, pest regulation), carbon sequestration and storage, erosion prevention, habitat for species, maintenance of genetic diversity and pollination (Fig. 2). For example, in the UK, active management for wildlife across 11 solar energy power plants (on predominantly former grazing land), increased diversity and abundance of broad-leaved plants, grasses, invertebrates and birds, compared with control plots[31]. A recent study in the US identified 3,500 km^2 of agricultural land near existing and planned ground-mounted solar energy power plants that could benefit from nearby indigenous pollinator habitat[32]. Lastly, restoration actions may confer a positive feedback to PV module efficiency. For example, the outplanting of native vegetation under panels in lieu of gravel underlayment may increase transpiration (water vapour as a by-product of photosynthesis), which cools panels. This response would increase PV module efficiency, a technological synergistic outcome, which may also extend panel lifespan[19,33].

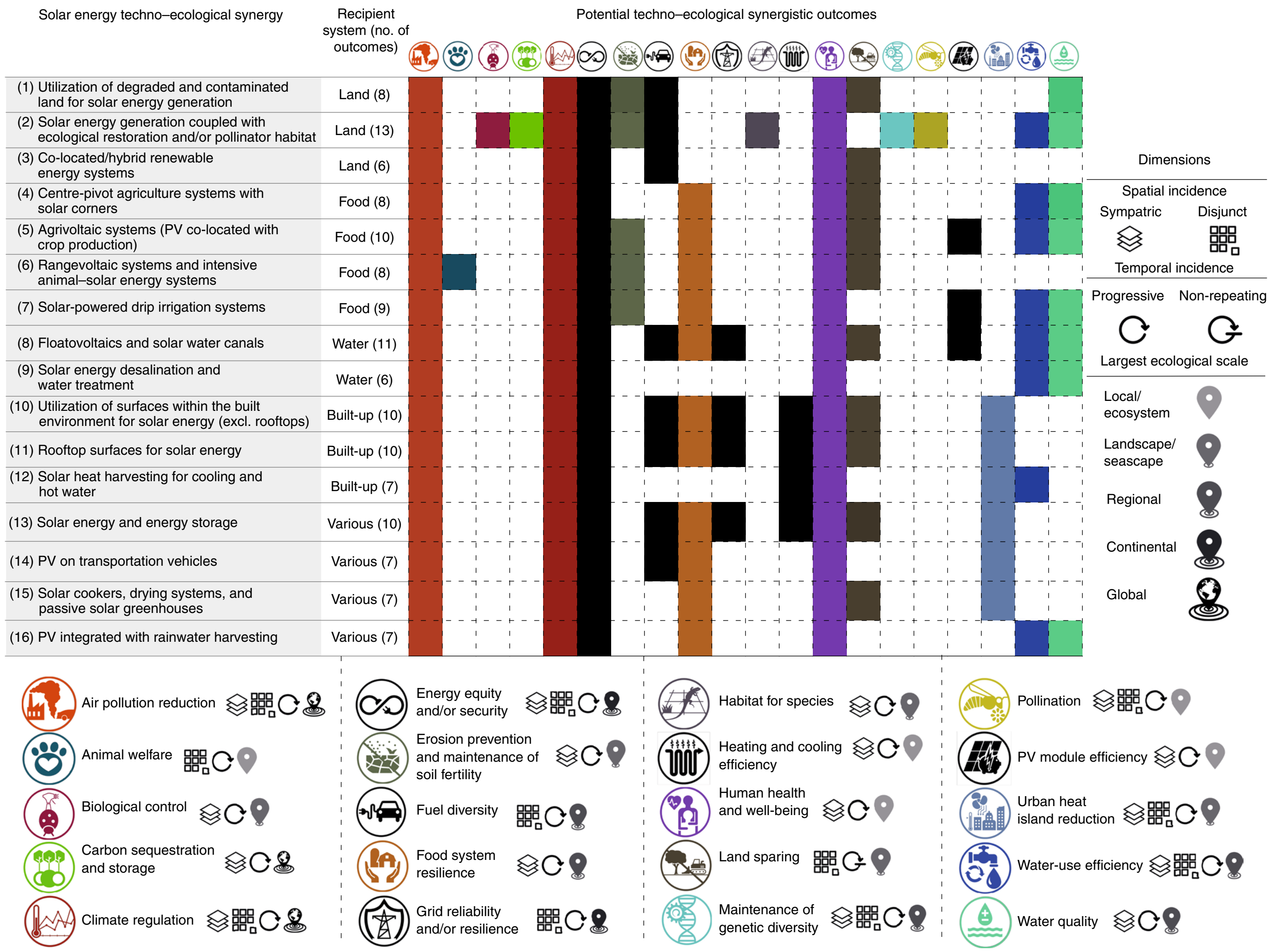

Fig. 2 | Framework for TESs of solar energy development. Each solar energy TES is characterized by its recipient system(s) (land, food, water and built-up system) and potential technological (black icons) and ecological (colored icons) synergistic outcomes. Also shown are three dimensions of techno–ecological synergistic outcomes: spatial incidence, temporal incidence and largest ecological scale. Spatial incidence describes whether a techno–ecological synergistic outcome occurs in the same place as the site of energy generation. Some outcomes overlap with the site of generation ('sympatric'), whereas certain outcomes are spatially separated from the site of solar energy generation ('disjunct'). Temporal incidence describes how a techno–ecological outcome develops. An outcome may occur and be measured gradually or in stages ('progressive'). By contrast, an outcome may occur and should be measured only once in time ('non-repeating'). Lastly, each techno–ecological synergistic outcome embodies a level of ecological organization that represents the maximum ecological scale in which an ecological outcome contributes goods and services (also known as its serviceshed). If the outcome is technological, this scale refers to the maximum scale at which the outcome is consumed, monetized, or valued by a particular beneficiary.

Contrastingly, studies have shown that using land for solar energy development can, under certain circumstances, be a net negative for the local ecosystem, landscape sustainability and global climate[6,29,34,35]. One study[29] found the use of olive groves and non-irrigated arable land, classified as environmentally 'suitable' within a regulatory framework for solar energy development, would actually reduce the potential for net avoided GHG emissions conferred by solar energy development by reducing the net CO_2 sequestered by these land-cover types. Further, the authors found that 66% of installations were sited on unsuitable land including century-old olive groves, which were noted by the authors for their significant cultural value within the Apulia region of Italy. Thus, land-sparing practices may also allay competition for limited land resources needed for agriculture[6], wildlife conservation[36], tourism, historically significant areas and cultural values/rights held by indigenous/tribal groups, including their viewsheds[37].

Trade-offs commonly emerge for decision makers in the use of land for solar energy development; however, TESs can help guide development towards optimum landscape sustainability. Notably, the application of TES across land systems prioritizes the use of existing infrastructure in developed areas for renewable energy over the use of land with potential for net losses in ecosystem goods and services.

Integrating TESs of solar energy and agriculture

Agrivoltaic systems (AVSs) are those within which both agricultural production (food or energy crops) and solar energy generation are co-occurring within the same land area. We identified ten potential techno–ecological outcomes of AVS, including land sparing, PV module efficiency, water use efficiency, water quality (for further discussion on water and AVSs see Supplementary Box 1) and erosion prevention and the maintenance of soil fertility (Fig. 2). Such outcomes may enhance the microclimatic conditions suitable for crop production. AVSs can be implemented in either energy-centric or agriculture-centric fashions, which can be proportionally customized according to needs and desired outcomes.

Table 1 | Degraded land types in the United States and their geographic potential for the development of solar energy with techno-ecological outcomes

Relative potential for restoration of ecosystem goods and services	Degraded land type	Description	Estimated area for potential solar energy development (km^2)
LOW	EPA sites (e.g., Superfund, Brownfield)	Hazardous waste sites; previously used for industrial or commercial purposes, including possible presence of environmental contaminants.	47,070 (ref. [24])
	Landfill	Used for disposal of waste beneath soil surface; releases leachate and landfill gas.	1,637–6,592[a]
	Abandoned mine land	Areas once utilized for mining activities; possible presence of environmental contaminants.	11,380 (ref. [24])
	Contaminated agricultural land	Land contaminated from cropland and grazing practices (such as, metal, saline-sodic, fertilizer contamination).	28,960[b]
	Abandoned agricultural land	Areas once used for agricultural productivity.	682,579 (ref. [24])
	Right-of-way	Land along transportation and distribution infrastructure (such as, roads, rail, transmission).	55,935 (ref. [24])
HIGH			
	Total		827,561–832,516

We performed a synthetic review of the literature to identify six total sub-types of degraded land in the US and their total respective area. For all degraded land types, local-scale ecological characteristics, existing infrastructure and potential risks may impact relative reversibility in unique ways. [a]Estimate based on median area of ten landfills (eight counties) in California (0.86 km^2), and scaled to estimate for number of capped and active landfills in the US: low (1,908) and high (7,683). [b]Estimate based on 20% contamination in irrigated croplands (144,800 km^2) of United States from refs. [66,67].

For example, a low-density PV installation may allow more insolation through to the soil surface. This is an example of an agriculture-centric AVS, as there may be a lower efficiency or higher cost to the energy system on a per area basis, without substantially altering agricultural productivity. Conversely, an energy-centric AVS might comprise shade-tolerant crops planted under a PV array of maximal density. Additionally, elevated PV installations, tall enough for farming equipment to pass under, can accommodate taller crops (Fig. 3a). Thus, AVSs offer economization of land-use driven by location- and commodity-specific priorities[19].

The use of land for energy and agricultural production necessitates novel metrics for valuation. The land equivalent ratio (LER) is a metric inclusive of yields and electricity generation (AVS crop yields / regular crop yield + AVS electricity yield / regular AVS yield), where LER > 1 is more effective spatially than separated crop and solar energy generation for the same area. A study of the LER of a durum wheat-producing AVS in Montpellier, France, found that the full and half density AVSs have LERs of 1.73 and 1.35 (ref. [38]). Modeling in India on an AVS where PV was integrated with grapes grown on trellises showed a 15-fold increase in overall economic returns compared to conventional farming with no reduction in grape yields[39]. Another simulation study in North Italy revealed solar panels confer more favorable conditions for rain-fed maize productivity (a C_4 plant) than full light, and LERs were always >1 (ref. [40]).

Another possibility for purely additive solar energy in agricultural landscapes and techno–ecological outcomes lies in the use of negative-space PV; specifically, the installation of PV arrays in the portions of fields that are unused for crop or pasture production. One option is to develop unused areas of land adjacent to existing crop/pasture fields with solar energy outplanted with low-growing, pollinator friendly plants (Figs. 2, 3b). Another prominent example of negative space is in the corners of fields where centre-pivot irrigation is used (for further discussion see Supplementary Box 2)[18]. In such irrigation configurations, where r is the maximum radius of the pivot on a square plot, an area of roughly $(4\pi)r^2$ is often left un-irrigated (Fig. 3c). Here, farmers may plant drought-tolerant crops or may purchase higher-cost centre-pivot systems with retractable arms that reach into corners. A different possibility, however, is to utilize these corners for PV solar energy, which confers eight TES outcomes (Fig. 2).

In some locations, PV arrays may have a positive effect on crop yields through shading, as well as reduced evapotranspiration from plants and soils[41], as evidenced by existing agroforestry, shrub-intercropping[42,43] and shade cloth-based agricultural practices. Indeed, the production of shade-tolerant ornamental and horticultural plants necessitates such conditions and for all plants, once light saturation is reached, any additional light energy is in excess as photosynthetic rates asymptote. This is particularly true for C_3 crops that have lower light saturation points. In other locations, yields may be slightly reduced but by less than the reduction in solar radiation[44,45].

Other key TES outcomes of AVSs are increased energy production due to aerosol reduction (important for human health and well-being) through increased soil moisture and vegetation cover. This may also support increased water-use efficiency, another coupled outcome. Reduction of aerosols is especially important in arid lands where water is scarce and where solar panel robotic washing technologies may be cost-prohibitive[46]. Further, water-use efficiency may be increased by: (1) repurposing the water used for cleaning panels for plant watering; and (2) shading from the panels, which may reduce evapotranspiration (Fig. 3a). Lastly, reductions in water use and/or consumption may reduce detrimental effects of abstraction on aquatic ecosystems and CO_2 emission and cost implications associated with groundwater overuse.

In both high-yielding modernized agricultural production systems and smallholdings far from the grid (often in developing communities), solar-powered irrigation systems are another appealing TES, with nine potential outcomes (Fig. 2). These systems may offset increasing costs associated with greater electricity use on farms, supporting food system resilience and enabling greater water-use efficiency and water quality. In Spain, energy consumption (per unit area; m^3 ha^{-1}) increased by 657% from 1950 to 2007 due to

Fig. 3 | Techno–ecological synergies of solar energy and examples of techno–ecological synergistic outcomes. a, Panel washing water inputs (left) on a PV installation are also inputs into agricultural productivity below, known as an agrivoltaic system leading to increased water-use efficiency, erosion prevention and maintenance of soil fertility, land sparing and other beneficial techno–ecological outcomes (Center for Agriculture, Food and the Environment, University of Massachusetts-Amherst, South Deerfield, MA, USA). Compare this to panel washing (right) on an installation where water inputs are directed towards graded, compacted and barren soil in California's Great Central Valley, which does not optimize techno–ecological synergistic outcomes, like PV module efficiency of food system resilience (Manteca, California; for further discussion on water-use efficiency in agrivoltaics, see Supplementary Box 1). **b**, In the US states of Minnesota (left) and Vermont (right), land adjacent to croplands is developed with PV solar energy (1.3 MW, fixed tilt and 1.1 MW, single-axis tracking, respectively) and outplanted with low-growing flowering plants for native and managed pollinators that help increase agricultural yields, reduce management (that is, mowing) costs, and confer the opportunity to produce honey and other honey-based commodities. **c**, Centre-pivot agrivoltaic systems occupy the corners of crop/pasture fields for solar energy generation but also produce the techno–ecological synergistic outcomes of air pollution reduction, land sparing, food system resilience and others in Dexter, New Mexico (for further discussion on centre-pivot agrivoltaics see Supplementary Box 2). **d**, Floatovoltaic installations can contribute to local- and regional-scale agricultural resource needs while simultaneously enhancing water quality and water-use efficiency, a beneficial ecological outcome, as demonstrated by this floatovoltaic system in Napa, California (left) and this floatovoltaic system under construction atop a water treatment facility in Walden, Colorado (right; for further discussion on floating PV systems see Supplementary Box 3). Credit: Dennis Schroeder, NREL (**a** left, **d** right); © 2018 Google (**c**); Greg Allen, Far Niente Winery (**d** left)

changes in farm-based water-management activities. This is largely associated with technological advances in pumping and moving water that have dramatically increased water-use efficiency (but the Jevons paradox can exist). For example, USDA Farm Ranch and Irrigation Survey of 2013 surveyed 1,592 US farms (>US$1,000 in products produced or sold) that used solar-powered pumps spanning 28,104 acres.

Additionally, PV-based systems may also provide access to energy where none existed previously. If coupled with efficient drip irrigation (as such systems often are; for example, 47% of surface irrigation in Spain was drip in 2018[47]), PV-based systems can further augment water-use efficiency gains (Fig. 2). In industrialized contexts where water is priced, this TES can reduce operational costs. In developing economies, landscapes where water would otherwise be hauled and spread by hand, these energy and water savings translate into labour savings, with important consequences for school attendance, women's welfare and equity, hunger, poverty and entrepreneurialism. A pilot project in northern Benin, for example, showed significant economic, nutritional, human capital and investment benefits of community-scale solar-powered irrigation projects[48,49]. Specifically, households using this TES produced, sold, and consumed more micronutrient crops than before, with potential lasting consequences for health and human capital accumulation.

Rangevoltaic systems—which we define as solar energy generation co-located with domestic livestock activities and associated infrastructure, notably grazing areas—as well as intensive animal–solar energy systems (for example, feedlots, dairy farms), can provide numerous potential techno–ecological outcomes ($n = 8$), notably enhanced animal welfare and food system resilience (Fig. 2). There is both political will and an economic case for this TES: The Ministry of Agriculture, Forestry and Fisheries of Japan updated the Agricultural Land Act in April 2013 allowing the installation of PV systems on crop-/pastureland and guidance within the UK purports PV installations are grazed by sheep and poultry[50]. Stocking densities of sheep similar to conventional grasslands may be attainable and poultry stocking densities up to 80% of that for conventional free-range systems, are suggested, thus representing substantial land sparing. Further, there are additional benefits both for livestock, such as the light and shade areas. Light and adequate shade (to reduce heat stress) are desirable environment conditions recognized by the Freedom Foods Certification Scheme in the UK and such favourable conditions improve both commodity (for example, milk) yields and quality. Additional benefits arise for energy production through negating the need for active and costly vegetation management (for example, mowing and herbicide application)[50].

Water and electricity mix with TESs of solar energy

Floatovoltaics are PV modules attached to pontoons that float on water and are typically fixed to a banking limiting lateral movement (for further discussion see Supplementary Box 3)[51]. Similarly, photovoltaics can be installed on fixed mounting systems over water canals, as was done across 19,000 km in Gujarat, India. To date, floatovolatics exist across the world (for example, USA, Israel, China, India, UK and Japan) and are particularly appealing for developers where land is more valuable for uses beyond electricity generation, as has been observed, for example, in designated wine-grape-growing regions (Fig. 2)[52].

Floatovoltaics have eleven potential techno–ecological outcomes and are capable of reducing water evaporation (Fig. 3d), may reduce algae growth and can be integrated over hydroelectric reservoirs. Reduced evaporative loss is of particular value in arid land environments, covering approximately 40% of Earth's terrestrial surface and where water is less abundant, costlier, and evaporation rates are high. For example, Gujarat's canal solar power project (1 MW) is noted for preventing evaporation of 34 million gallons of water annually. Moreover, panel shading may improve water quality by limiting light penetration resulting in lower water temperatures and dissolved oxygen limiting algae growth. A previous study[53] found that covering agricultural water reservoirs deters 1% of incoming solar radiation, decreasing algae growth and the need to filter reservoir intakes by 90%. Lastly, floatovoltaics increase PV module efficiency by lowering module temperature[52]. In California one study found floatovoltaics are as much as 2.8 °C cooler than ground-mounted PV, improving efficiency by 11–12.5% compared to ground-mounted installations[54].

Solar PV and thermal technologies can also be used to drive water treatment and desalination technologies to augment water supplies in arid or water-stressed regions (Fig. 2)[44,55]. A recent study found that solar-powered desalination was highly applicable for 30 countries that are experiencing water stress but also have a favourable solar resource, with regions in other countries also showing suitability[56].

Designing TES outcomes across built-up systems

An integral TES outcome of siting of solar energy infrastructure within the built environment—developed places where humans predominantly live and work—is that it does not require additional land. And yet, ten unique TES outcomes are possible from this TES (Fig. 2). On rooftops, solar PV panels have insulating effects on the building envelope that can confer energy savings and improve health and human comfort. In cities, albedos commonly average 0.15 to 0.22. Here, solar energy modules can increase albedo (increasingly with their efficiency rate) and reduce total sensible flux (~50%), especially relative to dark (for example, asphalt and membrane) or rock ballasted roofs. A study in 2013[57] modelled a high-density deployment of roof-mounted PV panels in the Los Angeles basin and found no adverse impacts on air temperature or on the urban heat island (UHI) and predicted up to a 0.2 °C decrease in air temperatures with higher efficiency panels. In Paris, France, simulating the effect of solar PV and thermal panels (for hot water) on rooftops showed[58] that during wintertime, both solar panel types slightly increase the need for domestic heating due to shading of the roof (3%). In summer, however, the thermal solar deployment simulation showed a 12% decrease in the energy needed for air conditioning and a reduced UHI effect by 0.2 °C during the day and up to 0.3 °C at night.

The roof-shading and UHI cooling properties of rooftop solar PV can further benefit urban areas. For instance, an increased solar panel deployment simulation for the city of Paris revealed 4% fewer people to be affected by heat stress for more than 12 hours per day during the 2003 August heatwave (Fig. 1)[58]. Given that more extreme summer heat stress is leading to an increasing number of heat-related, premature mortality events (for example, 11,000 deaths in the Moscow heatwave in 2010), even modest improvements in the UHI effect through solar panel deployment are practicable[59]. Also, where heat stress is associated with entering parked automobiles, shading parking lots with PV could reduce exposure to heat stress and aggressive driving resulting from discomfort[60].

In addition to energy generation, solar thermally driven cooling and heating systems (operative also with district systems, an enabling technology) can harvest solar radiation to produce maximal air conditioning at the peak time of day when the cooling is most needed. Heat harvesting is useful for various building applications including solar hot water heaters, which China is deploying at scale with 71% of the global total 472 GW_{th} solar thermal capacity installed within its borders in 2017. In the agricultural sector, solar drying has shown potential to replace fossil-fuel-powered desiccation equipment, through either directly exposing food produce, tea leaves, or spices to the sun's radiation or through indirect means, such as fans, to transfer heated air from a collector area into drying chambers[45]. The application of solar drying technologies in the food production process provides farmers greater control of storage conditions that reduce postharvest food losses, improve food quality and therefore support food system resilience (Fig. 2)[61].

Solar energy TES 'sundries' across multiple systems

Four solar energy TESs can be integrated into a variety of environments across land, food, water and built-up systems with 7–10 potential techno–ecological synergistic outcomes (Fig. 2).

Energy storage and solar energy—a resilient duo. As extreme weather events increase in severity and frequency, energy storage combined with solar energy offer unique TES outcomes, markedly as these weather events can often precipitate electric grid outages at regional scales. Historically, grid resilience to outages has most commonly been fortified with backup fossil-fuel-based (for example, diesel) generators, prone to complications arising from finite and/or long-distance supply chains and protracted periods of non-use. Notably, the aftermath of Hurricane Maria in Puerto Rico was described as "an epidemic of broken generators"[62]. For a complete discussion on storage and solar energy see Supplementary Box 4a.

Solar-based transportation across land-, air-, and seascapes. Physical and economic limitations still prevent industrial implementation of on-board solar for electric vehicles, but research and development on solar-powered vehicles is gaining momentum. The most economically viable and practical hybrid electric vehicle (HEV) system today involves charging plug-in HEVs at stationary PV solar installations, creating realizable synergistic outcomes for deployment of both technologies. For a complete discussion on 'solarized' transportation see Supplementary Box 4b.

Photovoltaic rainwater collection. PV panels may be fitted or integrated with gutters to collect rainwater, which can then be transported to store in tanks or rain barrels above or below ground, directed to a reservoir, or consumed immediately onsite in place of groundwater or a municipal source. Such a configuration produces up to seven techno–ecological synergistic outcomes and can serve populations where there is limited potable drinking water (for example, in a small agricultural field) or minimal rainfall. There are also energy savings associated with treating and pumping water or if used on high-rise buildings it could also offset energy costs for lifting water to upper floors[63]. Comparable mechanisms of water harvesting have been used on many types of rooftops to supply water for households, landscapes and farming uses.

Agricultural and urban solar greenhouses. There is potential to incorporate PV arrays into greenhouses, to either provide electricity required by greenhouse operations or to export power for other uses. Generating electricity from integrated PV panels potentially reduces energy costs in greenhouses, negates the need for a mains connection, and avoids the need for land. Benefits can be tailored to optimize any offset against potential reductions in yield, crop quality (for example, nutritional value), and aesthetics due to reduced radiation penetration. For further discussion on solar greenhouses and solar energy integration see Supplementary Box 4.

Conclusion

Achieving a rapid transition from fossil fuels to renewable energy sources on planet Earth to support human activities, in a manner benign to Earth's life support systems, is arguably the grandest challenge facing civilization today[64]. The consequences of climate and other types of global environmental change are a cautionary flag against the extrapolation of past energy decisions. Our model (Fig. 1), framework (Fig. 2), and assessment (for example, Table 1) serve to demonstrate that solar energy TESs are feasible across diverse recipient environments with outcomes that favour both technological (for example, PV module efficiency and grid reliability) as well as ecological outcomes. Specifically, such ecological outcomes support the sustainable flows of ecosystem goods and services (for example, carbon sequestration and storage, water-use efficiency habitat for species) to mitigate ecological overshoot.

In total, we found 16 solar energy TESs and 20 techno–ecological synergistic outcomes. The number of potential beneficial outcomes for individual TESs ranges from 6 to 13 with a median of 8, ranging from animal welfare to grid resilience to land sparing. The majority (80%) of synergistic outcomes occur in the same location (sympatric) as the energy generated, thereby creating positive local-scale incentives for TES solar energy development. The scale of ecological outcomes extends from local to global scales. Solar energy embodies a technology that is perhaps uniquely diverse, modular and scalable; however, we encourage the consideration of TES for other low-carbon energy sources.

Importantly, however, a solar energy TES is characterized not only by producing these ecological outcomes but also by supplementing their numbers and magnitude through capital investments into and management of the ecosystems that the solar energy TES enterprise depends on and/or manifests waste into (Fig. 1b). As achieving negative emissions is not a panacea to reversing effects of global environmental change[64], taken together, such actions may reduce climate-change damages, which are relatively well-known, (US$417 per tCO_2, ref. [65]) and mitigate other types of global change, the latter for which monetization of damages is less studied (for example, biodiversity loss and food insecurity).

Despite increasing commitments to transition societies toward 100% renewable energy, policies may be needed to embed solar energy TESs into the global economy. Such policies have begun to take form. For example, in 2016, grassroots environmental organizations in the state of Minnesota successfully advocated for legislation supporting the deployment of ground-mounted PV on over 1,600 hectares of land outplanted with native foraging habitat for bees, butterflies and birds, equating to 2.4 million homes with 6' × 12' pollinator gardens. The US EPA's RE-Powering programme has facilitated the development of 186 re-powering sites, including brightfields (1,272 MW), leveraging investments in PV on contaminated lands, landfills and mine sites.

Without deliberate and value-setting processes, decarbonization might proceed without consideration of potential TES outcomes, particularly as policy and regulatory discussions advance and expand globally. Thus, solar energy TESs may merit their own policies, incentives and subsidies in addition to those already in place for developing larger solar energy installations (for example, utility-scale PV solar energy). Additionally, these synergies could be considered in cost–benefit analyses of energy systems for the purposes of electric rate-making, resource planning, net metering, and other value-setting processes that affect distributed solar markets (for a one-page 'summary for policy makers' see Supplementary Information).

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Author contributions
R.R.H initiated the research and led the conceptual design and writing of the manuscript. All authors contributed to further content development and drafting of the manuscript.

Competing interests
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SUPPLEMENTARY INFORMATION

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Techno–ecological synergies of solar energy for global sustainability

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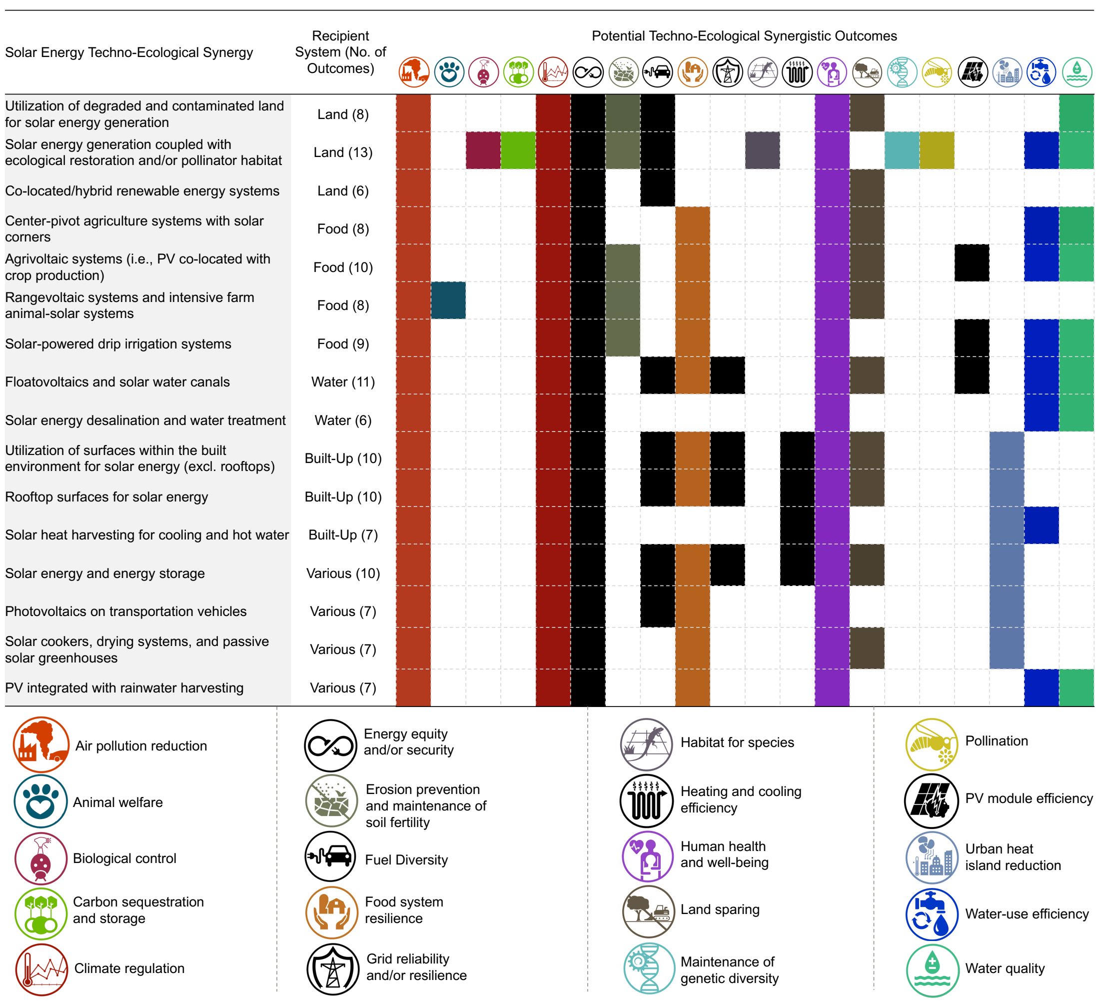
Techno-ecological synergies of solar energy for global sustainability

Summary for Policy Makers

1. Solar energy could become the largest energy source by 2050. There is a new model for engineering solar energy systems that maximizes both technological and ecological benefits.
2. Scientists call this type of installation a “techno-ecological synergy,” and there are over 15 different types of these installations that can be developed, including installations over land, water, in cities, and within agricultural systems. When these projects are built on or near where electricity is used, they are considered distributed solar.
3. The authors have created a framework (*below*) to show the full list of installations and to characterize their 20 unique benefits.
4. As governments increasingly commit to 100% renewable energy, they should valuate and appropriately incentivize the synergies outlined in this study so as to maximize solar energy generation potential while protecting our planet’s climate, air quality, water, land, and wildlife.
5. These synergies could be considered in cost-benefit analyses of energy systems for the purposes of electric rate-making, resource planning, net metering, and other value-setting processes that affect both distributed and utility-scale solar energy markets.



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Supplementary Box 1: Water Use Efficiency in Agrivoltaics

Figure 1 | Panel washing water inputs (*left*) are also inputs into agricultural productivity below (Center for Agriculture, Food and the Environment, University of Massachusetts-Amherst, South Deerfield, MA, USA photo: NREL) and panel washing (*right*) where water inputs are directed towards graded, compacted soil in California's Great Central Valley (Manteca, CA, photo: RR Hernandez).

Globally, agriculture consumes approximately 70-80% of freshwater while energy consumes about 15%, but these values can vary spatially[1,2]. Life cycle assessment methods demonstrate that life-cycle water consumption rates from solar photovoltaic (PV) energy can be an order of magnitude lower (0.4 m^3 MWh^{-1}) than commonly deployed nuclear (3.0 m^3 MWh^{-1}) and coal (2.1 m^3 MWh^{-1}) technologies, and approximately half that of natural gas (0.8 m^3 MWh^{-1}) technologies[3].

The potential for agrivoltaic systems (AVS) to produce energy and crops while saving water compared to conventional irrigated systems could be of much value, especially in arid regions. Total global consumptive irrigation water use is 1277 km^3 yr^{-1} [4]. Assuming just 1% of all cropping systems were AVS and that evapotranspiration was reduced by 10-30 %[5], this would confer an annual water savings of 1.3 – 3.8 km^3 yr^{-1}, with most benefits accruing in arid regions that could also see increases in crop performance. In addition to providing water savings, this represents cost and energy savings associated with irrigation. Using these conservative assumptions, in the United States this approach would save farmers who irrigate with electricity \$13 – \$41 per hectare on irrigation costs on more than 1,300 km^2 of agricultural land, representing annual cost savings of approximately \$1.7M – \$5.2M[6]. Further co-benefits would be incurred through a reduction in GHG emissions, associated with water supply, of 0.6-1.7 million t CO_2e (based on a CO_2e costs of 0.457 kg m^{-3} [7]). There is uncertainty in these figures (irrigation water sources and costs differ, the reduction in evapotranspiration rates will vary, and the water CO_2 estimates will vary) but this estimate gives indication of the potential water cost savings of cropping under solar arrays under very conservative assumptions.

The reuse of water used for washing panels for irrigation presents further water, monetary, and CO_2 savings (**Figure 1**). For example, assuming a median water use of 117 liters MWh^{-1} and an average capacity factor of 16.7%[8,9], a 5 MW solar installation would use 856 m^3 of water per annum for washing, and the water runoff that does not evaporate could be repurposed for irrigation of crops planted underneath or nearby the arrays. Many utility-scale solar projects require water for mirror or panel washing, for fugitive dust emissions control during construction, and/or for roads during operation. Where the water sources are groundwater or surface water, it is important to understand the implications of these withdrawals on ecosystem services or protected species. In

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California, for example, there are concerns that groundwater withdrawals could affect the habitat for the desert pupfish (*Cyprinodon macularius*), which depend on surface water pools that are interconnected by groundwater.

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Supplementary Box 2: Center-Pivot Agrivoltaics

Figure 1 | Center-pivot agrivoltaic systems occupy the corners of crop/pasture fields for solar energy generation but also produce the techno-ecological synergistic outcomes of air pollution reduction, land sparing, food system resilience, and others in Dexter, New Mexico (photo: © 2018 Google; Google Earth).

A recent NREL study[1] on the state of Colorado (CO, USA) estimated a 71% potential fill factor for the corners of center-pivot systems, and an installed capacity of over 900 km^2, equivalent to 56.8 GWh annual production potential, or 1.3 GWh per plot (**Figure 1**). At $0.10 per kWh, potential production from field corners is $5.7M. For reference, the state of Colorado generated a total of around 53,000 GWh annually in recent years[2] and spent around $77M for energy expenses for irrigation water in 2012, for 5.0B m^3 of water applied[3]. Installing PV in the corners of center pivot fields could theoretically offset 7% of the energy cost of irrigation in CO, providing an on-site source of energy that does not alter the availability of productive agricultural land.

At the national level, more than 57,000 farms (110,000 km^2) are irrigated using center-pivot systems, with the majority low- or medium- pressure[3]. Applying the same ratio estimates for Colorado to the entire United States, the theoretical PV area in center-pivot systems would be $A_{PV}=(4/\pi - 1)*A_{Irrigated}*0.71$ or 21,000 km^2. At 0.63 MWh/ha (as in Colorado), this would be equivalent to 1,350 $GWhy^{-1}$ potential production, or approximately 2% of farm electricity needs in the United States[4]. Such estimates are coarse, and would require refinement based on topographical features (e.g., streams intersecting field corners), but the potential generation is noteworthy because in most extant farms it is completely additive and a productive use of often under-utilized land. More research is needed to understand how much of center-pivot agriculture operate as agroforestry systems or where field borders are used to preserve habitat corridors or other biodiversity-enhancing activities.

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Supplementary Box 3: Floating Photovoltaic Systems

Figure 1 | Floatovoltaic installations can contribute to local- and regional–scale agricultural resource needs as demonstrated by this floatovoltaic system in Napa, California (*top*, Photo: Far Niente Winery) and this floatovoltaic system under construction atop a water treatment facility in Walden, Colorado (*bottom,* Photo: Dennis Schroeder, NREL).

In parts of the world such as Queensland and New South Wales, Australia, up to 40% of water storage volume is lost to evaporation yearly[1]. In the Colorado River Basin, the two largest reservoirs at Lake Mead and Lake Powell evaporate approximately 1.4 km^3 each year, approximately five times greater than the annual water usage of Denver, Colorado[2]. Reservoirs are essential in aridland environments, especially for agricultural and drinking water purposes. Floatovoltaic systems have been deployed to reduce evaporation on agricultural and drinking water (Figure B) reservoirs. Relatively few studies to date have evaluated the effects of varying coverage ratios and levels of shade from floatovoltaics on evaporation in reservoirs[1,3,4], but one known study in Alicante, Spain, observed that a 4500 m^2 floatovoltaic covering the entirety of the reservoir produces 425,000 kWh and saves 5000 m^3 of water via avoided evaporation per year[5]. As an order of magnitude estimate of scaling the results of this case up to a California-wide region, we apply this water saving to panel area ratio ($10m^3 : 9m^2$) with Hoffacker et al.'s (2018)[6] study which found 39 TWh/y of generation-based energy potential over all reservoirs in California's Central Valley. Installing floatovoltaic systems over this region's combined 104 km^2 of agricultural reservoirs could contribute 15% of the State's annual electricity needs[7] and save 0.12 km^3 of water per year. Specific savings would differ depending on each reservoir's coverage ratio, geology, and location, but this volume of water saved would be sufficient to irrigate an additional 126 km^2 of agricultural land in the Central Valley, given average irrigation rates per unit of land area (0.95 m^3/m^2 per year), which are approximately double that of the rest of the nation[8]. Far greater water savings would be possible when considering the 77,000 km^2 of farm impoundments (irrigation, livestock, fishing and sedimentation ponds, and water quality control structures) across the world, and considering potential improvements in irrigation efficiencies[9]. Additional benefits could also be realized when considering drinking water reservoirs and water treatment plants in arid regions.

Nonetheless, reductions in evaporation owing to floatovoltaics could have adverse impacts on local and global surface temperatures[10,11] and trade-offs may exist for wildlife, particularly avian fauna, if they are unable to distinguish PV panels from surface water[12]. However, very little is known about bird vision, visual cues, and perception of solar energy infrastructure in general. Investigating impacts on bird and bat populations needs further attention to determine if water-based solar installations confer higher mortality rates than land-based systems.

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Supplementary Box 4: Solar Energy Techno-Ecological "Sundries" Across Multiple Systems

The following three solar energy techno-ecological synergies can be integrated into variable recipient environments across land, food, water, and built-up systems with 7-10 potential techno-ecological synergistic outcomes (**Figure 2**).

a. Energy Storage and Solar Energy—A Resilient Duo. As extreme weather events increase in severity and frequency, energy storage combined with solar energy offer unique TES outcomes (**Figure 2**), markedly as these weather events can often precipitate electric grid outages at regional scales. Historically, grid resilience to outages has most commonly been fortified with backup fossil fuel-based (e.g., diesel) generators, prone to complications arising from finite and/or long-distance supply chains and protracted periods of non-use. Notably, Alvarez (2017) described the aftermath of Hurricane Maria in Puerto Rico as "an epidemic of broken generators."[1] Energy storage combined with islandable solar energy systems—systems capable of functioning independent of the grid during outages—may confer long-term reliability to support critical electricity-dependent services than diesel or propane generators across diverse recipient systems, as there is no need for a fuel supply chain. Such critical services may include air conditioning during heatwaves (the leading cause of extreme weather event-related mortality in the US), electrical medical and pharmaceutical needs during natural disasters, electric charging stations for vehicles during wildfire evacuations (and/or electricity to run fossil fuel-based gas/filling stations), and electricity to support commercial, non-governmental, and state-led activities that humans depend on in crises. Solar energy systems are also vulnerable to high winds, but can be hardened in places with exposures to hurricanes using best practices.

Some solar energy users need or choose to disconnect from the grid for a period of time or entirely. Islandable solar energy with storage systems can power microgrids as well as off-grid systems. In some cases, this can confer higher levels of energy equity, an increasingly sought synergistic outcome for groups whose social constructs and values may align with such autonomy, including indigenous and tribal groups; greater energy democracy for those seeking a sense of participatory identity in energy decisions as a *prosumer* (as opposed to a consumer) and within communities; or those who desire divestment from carbon-intensive sources of energy that may be compulsory with rate pay-based grid integration[2,3]. Lastly, solar energy storage can reduce grid congestion, provide essential ancillary services, and may also reduce or negate the need for additional build-out of transmission infrastructure and their associated economic and environmental costs, including increased subsidized wildlife predators like ravens. Importantly, such benefits (i.e., energy equity, grid reliability; see **Figure 2**) are present for integrated PV that is not islandable, in instances where prosumers benefit from local control, ownership, and net metering or other compensation policies.

b. Solar-Based Transportation Across Land-, Air-, and Seascapes. Physical and economic limitations still prevent industrial implementation of on-board solar for electric vehicles (EVs), but research and development on solar-powered vehicles is gaining momentum. Solar cars require large surface areas for rooftop solar panels and heavy energy storage systems that are operationally incompatible with conventional vehicle design and engineering, while limited deck space on vessels constrains solar energy systems on marine vehicles. Gasoline-powered hybrid

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electric vehicles (HEVs) that have already reached industrial maturity may be assisted by on-board solar cells to increase fuel economy, but few commercial applications have been marketable to date. The most economically viable and practical HEV system today involves charging plug-in HEVs at stationary PV solar installations, creating realizable synergistic outcomes for deployment of both technologies (**Figure 2**). But modeled engineering scenarios show promise for solar aboard recreational vehicles and ships to supplement auxiliary power typically produced by diesel generators[4]. Hybrid PV/diesel/battery power systems aboard ships are technologically viable and can be optimized for seasonal and geographic variation in solar irradiation along shipping routes[5]. On-board solar for marine vessels provides a viable solution to reduce greenhouse gas emissions from ships, a prominent issue continually raised by the International Convention for the Prevention of Pollution from Ships. Implementation of on-board solar systems for unindustrialized vehicles have also been proposed. Rooftop PV mounted on food trucks can completely power food-truck kitchens, eliminating the need to tie into the utility via a 'shore line'[6], and solar power aboard small-scale, distant-water fishing fleets may contribute to sustainable fishing operations[7]. Considerable research and development have been allocated to solar-powered, unmanned aerial and offshore vehicles for several applications, ranging from search and rescue to space exploration. Although technological challenges continue to limit widespread commercial applications for fully solar-powered vehicles, experimental and demonstrational endeavors have proven successful. PlanetSolar is one of the world's largest solar-powered boats, containing 8.5 tons of lithium-ion batteries in its two hulls; it circumnavigated the globe in 2012. The world's first fully solar-powered train was built in Australia in 2017, and the Dutch start-up Lightyear One is staged to release ten fully solar-powered, road-ready cars in 2019. Solar-powered EV charging and vehicle-to-grid applications offer further opportunities to "solarize" transportation. In California, the utility Pacific Gas & Electric is partnering with auto manufacturer BMW to pilot smart charging systems that allow EVs to charge when excess solar is on the grid to absorb electricity that is otherwise curtailed.

c. Agricultural and Urban Solar Greenhouses. There is potential to incorporate PV arrays into greenhouses, to either provide electricity required by greenhouse operations or to export power for other uses. Generating electricity from integrated PV panels potentially reduces energy costs in greenhouses, negates the need for a mains connection, and avoids the need for land. Benefits can be tailored to optimize any offset against potential reductions in yield, crop quality (e.g., nutritional value), and aesthetics due to reduced radiation penetration.

For example, small solar panels (< 0.1 m^2) have been successfully deployed on greenhouses to generate electricity for low-power devices, such as ventilation systems[8]. Actively heating or cooling greenhouses to maximize yields requires a greater surface area of the greenhouse roof to be covered with PV panels and effects on crop yields, including the layout of the PV panels, are less established. Yano *et al.* (2007)[8] surmised that annual electrical energy consumption in greenhouses around the world ranged from 2 to 140 kWh m^{-2} yr^{-1}. Experimental PV modules tested by Yano *et al.* in Matsue, Japan, generated between 14 and 102 kWh m^{-2} yr^{-1} depending on configuration; however, shading can affect crop yield. For example, covering 12.9% of a greenhouse roof was found to significantly reduce the yield of welsh onions, if installed linearly, although, when installed in a checkerboard pattern, yield was hardly affected[9]. Installation of solar panels covering 9.8% of the roof area of a tomato greenhouse was shown to affect fruit size and color but did not affect total production or marketable value[10]. Wavelength selective photovoltaics utilize only part of the solar spectrum not needed for plants, allowing "pink greenhouses" to harvest electricity and grow crops life-cycle simultaneously. Consequently, while it is possible for some greenhouses to be energy neutral or energy negative, current efficiencies suggest that in areas that necessitate higher energy demands or where solar potential is low, additional energy may be required.

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