Techno-ecological synergies of solar energy produce outcomes that mitigate global change

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Abstract | 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.

Keywords: climate change solutions, ecosystem goods and services, land-use and land-cover change, photovoltaic, renewable energy, sustainable energy, urban heat island

Introduction

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].

Techno-ecological synergy (TES) is a systems-based approach to sustainable development emphasizing synergistic outcomes across technological and ecological boundaries; first introduced by Bakshi and colleagues in 2015[1]. Global sustainability challenges are inherently coupled across human and natural systems[3] and resource use on Earth exceeded regenerative capacity approximately since 1980[4]. Thus, solar energy combined with TES may prove a promising solution for avoiding unintended consequences of a rapid renewable energy development 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 ones 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 (**Figure 1**). When TES is applied, demand is carefully measured, including the quantity of resources withdrawn from (e.g., water withdrawal, habitat loss) or materials released into (e.g., CO_2 emissions, 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_2-eq kWh^{-1})[9,10] than all carbon-intensive energy systems (coal and natural gas: 413 – 1144 gCO_2-eq kWh^{-1})[11–13] and similar to other renewable energy systems plus 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 (**Figure 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 (e.g., California Desert Renewable Energy Conservation Plan)[2].

When solar energy is developed with TESs, pollution and environmental degradation are avoided or minimized, reducing waste flows. Concomitantly, beneficial ecological outcomes are produced alongside technological outcomes (**Figure 1b**). For example, a community-owned solar farm (Westmill Solar) in Wiltshire, United Kingdom (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_2-eq kWh^{-1} is contingent on the supply of regulating ecosystems services to sequester approximately 48,000 g CO_2-eq 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 like 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.

Techno-Ecological Synergies of Solar Energy Framework

When applied to solar energy technologies, the outcome of TES produces both techno-centric products (e.g., PV module efficiency, grid reliability) as well as support for sustainable flows of ecosystem goods and services (e.g., carbon sequestration and storage, water use efficiency, 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 (e.g., 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 (**Figure 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).

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'). In 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.

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 (**Figure 1**) and framework (**Figure 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 provide 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 2X the area of California [CA]; **Table 1**). Here, the most degraded sites (e.g., EPA Superfund sites) could produce over 1.6 million GWh y^{-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 embodied capacity for carbon sequestration (e.g., shrublands, 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 GHG and dust emissions, as well as 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 (e.g., wind turbines) is another TES. Co-location optimizes land-use efficiency (e.g., MW/km^2 for measuring installed capacity per area[27], TWh y^{-1} for measuring generation per area[5]) and even more so when co-location happens on degraded lands (**Figure 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 is 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 (i.e., 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 (e.g., pest regulation), carbon sequestration and storage, erosion prevention, habitat for species, maintenance of genetic diversity, and pollination (**Figure 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 to 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 vapor as a byproduct of photosynthesis), which cools panels. This response would increase PV module efficiency, a technological synergistic outcome, which may also extend panel lifespan[19,33].

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]. DeMarco et al. (2014)[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 within Agricultural Systems

Agrivoltaic systems (AVS) 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 and water quality (for further discussion on water and AVSs see **Supplementary Box 1**), and erosion prevention and the maintenance of soil fertility (**Figure 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.

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, respectively, 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 (**Figure 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[38]. Modeling in India on an AVSs 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 rainfed maize productivity (a C4 plant) than full light, and LERs were always >1[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 (**Figure 2**, **Figure 3b**). Another prominent example of negative space is in the corners of fields where center-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 (**Figure 3c**). Here, farmers may plant drought-tolerant crops or may purchase higher-cost center-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 (**Figure 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 true particularly for C3 crops that have lower light saturation points. In other locations, yields maybe 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 aridlands 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 (**Figure 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 (**Figure 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 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 Jevons paradox can exist). For example, USDA Farm Ranch and Irrigation Survey of 2013 surveyed 1,592 US farms (>$1,000 in products produced/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, e.g., 47% of surface irrigation in Spain was drip in 2018[47]), PV-based systems can further augment water use efficiency gains (**Figure 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 labor 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—we define here for the first time as solar energy generation co-located with domestic livestock activities and associated infrastructure, notably grazing areas—as well as intensive-animal solar energy systems (e.g., feedlots, dairy farms), can provide numerous potential techno-ecological outcomes (n=8), notably enhanced animal welfare and food system resilience (**Figure 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 a desirable environment condition recognized the Freedom Foods Certification Scheme in the UK and such favorable conditions improve both commodity (e.g., milk) yields and quality. Additional benefits arise for energy production through negating the need for active and costly vegetation management (e.g., mowing, herbicide application)[50].

Water and Electricity Mix with TESs of Solar Energy Across Water Systems

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 19K km in Gujarat, India. To date, floatovolatics exist across the world (e.g., USA, Israel, China, India, the 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 (**Figure 2**)[52].

Floatovoltaics have eleven potential techno-ecological outcomes and are capable of reducing water evaporation (**Figure 3d**), may reduce algae growth, and can be integrated over hydroelectric reservoirs. Reduced evaporative loss is of particular value in aridland 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 34M 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. Martinez-Alvarez et al. (2010)[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 CA (US), floatovoltaics were 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 (**Figure 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 favorable solar resource, with other regions in other countries also showing suitability[56].

Designing TES Outcomes with Solar Energy 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 (**Figure 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 so as their efficiency rate increases) and reduce total sensible flux (~ 50%), especially relative to dark (e.g., asphalt, membrane) or rock ballasted roofs. Taha (2013)[57] modeled 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 0.2°C decrease in air temperatures with higher efficiency panels. In Paris, France, when simulating the effect of solar PV and thermal panels (for hot water) on rooftops, Masson et al. (2014)[58] show 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, France revealed 4% fewer people to be affected by heat stress for more than 12 hours per day during the 2003 August heat wave (**Figure 1**)[58]. Given that more extreme summer heat stress is leading to an increasing number of heat-related, premature mortality events (e.g. 11,000 deaths in the Moscow heat wave 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 (**Figure 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 (**Figure 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 (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."[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 (EVs), but research and development on solar-powered vehicles is gaining momentum. 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. 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 belowground, directed to a reservoir, or consumed immediately onsite in place of groundwater or municipal source. Such a configuration produces up to seven techno-ecological synergistic outcomes and can serve populations where there is limited potable drinking water (e.g., 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 (e.g., 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 (**Figure 1**), framework (**Figure 2**), and assessment (e.g., **Table 1**) serve to demonstrate that solar energy TESs are feasible across diverse recipient environments with outcomes that favor both technological (e.g., PV module efficiency, grid reliability) as well as ecological outcomes. Specifically, such ecological outcomes support the sustainable flows of ecosystem goods and services (e.g., 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 six 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, 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 (**Figure 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, (\$417/tCO_2[65]) and mitigate other types of global change, the latter for which monetization of damages is less studied (e.g., biodiversity loss, 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 (US) 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' x 12' pollinator gardens. The US EPA's RE-Powering Program 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 (e.g., 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 Materials*).

Figure 1. Conceptual model demonstrating how techno-ecological synergies (TESs) of solar energy produce mutually beneficial technological and ecological synergistic outcomes that serve to mitigate global change-type challenges. Without TES (a), 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. In contrast, solar energy development with TES (b) 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 favorable ecological outcomes, which are augmented by the investment of capital into and management of ecosystems (e.g., restoration activities). Overall, solar energy with TES results in a beneficial change in the *direction* and *magnitude* of flows occurring between the ‘natural system’ (e.g., desert, forest) and the ‘technological system’ (i.e., solar energy development) relative to solar energy without TES.

Figure 2. Framework for techno-ecological synergies (TESs) of solar energy development. Each solar energy TES is characterized by its recipient system(s) (i.e.., land, food, water, built-up system) and potential technological (black icons) and ecological (colored icons) synergistic outcomes. Shown also 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'). In 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.

Table 1. Degraded land types in the United States and their geographic potential for the development of solar energy with techno-ecological outcomes. 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. Details on methodologies and sources are included as footnotes. Each row includes a qualitative color-based metric for relative potential restoration of ecosystem goods and services, degraded land type, a brief description, and geographic potential in area (km^2). For all degraded land types, local-scale ecological characteristics, existing infrastructure, and potential risks may impact relative reversibility in unique ways.

Figure 3. Techno-ecological synergies of solar energy and examples of techno-ecological synergistic outcomes: **(a)** Panel washing water inputs (*left*) on a photovoltaic (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 photo: NREL). 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, CA, photo: RR Hernandez; 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 (i.e., mowing) costs, and confer the opportunity to produce honey and other honey-based commodities (photos: Fresh Energy, Inc.). **(c)** 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; for further discussion on center-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*, photo: Far Niente Winery) and this floatovoltaic system under construction atop a water treatment facility in Walden, Colorado (*right,* photo: Dennis Schroeder, NREL; for further discussion on floating PV systems see **Supplementary Box 3**).

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