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Photovoltaic + Photosynthetic Coexistence: Towards a Sensible Accelerated Mass Integration of PV Onto a Perturbed Planet

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Abstract

The urgent massive-scale deployment (perhaps a 50-fold increase in the current installed amount by 2050) of solar photovoltaic (PV) energy onto the myriad of landscapes on Earth is confronted by considerable ecological, economic, and social/ cultural/ aesthetic challenges. To begin, a comparison of PV with other “anthropocene photon transformation operations” (primarily agriculture and forestry) is accompanied by observations on the reasons for the solar industry’s recent rapid rise and expected continued exponential growth. The report then demonstrates challenges and best-case integration options for high-density PV installations in urban areas, and lower-density ecovoltaics and agrivoltaics on rangeland and farmland. Close attention is given to the spacing between and under PV arrays. Critiques on, and proposals for accurate nomenclature to describe a variety of non-standard solar PV installations are offered. The blurry line between agriculture and nature on rangelands is recognized, as proposals for lowest-impact PV integration are offered. The challenges of rural PV integration on landscapes as diverse as forests, savannas, and deserts are detailed, with consideration of competing existing or potential deployment of trees and biofuel plantations. Paradigm-shifting reconsiderations of culture and aesthetics on rural landscapes, and the evolving roles of farmers, are explored. Finally, it is argued that to achieve meaningful levels of synergistic PV integration, historical support from public and educational sectors will be essential.

Palabras clave: agrivoltaics; ecovoltaics; energy transition; solar energy

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Coexistencia fotovoltaica + fotosintética: hacia una integración de masa acelerada sensible de FV en un planeta perturbado

Resumen

El urgente despliegue a gran escala (quizás un aumento de 50 veces la cantidad instalada actual para 2050) de energía solar fotovoltaica (FV) en innumerables paisajes de la Tierra se enfrenta a considerables desafíos ecológicos, económicos y sociales/culturales/estéticos. Para empezar, una comparación de la energía FV con otras “operaciones antropocénicas de transformación de fotones” (principalmente agricultura y silvicultura) va acompañada de observaciones sobre las razones del reciente y rápido ascenso de la industria solar y el esperado crecimiento exponencial continuo. Luego, el informe demuestra los desafíos y las mejores opciones de integración para instalaciones FV de alta densidad en áreas urbanas, y la implementación de *ecovoltaica* y *agrivoltaica* de baja densidad en pastizales y tierras de cultivo. Se presta especial atención al espacio entre y debajo de los paneles FV. Se ofrecen críticas y propuestas de nomenclatura precisa para describir una variedad de instalaciones FV no estándares. Se reconoce la línea borrosa entre agricultura y naturaleza en los pastizales, a medida que se ofrecen propuestas para una integración FV de menor impacto. Se detallan los desafíos de la integración de la energía FV rural en paisajes tan diversos como bosques, sabanas y desiertos, teniendo en cuenta el despliegue competitivo existente o potencial de árboles y plantaciones de biocombustibles. Se exploran reconsideraciones culturales y estéticas en los paisajes rurales, y los roles de los agricultores. Finalmente, se argumenta que para lograr niveles significativos de integración FV sinérgica, será esencial el apoyo histórico de los sectores público y educativo.

Palabras clave: agrivoltaica; agrovoltaica; fotovoltaica; energía solar

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1. Introduction

Apart from drying and evaporation techniques, and passive solar architecture (which remain outside the scope of this article), purposely cultivating plants for food, feed, fuel, fiber, structural material, and beauty – nowadays collectively categorized under the broad umbrellas of *agriculture* and *forestry* - have dominated what can be labeled *anthropocene photon transformation operations* ("APTO") since the dawn of agriculture some 12,000 years ago. In recent decades, solar photovoltaic (PV) energy systems have joined the APTO club, jostling onto plants' prior vast monopoly as consumers of photons on the finite sun-exposed surfaces of Earth.

Since the 20th century, market dynamics have pushed large crop and timber monocultures (single species cultivation; low to zero integration with existing diverse ecosystems) to become the mainstream way of carrying out APTO in industrialized countries. While regenerative organic polyculture APTO may seem like a noble maxim and indeed an imperative to many affluent and educated citizens – not to mention a prime survival strategy for subsistence farmers - it continues to face rejection by capital markets and adherents to Baconian, Cartesian, and related philosophies that deify humankind's dominion over nature.

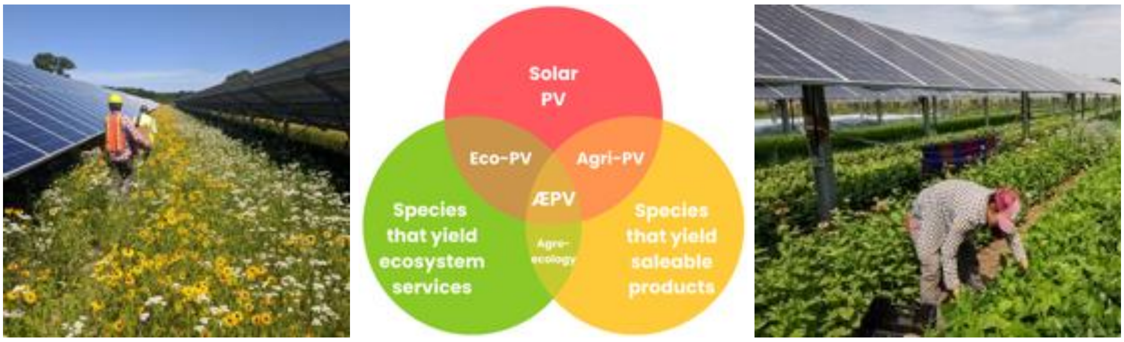
Macro monoculture APTO is inexorably linked to the reduction of biodiversity, cumulatively manifested as the *Anthropocene Extinction* ("AX"). AX has so far largely been driven by worldwide deforestation for agriculture (as well as pollution, overfishing, hunting, and other factors). However, the recent onset and growing threat of climate change, coupled with continued deforestation and land use change, threatens to significantly accelerate AX. The combustion of fossil fuels (FF) intertwines climate change, agriculture, and AX, as the greenhouse gas (GHG) emissions that are causing climate change are largely attributed to FF. FF has also enabled a historic global expansion of agriculture, leading to increased deforestation and decreased biodiversity.

Indeed, other macro crises of social unrest, political upheaval, war, pandemic, and resource scarcity have accompanied humans over varying geographies, intensities, and durations over the millennia. However, this relatively new, truly global emergency confronts us on a much graver level. Scientists and activists increasingly, repeatedly, and emphatically call for dramatic policy and lifestyle changes to prevent us from reaching "tipping points" and "planetary boundaries" on both biodiversity and climate, after which, return to stability may not be possible (Meadows, 1972) (Rhodes, 2019) (Montoya et al., 2018). While humans should thus optimize APTO siting, configuration and operations for increased ecosystem compatibility and reduced resource footprints and emissions, short-term economic efficiency continues to exert an oversized influence on the key parameters of most large APTO. Moreover, on top of ecological and economic considerations, aesthetics may also influence the characteristics of an APTO at the expense of environmental parameters.

This article seeks to apply such a triple lens of ecological, economic, and aesthetic considerations to the APTO newcomer, solar PV. Though PV's competition with plants may seem at first glance a dichotomous clash of "anthropocene versus natural", the plant kingdom is by no means a unilateral bloc, especially considering the schism between farmed plants for the benefit of humans ("APTO plants") and spontaneous wild plants for the benefit of the other >8M species on Earth ("non-APTO", or "eco plants"), a conceptual frame of reference which, though inherently suffering from several levels of nuance and overlap, can be useful to comprehend humans' footprint on nature. Despite such subtleties, for the purposes of this article, such a triptych of "eco plants, APTO plants and PV" is proposed as 3 future main categories of consumers of photons on Earth.

The broad range of PV projects which are co-located with the cultivation of saleable APTO plants (as well as other saleable non-plant species) are labeled *agrivoltaics* (or "agri-PV;" image example in Figure 1) while PV's coexistence with a mix of native plant species that are not harvested and sold has been referred to as *ecovoltaics* (or "eco-PV;" image example in Figure 2.) Due to PV's inherent incompatibility of co-location with forestry (due to the height of tall trees), the "APTO plants" which are proposed for integration with PV largely fall within the category of *agriculture*. "Agroecology" covers the overlap area between agriculture and diverse ecosystems, and "agri-ecovoltaics", abbreviated as *ÆPV,* is thus proposed as a designation for projects that include significant contributions from all 3 areas. It is hoped that the simplified diagram in Figure 2 may facilitate a conceptual understanding of this interplay; it is examined in further detail later.

Figure 1. **Eco-PV**; 2. **Conceptual relation between PV, agriculture, and ecosystem land use**; 3. **Agri-PV**



Sources: 1: Agrisolar Clearinghouse (US); 2: author; 3: Jack's Solar Garden (US).

One of the most prominent proposals to combat climate change is an unprecedented, massive global deployment of PV, as a major part of the greater "energy transition" away from FF. Though the energy transition also involves considerable implementation of other renewable energies such as wind, geothermal, hydro, marine, and sustainable bioenergy, as well as nuclear energy, PV currently shows the greatest promise within the renewables to deliver a substantial volume of energy with low embodied carbon, low resource footprints, and modular rapid deployability (as compared to FF), while avoiding the radioactivity risk associated with nuclear fission (Wikoff et al., 2022; Ludin et al., 2018).

1.1 *Breaking up a 350,000 km^2 PV blanket over the surface of Earth*

Recent ambitious forecasts call for attaining a cumulative installed capacity of 70 terawatts-peak (TW_p) of PV by 2050, which would represent >50 times the amount of PV that had already been installed worldwide by 2023 (Haegel et al., 2019). Considering a 200 watts-peak (Wp) per m^2 average PV module efficiency, which can thus be extrapolated to 2 megawatts-peak (MW_p) per hectare, 70 TW_p translates into approximately 350,000 km^2 of opaque inert photovoltaic surface (0.2% of the world's landmass, equivalent to the size of Germany). Of course, an enormous two-dimensional PV blanket will not be laid upon Germany, but rather splintered into many millions of PV systems of various sizes around the world, featuring a total of circa 140 billion PV modules (considering an average size of 2.5 m^2 or 500 W_p per module in this 70 TW_p scenario).

It must be recognized that some commercially available PV modules in 2024 already display efficiencies exceeding 220 watts-peak (Wp) per m^2, and laboratory experiments have proven efficiencies of 395 Wp/ m^2 (France, 2022). Likewise, alternative novel lower-cost PV technologies come in at efficiencies of less than 200 Wp/ m^2. Though it's impossible to predict what average PV efficiency will be in 2030, 2040, or 2050, and what humanity's energy use will look like then, this "350,000 km^2 by 2050" figure can be considered a workable order of magnitude for now.

The exploration of the spacing between and under PV modules and arrays on individual projects is a major focus of this article. To date, inter-PV spacing along the X and Y axes has traditionally been meticulously minimized in the interest of achieving a lowest Levelized Cost of Electricity (LCOE) - the final cost of a kilowatt-hour into which are bundled all the capital and operational expenditures for equipment, labor, and interest that are needed to build and operate a PV system for several decades. Not unlike economically optimized large-scale crop and timber APTO, most PV installations around the world have been built in "monoculture" or "single use" clusters of PV modules and arrays. Due to the finite area available on a delineated parcel of land or building, and the desire to maximize the return on investment (ROI) on a PV project with a single revenue stream, inter-PV spacing (like inter-crop and inter-tree spacing) is kept minimal. The z axis (the distance between PV modules and the surface of the Earth or host structure) of PV arrays has also traditionally remained short to maximize ROI.

There have already been publicized cases of single-use PV projects coming into direct conflict with agriculture, in which public authorities have judged PV as a “higher priority for the public good,” and thus expropriated farmland (Martín-Arroyo, 2022). The opposite however is more common: proposed PV projects denied construction permits in favor of existing agriculture, forestry, or natural land use. Dual-use PV formats such as agrivoltaics show a major potential to address this land conflict, as is demonstrated throughout this article.

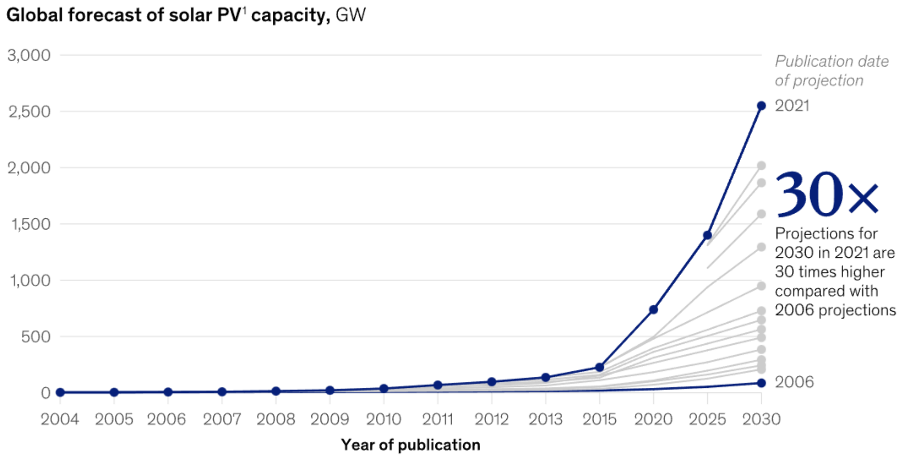
Inspired by agroforestry and other polycultures, increasing spacing to various extents between and under PV arrays shows great promise to host both “eco plants,” “agri plants,” and/or eco and agri animals within the finite boundaries of a PV project area, facilitating a wide range of benefits from food security to biodiversity rehabilitation to carbon capture, and other Sustainable Development Goals (SDGs). Appropriate system design and operation is essential to achieve successful integration, as is detailed later in this text.

Though the term “dual use solar” has typically been narrowly associated solely with agrivoltaics (particularly in the US), a broader definition can be considered to classify all PV projects that host any secondary revenue-generating activities (industry, transportation, leisure, parking, and other applications) or ecosystem services within the array areas. This general concept has been labeled as “integrated photovoltaics” by the Fraunhofer Institute (*Integrated Photovoltaics - Fraunhofer ISE*, 2022.) Inter-PV spacing need not however be increased when “PV skin” is incorporated onto a non-photosynthesizing anthropocene object or structure which does not benefit from additional irradiance, as discussed in Section 2. While certain high-value parallel revenue streams have already successfully engendered dual use PV projects without public aid, ecosystem services and many forms of agriculture are comparatively less immediately lucrative. It is thus proving a challenge to convince PV asset investors to make the required system modifications to foster these second uses, without direct short-term monetary compensation (Pascaris et al., 2020).

1.2 Solar PV-: humanity’s sudden prime decarbonization strategy

Solar PV went from a laboratory curiosity to a serious topic of NASA-funded research and niche remote power source between the 19th and 20th centuries, finally reaching megawatt scale at the turn of the millennium, buoyed by government subsidy programs in Europe, Japan and North America. However, it was the dramatic expansion of industrial PV manufacturing in China that catapulted solar power to grid parity in several key markets in the past decade, as prices plummeted. In the last few awe-inspiring years, even the most aggressive PV deployment forecasts have been exceeded, as shown in Figure 4 (*An Era of Renewable Energy Growth and Development | McKinsey*, 2022).

Figure 4. **Historical projections of PV deployment in 2030 (2006-2021)**



Note: Today's projections for solar and wind power capacity in 2030 predict values much higher than those projected in 2006. Source: McKinsey (2022).

PV reached the milestone of 1 TW_p of global installed capacity in 2022, many years earlier than expected, and despite the crippling global pandemic of COVID-19. Nowadays, some forecasts – even more ambitious than the “2.5 TW_p” figure shown on the McKinsey graph above - call for up to 10 TW_p of PV to be deployed globally by 2030, a tremendous jump from the <0.1 TW_p predictions made for 2030 back in 2006 (Berney Needleman et al., 2016), yet just a fraction of the proposed “70 TW_p by 2050”, as noted earlier.

The global energy mix that powers our 8+billion-person growing society is, by nature, constantly in flux. Other renewable energies as well as nuclear power are also certainly expected to make increasingly significant contributions towards decarbonization in the coming years. Nevertheless, the specific focus of this article is on PV, and its best-case integration scenarios onto the planet’s landscapes; “best-case” referring to minimized initial disruption of existing diverse ecosystems during construction, subsequent successful coexistence with (and perhaps improvement or boosts in complexity of) ecosystems and/or sustainable agricultural activities, and other support of SDGs.

It must also be noted that improving energy efficiency is also a major tenet of the energy transition, with such core goals as increasing efficiency of appliances, lighting, transport, buildings, agriculture, industrial processes and other anthropocene activities. The International Energy Agency’s (IEA) Sustainable Development Scenario calls for energy efficiency measures to deliver more than 40% of the energy-related greenhouse gas emissions reductions over the next 20 years needed to achieve the goals of the Paris Agreement on climate change (*Energy Efficiency 2020 – Analysis*, 2020.).

Nevertheless, despite such calls for energy efficiency, and implorations of *degrowth* - major decreases in energy use across society - humans continue to consume energy at startling rates. An additional overall 50% increase in global energy use from 2020 levels has been predicted for 2050, though signs strongly suggest that the lion’s share of this new capacity will be powered by renewable versus as opposed to non-renewable fuels (*EIA Projects Nearly 50% Increase in World Energy Usage by 2050, Led by Growth in Asia*, 2020).

It should be recognized that all of the above cited terawatt-scale PV deployment forecasts take into account parallel forecasts of global increases in both energy efficiency and energy consumption. And of course, *forces majeures* – whether *acts of God*, or acts of man – such as natural disasters, pandemics, wars, climate change, artificial intelligence (AI) and the anthropocene extinction (AX), must be factored in as forces that may significantly affect such long-term forecasts.

1.3 Objectives and methodology

This report’s main objective is to offer a panorama of the least-disruptive ways to distribute the aforementioned gargantuan area of 350k km^2 of impermeable, inert, generally opaque surface into existing built-up areas, ecosystems and agricultural operations. A major intent is to show that channeling public capital into subtle variations on PV system architectures (particularly increasing inter-PV and under-PV spacing, enabling a broader range of ÆPV compatibility) could potentially result in significant benefits for food security, ecosystems, and local communities, and that at a global multi-decade scale, become a considerable tool in mitigating biodiversity decline and further combating climate change beyond PV’s already impressive low-carbon profile. Continuing this investigation will be essential if humans are to carry out the Herculean task of deploying 70 TW_p of PV as not only a decarbonization and energy security strategy, but as a tool towards decelerating the Anthropocene Extinction.

The first of the three body sections provide an essential overview of the often-overlooked core characteristics of PV, with particular attention to their resemblance and compatibility (at high power densities) with urban anthopocene structures. Reducing PV power densities – by increasing the horizontal spacing between energy-generating surfaces- is the focus of the second central section, with emphasis on PV integration onto porous landscapes with low-stature vegetation. The more complex challenge of PV integration on wetter, more biodiverse biomes with bushy woody growth and trees is also examined, with inquiries on the feasibility of increasing vertical spacing. The last of the three core sections considers siting of multi-use PV, considering best-case integration scenarios on various landscapes, and examples of land use competition from tree plantations and biofuels. Aesthetic debates of ground-mounted PV, with attention on the choices that the public sector will face in terms of balancing local energy, food security, and biodiversity with landscape aesthetics are discussed towards the end. The article is informed by literature review, with strong emphasis on recent publications, given the nature of the dynamic and fast-evolving debate of massive PV deployment.

2. Minimizing inter-PV spacing in the city

2.1 Opaque inert PV "skin" for opaque inert buildings and infrastructure

Whereas the photosynthetic surfaces of leaves are biodegradable and ephemeral, PV cells are inert, impermeable, and encapsulated inside either durable glass, polymer, or a mix of the two. PV modules are highly recyclable, but purposely not biodegradable, in the interest of longevity under harsh outdoor environments (Deng et al., 2022). Such characteristics marry well with buildings and infrastructure, which may last hundreds of years if cleverly built and cared for. As it is much easier to ecologically integrate PV modules within the relatively uncomplex ecosystems of buildings in cities - as opposed to complex biologically-rich natural landscapes - urban built environments are widely recognized by ecologists as the highest-priority application for PV at high power densities (Yan & Wang, 2019). As anthropocene structures are usually (to varying extents) utilitarian, it may be argued that almost all PV on such artifacts could be considered "dual use."

"Distributed-scale solar" refers to those projects (often urban/ peri-urban rooftop and small ground-mount) in which the PV electricity is locally consumed, on the customer's side of the meter. This sector of PV represents approximately 40% of total PV installed capacity globally, and has been driven by support by the urban public sector in ramping up PV deployment in cities for over two decades (Mah et al., 2018) (*Approximately 100 Million Households Rely on Rooftop Solar PV by 2030 – Analysis*, 2022). Yet the utopian goal of implementing uninterrupted "PV building skin" with maximized power density and minimized inter-PV spacing on both the roofs and façades of structures inherently faces steep economic and aesthetic challenges, with most projects ending up with a patchy distribution of PV on roofs, and façades still rarely solarized. Though public funding can help narrow the gap between such "lowest-cost urban PV" and higher levels of coverage and/or improved aesthetics, identifying thresholds and targets is a major perpetual challenge (Goel, 2016).

Whether on flat or inclined roofs, vents, air conditioner units, chimneys and other rooftop equipment and architectural features often protrude upwards on roofs, breaking surface continuity and casting shadows, hindering PV's full deployability (Figure 6). Furthermore, PV-free access lanes are often included so that operations and maintenance (O&M) technicians as well as firefighters are able to reach the PV modules and these other rooftop elements (Figures 5, 6, and 7). Such design decisions may be driven by ergonomic optimization of operations, requests from building owners, or legal obligations from local authorities having jurisdiction. Structural support issues also may limit the amount and type of PV permitted on roofs (Figure 7 showing PV arrays arranged above horizontal joists). Likewise, limits on system size due to building energy consumption, local power grid capacity, or financial models have left many buildings' roofs with just a small section of PV on otherwise large obstruction-free surfaces (Figure 6).

Some large roofs with less obstructions feature areas in which continuous PV sections of several hundred square meters may be installed at low cost just a few centimeters above the roof (Figure 8). Other, albeit more costly, examples of raised continuous canopy structures (typically employing robust steel vertical structural supports) built on top of roofs exist, often serving a dual use as a shelter for parking (Figure 9) or leisure activities (Figure 10). Most PV carports however have been installed on ground-level parking areas, as opposed to garage roofs. If it is desired that some sunlight reaches the area beneath the PV canopies, while avoiding the loss of rain protection that increased inter-PV spacing would cause, semi-translucent PV modules may be employed, though it should be noted that such equipment is typically more expensive than lowest-cost urban PV installations.

Figures 5, 6, 7. **A selection of discontinuous PV arrays on flat roofs**

Sources: 5: author / Solar Energy Systems LLC; 6 and 7: Google Earth (all US)

Figures 8, 9, 10. **A selection of large continuous rooftop PV arrays**

Sources: 8: author / Solar Energy Systems LLC; 9: Solaire Generation; 10: Brooklyn Solar Works (all US)

2.2 *PV + plants on some pioneer urban projects*

Rooftop eco-PV (the deployment of PV on biodiverse green roofs) has been documented in varying formats in recent years (Figures 11 and 12), though the sample size of this remains too small to make conclusions about the required increase in spacing between and/or under PV. A few instances of *rooftop agri-PV* have also been documented (Figure 13) though such projects represent an even smaller sample set globally than rooftop eco-PV. Nevertheless, such formats show interesting potential to contribute towards multiple SDGs; further research and project implementations are encouraged. As photon harvest is thus shared between the PV and the photosynthesizing species cohabiting the roof, highest-density "PV building skin" is thus not feasible; some increase is spacing between modules and/or cells, and under modules is required to allow enough photons to reach the plants.

Figures 11, 12, 13. **PV + vegetation on roofs**

Sources: 11: author /UfaFabrik (Germany); 12: Over Easy Solar AS (Sweden); 13: Hinren Engineering (India)

2.3 *Residential PV, BIPV, and aesthetic considerations*

PV on flat roofs is usually not visible from the ground level, and therefore relatively immune to accusations of aesthetic transgression. Heated aesthetic debates however have been documented on residential solar for many years, as PV arrays are indeed usually visible from the street (Zalamea-León et al., 2018). A wide range of architectural integration can be observed from "noticeable but integrated" (Figure 14) to "rather jarring" (Figure 15) though such judgements are of course subject to personal opinion. Nevertheless, there are generally greater attempts at architectural harmony on residential PV than commercial rooftop projects, due to their increased visibility to the public. There have been many instances of neighborhood associations successfully legally prohibiting rooftop PV on homes as disruptive to the visual continuity of their community, particularly in the US (Caffrey, 2010). Essentially camouflaged (Figure 16) rooftop tiles are also now increasingly available, whether to circumvent such aesthetics legislation, or simply for architectural taste. The cost premium associated with such residential building-integrated PV ("BIPV") is typically covered by homeowners. While suburban PV transforms photons into electricity, another major format of suburban APTO is the monoculture grass lawn, which transforms photons into subjective beauty. Like PV, lawns in some suburban communities in the United States have also been subject to legal action on aesthetic grounds, with homeowners receiving fines for not conforming to established criteria on upkeep or species selection (Sisser et al., 2016).

Figures 14, 15, 16. **Residential rooftop PV arrays**



Sources: 14: Greentech Media; 15: Quora; 16: PV Magazine (locations unknown)

Finally, the vertical façades of buildings and structures represent a tremendous potential albeit economically challenging surface for PV to colonize. PV façade systems, somewhat synonymous with *BIPV*, already began to appear before the turn of the millennium in a limited amount of expensive pioneer projects. In the early 2000's, most BIPV retained the trademark blue/black colors of PV, clearly announcing its electricity-generating function to passers-by (Figure 17.) However, dyed PV modules in different colors and patterns (such as brick: Figure 18) have been available in multiple varieties for over 2 decades and have seen an increase in uptake in recent years, paving the way towards true urban camouflaged PV building skins. However, as BIPV remains amongst the most expensive PV applications, market growth has been limited, though increasing (Gholami et al., 2021).

Figure 17. **Uncamouflaged BIPV façade with standard modules (2004);** 18. **brick-mimicking BIPV (2022);** 19. **semi-translucent BIPV roofing (2014)**



Sources: 17: author/ altPOWER (US); 18: PV Magazine International (Canada), 19: ArchDaily (Netherlands)

Urban distributed-scale PV shows major promise, yet bureaucracy and economics have often slowed down deployment (Goel, 2016). However, recognizing its high potential levels of integration while typically eliminating land-use conflict, some regional governments have placed it as the highest priority, sometimes while prohibiting or enacting severe restrictions against rural ground-mounted PV on the grounds of avoiding agricultural and/or ecological displacement, and/or for aesthetic reasons. Other jurisdictions have prudently acknowledged the urgent need to accelerate overall installed PV capacity, requiring a simultaneous deployment of PV on multiple categories of surfaces, and thus permit rural land-based solar as well, under a range of conditions, while favoring urban PV (*Banque des Territoires*, 2022).

3. Adapting lowest-cost PV for vegetation & animal integration

3.1 Power densities on LoCoPV

Contrary to FF, hydro, and nuclear power stations, which concentrate hundreds of megawatts of electrical generating capacity in relatively compact geographical footprints (albeit without considering the mining and hydrological footprints of those technologies), PV is more extensive and thus more visible on landscapes in its most common format, *ground-mounted PV*, which when built on projects exceeding a few hectares, is referred to as "utility scale" PV. Observing typical utility-scale PV systems that occupy fields, a similarity to another APTO- large monoculture crop plantations- is apparent, as the photon harvesting arrangements on both are laid out in repetitive parallel rows for efficiency, as noted above.

Though not prevalent in common discourse, the term *LoCoPV* is proposed here to refer to the "lowest-cost" ground-mounted utility-scale PV installations built on rural land, with the primary function of delivering the highest ROI by supplying the lowest-possible LCOE. LoCoPV is fine-tuned to minimize spacing between and under PV, as leaving such "wasted space" is considered uneconomical, and thus detrimental to LCOE. Spacing within LoCoPV arrays is dictated primarily by the avoidance of shading from other modules and vegetation, and considerations of ergonomic access by operations and maintenance (O&M) crews (Aronescu & Appelbaum, 2017).

While rural PV is generally seen as an "extensive" form of energy, LoCoPV is optimized to keep it as dense ("intensive") as project-specific financial models and local environmental regulations will allow. It should be noted that as *dense* concentrations of PV modules per hectare lead to increased *intensification* of energy generation (more megawatt-hours per hectare per year), these terms may be used somewhat interchangeably when referring to PV deployment. Indeed, the most intensive version of rural ground-mounted LoCoPV is similar to the highest-density continuous urban PV skin (roughly 200 W_p/ m^2, or 2 $MW_p/$ hectare, as noted in section 1.1), as prescribed for anthropocene surfaces, as shown in Figure 20. It should be noted that this *super-dense* format is currently very rare, and immediately raises questions about soil sealing and stormwater management.

Such "impermeable PV skin on porous earth" represents zero ecosystem integration and is thus strongly discouraged. "Wrinkling" a similar density of PV capacity into arrays that typically face east and west is sometimes deployed, featuring narrow access lanes for human workers to access arrays for maintenance (Figure 21). Nevertheless, on these super-dense configurations popular in the Netherlands and other areas with very high land prices, ecosystem and/or agricultural integration remains very limited, and sunlight penetration to the ground very scarce (Figure 22). Minor de-intensification of this design has been shown to somewhat reduce soil deterioration, yet true robust ecosystem integration remains out of reach (*Novel Design for East-West Solar Parks Reduces Soil Deterioration*, 2021).

Figures 20, 21, 22. **Highest-density ground-mounted PV: flat and wrinkled**

Sources: 20: Solar Industry Magazine (US); 21: author (Belgium); 22: PV Magazine (Netherlands)

Such super-dense formats represent just a fraction of the LoCoPV installed around the world. *Mainstream ground-mounted LoCoPV* projects rather feature inter-row spacing that is wide enough for maintenance vehicles such as pickup trucks to circulate, which often coincides with the area that is shaded by the neighboring PV array. By far, the two most common formats of LoCoPV are fixed systems (Figure 23), typically facing the south (in the northern hemisphere) or north (in the southern hemisphere) and dynamic single-axis trackers (aligned in long north-south rows: Figure 24) (Aronescu & Appelbaum, 2017). Lower land costs may facilitate slightly wider row spacing. As opposed to a continuous "PV skin" of 2 MW_p/ hectare, most mainstream LoCoPV comes with "array power densities" between 0.9 and 1.5 MWdc per hectare [with corresponding ground cover ratios (GCR) of around 0.5 to 0.75], though overall "site power densities" are lower, to varying degrees, due to site geography, as explained below.

Figures 23, 24. **Common topologies of LoCoPV: fixed south-facing; single-axis trackers;**
Figure 25. **diagram comparing array and site power density**

Sources: 23, 24: author (USA, Chile); 25: Google Earth + superimposition by author

In Figure 25, the small area delineated in green (total 14.5 m^2) shows (4) 450 W_p PV modules (totaling 1800 W_p) which occupy approximately 9 m^2, and an inter-row "PV-free" area (maintenance vehicle corridor) of 5.5 m^2. As this design is modularly repeated throughout the project, it can be considered that the project utilizes a PV "array density" of approximately 124 W_p per m^2, which could be extrapolated to 1.23 MW_p per hectare. However, due to the diagonal aspects of the property polygon, a significant amount of space is left PV-free, as it would require uneconomical customized lengths of the mounting system and de-optimized cabling.

The larger area delineated in red (total 2187 m^2) shows (260) 450 W_p PV modules (totaling 117,000 W_p) which occupy approximately 585 m^2, and an open PV-free area of 1602 m^2. This translates to an overall "site density" of approximately 53 W_p per m^2, extrapolated to 0.53 MW_p per hectare. Aside from property boundaries, other hydrological, ecological, and/or ergonomic aspects of projects are often responsible for the difference between array and overall project densities. Considering this significantly variable spread between the two values, array power densities are utilized in this article as indicators of PV density. Overall site densities are favored by governments and land use statisticians, so more data is available on them as opposed to array densities. The noteworthy Solar Futures Study by the US Department of Energy selected 0.374 MW_p per hectare as an average PV site power density (Ardani et al., 2021).

Beyond the optimized power density of PV arrays, another characteristic often observed on LoCoPV has been low vegetation biodiversity. As the movement of machinery and crews can damage existing vegetative cover on PV sites during the construction phase, a combination of local regulations and common sense regularly calls for the seeding of the grounds upon completion of construction, to stabilize soil and decrease the amount of dust that can dirty PV modules. For such seeding, there has unfortunately (until recently) seemed to be little incentive to spend more capital than on the absolute cheapest grass species, or even gravel, if permitted by local authorities. (McCall et al., 2023).

3.2 *Lowest-cost ecovoltaics*

Nevertheless, perhaps partially as an altruistic, ESG- (environmental, social, governance) or CSR- (corporate social responsibility) driven desire to increase biodiversity, and certainly partially due to the recent realization that a more focused design on the biological elements of a PV site may translate into improved ROI, an increasing amount of PV projects have been incorporating some ecosystem services-facilitating elements. Studies and experiences have shown that such techniques as planting native groundcover species (though often a higher initial cost than turfgrass or gravel) can decrease long-term O&M expenditures on vegetation and soil erosion management (McCall et al., 2023). Some of these native species that show long-term stability are flowering plants, which have been shown to boost pollinator populations, leading to the coining of the term “pollinator-friendly solar” in the US. There have not been any findings that such pioneer entry-level ecovoltaics projects have chosen to significantly increase the spacing between or under PV from the mainstream LoCoPV figures of 0.9 to 1.5 MWdc /ha to accommodate these blends of native flora.

Growth rates of certain sun-loving species in the semi-shade of PV arrays may be lower than their counterparts in full sun, but as these plants are not harvested and sold, the commercial pressure for maximized yields common on agrivoltaic projects is not present. There is a strong argument to consider this “not for sale” aspect of the species cohabitating with PV as the prime tenet that sets ecovoltaics apart from agrivoltaics. The direct beneficiaries of ecovoltaics are thus ecosystems rather than Homo sapiens, although humans often indirectly benefit from the ecosystem services generated on such sites. To what extent the selection of a particular plant species on an ecovoltaic project may correspond to non-use or option values should be examined on a case-by-case basis (Azqueta & Sotelsek, 2007).

Confoundingly, ecovoltaic projects are often presented under the agrivoltaics banner in the US and China, though rarely so elsewhere. Perhaps since the Department of Agriculture in the US (USDA) is active in such a staggeringly wide variety of aspects of agri-food systems and ecology, the term *agriculture* has taken on a much broader meaning nowadays than the comparatively narrow reference to peri-urban and rural wheat fields around Rome, from which its Latin linguistic root *ager* stems (Harris & Fuller, 2014). Considering examples such as the *Conservation Reserve Program*‘s funding of long-term (and perhaps permanent) fallow and biodiversification of plots of land under the auspices of the USDA, the association of biodiverse lands that *do not* yield farm products over many years as a form of “agriculture” persists in the US (Stubbs, 2014).

In any case, “ecovoltaics” is intended as a conceptual label, and precisely quantifying and qualifying the plant species that would push a LoCoPV project over the threshold to earn an ecovoltaics designation is best left to local public authorities. Indeed, a PV project that just barely crosses this yet-undefined line into ecovoltaic status could be categorized as “lowest cost ecovoltaics”: *LoCoEco-PV,* like the projects noted in the first paragraph of this section 3.2.

The term “low impact solar” should also be noted, as having arisen along with this genesis of *proto ecovoltaics* in the United States to loosely describe a variety of vegetation management, animal grazing, and civil engineering practices to reduce environmental impacts on PV projects, though the term’s correlation with crop agrivoltaics remains unclear, due to the latter’s small sample size in the US (McCall et al., 2023).

3.3 Lowest-cost agrivoltaics

For trimming of PV site vegetation, sheep are increasingly employed on mainstream ground-mounted LoCoPV projects around the world, to dine on selections of groundcover species that vary widely in diversity. Apart from carefully tucking away cables and loose equipment, and perhaps a slight increase in height of PV arrays, there are no major modifications required for mainstream LoCoPV to accommodate sheep. A minority of sheep on PV sites are used for dairy or wool products, while virtually all sheep on solar sites are eventually intended to be sold for meat. Such sale of agricultural products from animals that have been mostly or completely nourished on vegetation that grew within the boundaries of a PV site appears clearly linguistically worthy of the label “agrivoltaics,” despite ongoing debates. Sheep grazing on PV sites has quickly become by far the most popular agrivoltaics format in the US: indeed, a *lowest-cost agrivoltaics*, or “LoCoAgri-PV”. Crop agrivoltaics however tend to require more specialized design considerations and are addressed in the following section.

Developed in the late 1960's, *land equivalent ratios* (LER) are a tool initially utilized by intercropping and agroforestry proponents, and recently enthusiastically embraced by agrivoltaics researchers, that show boosts in land efficiency when 2 or more crops are co-located on a single parcel (Willey & Osiru, 1972) (Maitra et al., 2021) (Dupraz et al., 2011). In the case of sheep, a standard grazing pasture which yields a standard quantity of meat per year could be considered a "1", while the electricity output of a mainstream LoCoPV PV system (a precise GCR being heatedly debated) would also be rated a "1"; in the ideal simplified scenario in which the sheep integration does not require the PV design to stray from LoCoPV (or vice versa), and the annual meat delivered per hectare is the same with or without the PV, the resulting LER would be 1+1= "2."

Any LER above 1 is thus considered some sort of improvement, providing the added cost of integration has not exceeded the increased revenue (Dupraz et al., 2011). LERs above 2 are fantastic, and typically limited to sunny arid regions. Although the configuration of the PV system remains the same, climate varies from year to year, leading to annual fluctuations in LER. For example, Trommsdorff et al noted how a potato crop on an APV project of elevated PV modules at 5 meters in southern Germany registered a LER of 1.57 in 2017, followed by 1.86 after the hotter summer of 2018. Clover grass on the same project, however, dropped from 1.70 to 1.67 in the same time period (Trommsdorff et al., 2021). Considering the market drive of agricultural products, LER analysis is more commonly performed on agri-PV than on eco-PV, which may involve non-use values.

While such high-LER projects can proudly call themselves "*agrivoltaic"*, this term is not exclusive to such success. *Agrivoltaics* is also unfortunately associated with more poorly designed projects, particularly those with ambitiously dense PV arrays exceeding 1.2 MWp/ ha, in which significant agricultural yield reductions (as compared to control plots or historical data) have been observed, even to the point of triggering the abandonment of farming.

In the interest of not treating agrivoltaics as a "single thing", but rather the dizzyingly complex variety of project formats that it is, Dr. Macdonald conceived a "3 Cs" framework in 2021, which was later folded into the US National Renewable Energy Laboratory's 2022 "5 Cs" report, detailing how {Climate, [PV array] Configurations, Crops/ Cultivation methods, Compatibility, and Collaboration} factors can greatly influence the success or failure of an agrivoltaic project (Macknick et al., 2022).

Finally, if there is a blend of local plants on a PV site which provide ecosystem services, and some of these plants are ingested by sheep, which are then sold for meat, daily, or wool, then it can be argued that the project deserves an "ÆPV" designation- *agri-ecovoltaics*. Likewise, a mix of agri and eco plants integrated on the same PV site could also be called ÆPV.

Though agrivoltaics already seems like a noble undertaking as opposed to segregated monoculture PV or crops, a site devoid of ecosystem service-providing species is not desirable, so efforts to turn every agri-PV project into an ÆPV project should be encouraged. In any case, it should be noted that establishing nomenclature to describe the numerous deviations from LoCoPV is challenging, and indeed currently far from settled. The term "agrivoltaics," related labels, and local translations are indeed the subject of nuance and debate in different countries (Toledo & Scognamiglio, 2021).

The entry-level ability of LoCoEco-PV and LoCoAgri-PV to host a variety of living things is noteworthy, though their compatibility with a broader (particularly taller) range of farmed and wild plant and animal species is limited. Nevertheless, on sites with very short stature (or an absence of) autochthonous vegetation and animals, typical of dry, sunny rangelands of the world, LoCoAgri-PV and LoCoEco-PV might indeed be quite appropriate options, as the shade from a high concentration of PV may be beneficial to the vegetation and animals. On several sites in temperate and arid regions, researchers have noted improved vegetation health and yield improvements on low-cost agri- and eco-PV arrays without increases in spacing from mainstream LoCoPV (Sturchio et al., 2022). This point is again examined in Section 4.2.

3.4 RIIC & XRIIC: stretching out X, Y, Z (and T) to share more photons

To attain the sunlight and spacing requirements that many crops need to thrive, or to accommodate larger animals, the PV needs to somehow move a bit out of the way. This can be done in by *de-intensifying* one or more of the three dimensions of space, or the time dimension.

Table 1: **De-intensifying PV's axes to increase the amount of irradiance that reaches the Earth**

Axis	**Description**	**Methods**
X	Continuous plane of array	Additional spacing may be included between PV modules (Figure 26), or between PV cells within modules; or, alternative semi-translucent cell technologies may be employed
Y	Area between rows	Increase inter-row spacing between arrays (Figures 27 and 28)
Z	Height	Increase height of array (Figure 26)
T	Time (for trackers)	Implement smart algorithms that "back-track" PV modules away from the sun, ideally at moments when the plant can best utilize the light, and/or when the value of the electricity on local spot markets is low

Source: authors.

Figures 26. **Increased X and Z**; 27. **increased Y**; 28. **PV trackers on an inter-row agri-PV project**

Sources: 26: Earth.org (Kenya); 27: Engie Green France; 28: author/ Engie Italia SpA

Significantly increasing the spacing between or under PV modules (or de-optimizing the tracker algorithm from a sole focus on PV generation) either will reduce the amount of PV deployable on a given plot of land, increase the costs of the mounting structure, increase the overall lengths and thus costs of cabling, reduce energy generation, or a combination of these, thus representing a clear deviation from LoCoPV. Therefore, in an open market competition for PV projects, funds must be obtained to cover the difference in LCOE between LoCoPV and such evolved formats of agri- and ecovoltaics, or a project will likely not be realized. Alas, the first word of this paragraph – *significantly* – is worthy of profound scrutiny and quantification beyond the scope of this article.

Table 2: **Varieties of ground-mounted PV**

Array density (approx..)	**Agri-/Eco- or ÆPV?**	**Format**	**Sub-varieties**
Super-dense >1.5 MW$_p$/ha (0,75 GCR)	No	**LoCoPV** (Lowest cost PV)	Very high PV ground cover; often significant biodiversity, hydrological and soil health risks
Mainstream 0.9 - 1.5 MW$_p$/ha (0.45-0.75 GCR)	No	**LoCoPV**	**PV + gravel or grass monoculture**: Lowest-cost; monoculture crop of electricity with little consideration to ecology other than low-cost grass, or perhaps just gravel. Mechanical or chemical vegetation management
	Yes	**LoCoPV**	**LoCoEco-PV / LoCoAgri-PV/ LoCoÆPV** : implementation of some short-stature native species &/or grazing to reduce O&M costs
Varies 0.5 - 1.3 MW$_p$/ha	Yes	**RIIC** (Reduced-Intensity; Increased Compatibility)	**Reduced-density:** De-intensified X and/or Y axes
			Elevated: Increased height of Z axis
			Smart Tracking: algorithm to share sunlight between PV and plants
Varies 0.1 - 1.3 MW$_p$/ha	Yes	**XRIIC** (Extra-Reduced-Intensity; Increased Compatibility)	X axis: <50 W$_p$/ m^2 &/or Y axis: >15 m inter-array spacing &/or Z axis >4 m

Source: authors.

Largely due to the notion of a financial contribution by a co-located agricultural revenue stream (to cover or at least reduce the aforementioned delta), and/or by governmental or research subsidies, such *Reduced Intensity, Increased Compatibility* (the acronym *RIIC* is proposed) projects have come almost exclusively in agrivoltaic rather than ecovoltaic formats. Nevertheless, such formats show a noteworthy (albeit more financially complicated, due to non-use values) potential for ecovoltaics, such as raised arrays over medium-stature plant species on shrubland, or medium-size wild mammal integration. Whether eco-PV, agri-PV, or ÆPV, the carbon, water, mining, and other footprints associated with RIIC & XRIIC's increased quantities of steel and cabling per hectare, would have to be compared not only to the soil carbon sequestration potential per hectare, but other ecosystem services, biodiversity, socioeconomic, and other resilience benefits which the RIIC/XRIIC project might enable, although they may be challenging to assign a monetary value. Elevated RIIC/XRIIC could also prove more resilient than LoCoPV during flood events, for example.

Alas, as in the case of eco- and agri-PV labeling noted earlier, identifying the threshold that earns a RIIC designation is challenging. Leaving 10 instead of 1 centimeter between PV modules on the X axis? Increasing the Y axis by 1 extra meter? Raising the PV array by 30 centimeters as compared to mainstream LoCoPV? Such subtle differences on projects may mean the difference between successfully cultivating (in the case of agri-PV) or hosting (in the case of eco-PV) a certain species or excluding it from the site. These are example dimensions; RIIC is proposed here for its conceptual value, though illustrative ranges are suggested.

Recently in Germany, France, and Italy, public entities have issued legislation dividing agrivoltaics projects into 2 classes, with "Class A" (or "advanced agrivoltaics") referring to elevated (increased Z axis) RIIC/XRIIC formats, and eligible for favorable treatment such as subsidies or facilitated land access. Reduced-density (increased x &/or y axes) RIIC, however, despite an increased cost and a proven compatibility with a broad range of farmed and wild species, have apparently not received as preferential status (Vollprecht et al., 2021). *Vertical bifacial* PV, for example, is a reduced-density RIIC format (increased Y axis) with a very small PV footprint and excellent compatibility with large agricultural equipment, and thus one of the most appropriate PV mounting options to integrate with large scale agronomic farming (Figure 27), and accommodating of extra-wide machinery in its XRIIC format. Alas, the increase in cabling due to extra wide rows brings project economics too far away from LoCoPV, challenging viability. More public and research support on this promising format is encouraged.

The dynamics of RIIC's additional contributions to society and ecology clearly shift from LoCoPV's pureplay energy-centric land-take. The resource footprints associated with RIIC's increased requirements of steel and copper (or potential substitution with structural wood and other electricity-conducting metals) need to be weighed against boosted local food security, employment, public acceptance of PV, and ecosystem services, as noted. These are some of the key factors that have led governments such as France, Italy, Germany, China, Japan, and the US to lend public financial support to RIIC agrivoltaics. Yet despite recent increases in activity and interest, RIIC remain a small minority of new PV activity in most countries. To reach local gigawatt and global terawatt scales of RIIC will either require significant outlay of public funding to support such projects, or legislation limiting the deployability of LoCoPV, while allowing RIIC. It is not the intention of this paper to delve into the myriad design minutia of RIIC; researchers around the globe are already producing a growing body of literature that demonstrate documented levels of compatibility with different plant and animal species, in different climate zones, for the different array configurations of RIIC (Mamun et al., 2022).

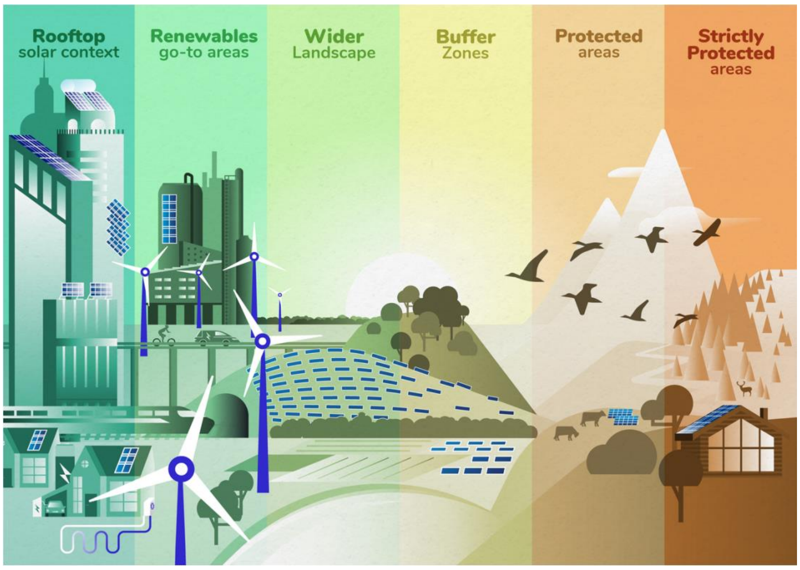
Finally, it should be noted that there are limits to PV integration into ecosystems. Making "XXXRIIC" structural modifications to integrate PV in areas of very tall trees (as noted in Section 4.2), or in regions where herds of very large animals such as elephants roam would be exorbitantly expensive and thus not recommended.

4. Siting Agri and Eco-PV

PV energy is generated instantaneously and thus must be immediately consumed or stored. As energy storage adds a layer of cost, it is preferrable that PV energy be either used onsite at the same site it is generated, or connected to the local power grid, where it may be used by another consumer connected to the same grid. This concept – particularly the need for an adequate point of interconnection to the power grid - has largely driven LoCoPV siting. LoCoPV projects have thus been sited at a wide range of distances from their energy end users, and new transmission lines are being built around the world to connect LoCoPV on remote cheap land with urban consumers.

The potential paradigm shifts of hydrogen-based liquid fuels and fertilizers synthesized by electricity and water are showing increasing signs of future viability, a sea change that would open up PV siting to more areas that may be accessible by roads, rail, or sea, as opposed to power grids (Hosseini & Wahid, 2020). In any case, PV is already, and will continue to be deployed over a very diverse range of landscapes, and indeed seascapes. Alas, while the notion of deploying massive floating offshore PV arrays may be attractive to those who prefer to minimize PV deployment on landscapes, the sea is a much less accessible, underexplored 3-dimensional realm, and measuring the effects on marine ecosystems will be much more difficult than monitoring those on land. Offshore PV development is encouraged in the interest of diversification, but with such caveats. For terrestrial deployment of PV, the conceptual illustration of the spectrum from urban to rural PV offered by the European Environmental Bureau (Figure 29) is helpful to envision most appropriate-case deployment scenarios on land (Lipcaneanu, 2022).

Figure 29. **PV deployment across landscapes**



Source: (Lipcaneanu, 2022).

4.1 *Most challenging for PV: - forests*

Biodiverse areas with dense concentrations of old-growth, tall (exceeding 4 meters) trees, food-bearing or not, are simply not a good match for solar PV. In the case of “trees over PV,” the shade cast by the trees onto the PV would significantly reduce energy generation. In the opposite scenario, “PV over trees,” the notion of XRIIC siting PV more than 4 meters above trees -as noted- faces heavy steel requirements and thus steep economic challenges. Proposals to deforest and convert biodiverse tall wooded climax ecosystems to PV are not advisable for several obvious reasons. This is not to say that all “PV-forest integration” is impossible, as the definition of forest is rather elastic.

For thousands of years, forests were widely viewed as dangerous, wild, underexploited wastes of land. From pre-historic deforestations by fire, abetted by primitive humans in order to scare their dinner out of the forest (and pre-cook some of it as well), to the much broader assault on the forests in many global regions during the Middle Ages, Industrial Revolution, and post-WWII period for fuel, structural material, and to open land for crop cultivation, humans have been a major agent of huge-scale ecosystem change for millennia, typically establishing post-deforestation APTO for food and more recently, alternative formats of bioenergy such as oil crops (M. Williams, 2003).

Only recently has the word “forest,” along with “trees” and other nature terms acquired a much more hallowed mainstream connotation, as humans have realized the ecological and carbon-storing importance of vertical nature. However, quotations such as “*Forests* are home to around 80% of terrestrial biodiversity” may falsely lead readers to believe that any type of conglomeration of trees is a biodiversity hotbed and thus sacred. Inadvertently grouping chemical-heavy fast-yielding monoculture tree farms together with ancient Sequoias and the Amazon rainforest (Aerts & Honnay, 2011) should be painstakingly avoided. Though the general notion of “deforesting” land for a PV project sounds instinctively awful, one must consider the precise forest being considered before reaching conclusions.

Rotated monoculture plantations of trees for industry, from palm to pine to eucalyptus, regularly receive the “forest” label, despite the stark disconnection with pre-existing diverse ecosystems they may have replaced, little new biodiversity, and potentially troubling water and chemical footprints. Such tree farms may essentially be biofuel or pulp operations masquerading as nature. Often in time, tree farms exhaust their utility and are removed, either gradually, or by clear cutting. On a stark landscape devoid of trees recently harvested for industry, the proposition to plant yet another generation of the same, or a similar feedstock crop, may not be the most ecologically beneficial option for a plot of land. RIIC Ecovoltaic or ÆPV formats with small to zero chemical and water footprints, and abilities to host and protect vibrant, albeit short-stature, woody, carbon-capturing vegetation and wildlife may be a more favorable alternative. There are already instances around the world in which end-of-life tree farms have been replaced with PV, though probably in non-RIIC LoCoPV formats (Phuang et al., 2022).

In any case, the proposal to site PV on former “forest” land (or even land that may never have never hosted forest, but is intended for afforestation) may face social challenges. Indeed, along with the urgent need to deploy 350k km^2 of PV surface come urgent calls for reforestation or afforestation, such as the “trillion tree initiative,” which face similar challenges as PV in finding land for such vast tracts around the world. Absorbing a large part of the 1.6 trillion tons of CO_2 that humans have emitted since pre-industrial times is a Herculean task, and the often underdefined notion of “planting trees” is regularly promoted as a prime drawdown strategy (Fountain, 2022). Determining reforestation and afforestation goals for a given region in the face of energy and food autonomy and other desires is politically and scientifically complex, and worthy of much research and debate, far beyond the scope of this report.

4.2 Low-stature rangelands and farmland:

LoCoPV seeks ideally large flat continuous inexpensive landscapes, and most of these are found on what is typically categorized as “rangeland”, which often includes desert. Large-scale desert-sited LoCoPV is already established as a mainstream deployment format and will undoubtedly continue to play a key role in the future of solar. Considering the abundance of sunlight on such sites, dual use agri- and eco-PV could be supported, though hydrology issues must be considered. Indeed, most pioneer *green hydrogen* PV projects are being sited in very sunny regions such as the Middle East, western Australia, and southern regions of the US. If such projects are sited not far from coastlines (for facilitated export of liquid fuel via tanker ship), the accessibility of seawater and its potential PV-powered desalination may aid co-located crop cultivation and/or rewilding. (Hosseini & Wahid, 2020). Economic analysis, life cycle assessment (LCA) and related resource footprint studies would be encouraged for such new endeavors.

In regions with slightly higher precipitation, such as savanna, steppe, and grassland, many surfaces with relatively lite anthropocene impact abound. Whether or not due to some grazing, the question if many of these lands deserve to be categorized as "agriculture" is the subject of debate. Biodiversity levels vary widely in these biomes. Some ambitious afforestation campaigns have been shown to be inappropriately directed to such low-precipitation areas, categorizing grasslands as "degraded forests" (George, 2022).

Alas, the common LoCoPV practice of grading a landscape before construction has seen PV projects on such lands eradicate low-lying shrubs and other woody growth, though new *low-impact* PV construction techniques are proving that such destructive works may not be required. Furthermore, funding and research on RIIC design formats that can better accommodate such bushes and the animals common on these biomes are encouraged. For eco-PV RIIC, little required post-construction intervention on sites, other than routine maintenance, and digital remote monitoring are characteristics that could foster long-term continuity and complexification of ecosystems.

Various types of low-stature agriculture may also offer an attractive co-habitat for PV on such lands. Most formats of agriculture are essentially already forms of "degraded ecosystems", to varying extents, on which a transition to more environmentally friendly techniques could be supported by the aid of some of the revenues from the PV, on the path towards true ÆPV. On degraded sites on which farming has already been abandoned, and regional climate, water, and/or demographic stress makes it difficult to secure reliable farm labor, PV developers should be required to build *agriculture-compatible* PV projects (with region-appropriate GCR) at the least. Forcing PV operators however to cultivate crops immediately upon commissioning should be eschewed in favor of implementing a rigorous multi-year soil rehabilitation regime (eco-PV). This way, soil can regain fertility, moisture, resistance against erosion, and increased biodiversity, so that farming can potentially resume in the future once the labor question is resolved via new local generations, immigrant arrivals, or autonomous robotic solutions. As noted in Section 3.4, it is not within the scope of this report to recommend specific crop-PV designs, though a final note is offered here regarding PV's competition with biofuels.

The transformation of annual crops into liquid fuel became a USD 65.4 billion global market by 2019 (George, 2022). Despite evidence that PV shows efficiency rates per hectare vastly exceeding that of biofuels such as ethanol, the biofuels industry remains politically and culturally entrenched in many countries (E. Williams et al., 2015). It is hoped that such compelling evidence of PV's superior efficiency is further diffused and comprehended, so that high-LER ÆPV generating electricity and foods with a more diverse nutrition profile, while fostering biodiversity, may be established on former ethanol plantations.

Much like the mystique that accompanies the term "forest," it is perhaps the psychological camouflage that biofuel crops such as corn, sugar, and oil palm benefit from that is responsible for levels of societal acceptance – as they are green biological plants, they visually integrate much easier into rural landscapes than the striking glass and steel structures of PV. Indeed, many of agriculture's contemporary myriad, often monoculture, formats had already altered the earth so many generations before today that their distant histories of stark ecosystem modification are forgotten. Monocultures are often accepted as typical rural cultural landscapes, and even lauded in certain cases as UNESCO World Heritage sites, despite detrimental environmental characteristics (Rössler, 2006). The canonization of the North American monoculture grass lawn as a manifestation of beauty by certain demographics is yet another example.

The increased spacing and multiple utility of RIIC formats may not only provide a less strident visual on landscapes - as opposed to typical tight clusters of LoCoPV - but the diffused knowledge that the land is being optimized, soil health improved, biodiversity boosted, and jobs retained, may aid social acceptance. Nevertheless, the variety and high crop integration potential of agrivoltaics today is still poorly understood; the notion of siting PV on farmland as a zero-sum transaction in which "farming stops and energy generation begins" often persists. Indeed, nothing in history has ever truly resembled this new paradigm of integrated renewable energy-generating infrastructure on farmland, which allows (and may enhance) simultaneous farming.

Maintaining historical farming practices for the sake of retaining cultural heritage, knowing that such practices were developed outside of a climate change context - and now face steep market, demographic, and climatic challenges – is proving to be a significant challenge (Aladro-Prieto et al., 2022). The notion of integrating visible technology (such as agrivoltaics) with a clear potential to inject viability into such operations may be depicted as an undesirable clash of aesthetics, and thus rejected, as expressed in Hidalgo and Horeczki – "Every new piece of infrastructure built to meet the challenges of the times takes away a piece of the cultural landscape" (Espino Hidalgo & Horeczki, 2022). Yet the same article admits that investments need to be made to reduce rural vulnerability, which stems from the "lack or poor quality of mobility infrastructure, poor access to digital connectivity", both of which issues could benefit from the availability of low-cost locally-generated energy.

5. Conclusions

As PV is expected to generate an increasingly substantial portion of anthropocene energy over the coming years, already considerable debates over the economic and ecological aspects of siting utility-scale PV generation along the spectrum from cheap remote lands endowed with high solar resources (often thousands of km from end users) all the way to ultra-local deployment will intensify. Many highly industrialized temperate regions already host globally-leading concentrations of PV, and will ostensibly remain bound to decarbonization and energy autonomy targets on multiple geopolitical levels, from regional economic bloc (such as the European Union) to national, regional, and even city levels. 2030 is a common target year for such goals; beyond 2030, the envisioned renewable energy buildout in following decades shows a strong potential to dwarf the already substantial yearly deployments expected to be achieved during the 2020's.

As FF still dominate global energy flows, the list of net energy-exporting countries remains small, limited to those nations endowed with abundant hydrocarbons beneath their soil or in the seas within their borders. Norway is the only European country on this list. While renewables will conceivably enable many dozens of countries to eventually reach the prior unimaginable goal of national energy autonomy (and indeed, energy export), this will remain out of reach for many of the most industrialized population-dense nations of Europe, without significant landscape and lifestyle modifications. A few nations in East Asia will face similar conundrums, as will many island states. In large countries like the US and China, in which high-irradiance deserts within their borders contrast with industrialized megalopolises in comparatively cloudier areas, domestic mismatch between generation and use of renewable energy may cause friction among regions.

The concept of net food export is more complicated, as humans (regardless of where they live) have universal needs and widely varying wants for of an increasing variety of foodstuffs. Debates over the levels for which sovereign entities should be held responsible for the production of food (and which types), energy, and hosting carbon-sequestering biodiverse landscapes is out of the scope of this article, but should provide abundant material for hundreds of new articles.

Following the social contract under which farmers have operated for 12,000 years – harvesting photons over large swaths of the countryside, and selling them to urbanites in the form of food, fiber, fuel and other products - we are already witnessing such land stewards integrate PV among their APTO offerings, as a rural product to be consumed by city dwellers. Alas, in the absence of consciousness of the benefits and relative ease of deployment of agrivoltaics, there have already been many more cases in which farmers have just replaced their historically biological APTO with PV, rather than integrating agri-PV, and thus diversifying their APTO portfolio. It is hoped that accelerated diffusion of the best practices of agrivoltaics and ÆPV will counter this predicament.

Yet beyond economic and ecological aspects, it seems that aesthetics and culture – perceptions of landscape beauty and identity – may be among the biggest barriers facing the major ramp-up in PV deployment forecast for the coming years and decades. Whether on a national, regional, local, or even individual business level, a key tradeoff of hosting energy and/or food production has historically been that of accepting various types of sensory dissonance in exchange for capital. Though solar panels may not be regarded as "beautiful", farmers may choose to tolerate their appearance in exchange for rent received from the asset, and/or resilience: the physical protection that agrivoltaic or ÆPV arrays may provide their farming operations from inclement weather, and the establishment of a reliable onsite source of energy. However, like residential PV and American lawns, the public may react with legal action if they find the visual appearance of a neighboring private property as displeasing.

Those fortunate communities that live and work out of the sights of mines, petroleum wells, and refining and power generation infrastructure have already enjoyed over a century of essentially *invisible energy*. Alas, the future of extensive renewable energy generation will not be "invisible." Now that FF are becoming increasingly scarce, it is clear that FF is the culprit for many environmental problems, and the promise of cheap nuclear fusion is not yet realized, society has little choice but to quickly transition to renewable energy.

Noteworthy is the ubiquitous presence of technology in our societies; all of these machines need "food" just as we humans do. However, instead of a diverse diet of delicate bio-based species, machines can consume a monotonous diet of electrons, which must be generated somewhere. Furthermore, on top of our existing power consumption, calls for re-industrialization of regions in rich countries, whether for factories for consumer goods such as cars, computers, heat pumps, batteries, and indeed renewable energy equipment, will further require the establishment of corresponding energy generation capacity. Besides FF, bioenergy has already supplied "food for machines" for centuries. If the harvest of corn, sugar beets, sugarcane, rapeseed and other crops for use as biofuels can be considered "agriculture," there is a strong argument for the application of this designation to PV.

The hope of cheap nuclear fusion has loomed on the techno horizon for many years, and continues to do so; alas, this technology is still far from guaranteed to make a considerable contribution to solving the world's problems. Rather than expecting a miracle within a few decades that will be able to power humanity to the space age, and clean up our air and oceans at low cost, we should err on the side of caution and continue to implement more already-proven renewable energy infrastructure such as PV. One may retain some hope for the silver bullet of cheap safe nuclear fusion, but in the interim, we must act to hedge its potential delay. In a scenario in which the economics and technology behind nuclear fusion take another half-century to become competitive with PV, so 2 or 3 generations of humans may have to bear some "ugly" landscapes before the solar can be taken down and recycled, if fusion indeed comes through, and if societies have still not accepted RIIC at that point. As tree leaves can be considered ephemeral on the scale of months and years, so can PV arrays, on the scale of many decades.

As noted above in section 2.1, the idea of "camouflaged PV" is most often associated with BIPV, but deep landscape integration of PV should not be dismissed as impossible. Conceptual sketches and models of *solar trees* exist (Figures 30 & 31), and despite steep financial and technical challenges, research continues, though significant implementation is not expected this decade (Almadhhachi et al., 2022).

Figures 30, 31. **conceptual PV "trees"**; 32, 33. **camouflaged cell phone tower "trees"**

Sources: 30: downtoearth/org/in; 31: sciencedirect.com; 32 & 33: author.

Legislation to curb the perceived ugliness of cell phone transmission towers has given birth to the *techno species* of artificial trees designed to camouflage such technology (Figures 32 & 33.) Aesthetic opinions are divided between those that appreciate such attempts by these first-generation pseudo trees to blend into landscapes, while others may be appalled at their tackiness. All things considered, long-term deep landscape and ecosystem integration of camouflaged XRIIC ÆPV may be one of the least-bad options for humanity's energy transition over this century.

Apart from public acceptance of various forms of PV on various landscapes, ramping up education and workforce development to train millions of people in the optimized design, engineering, manufacturing, logistics, planning, construction, and operation of agrivoltaic and ecovoltaic systems is probably the steepest challenge that is being faced. Substantial mobilizations of public funds to support such training, as well as the projects themselves – clever design, construction, and monitoring of the first waves of more-appropriate technology such as RIIC - will be crucial to reach decarbonization, biodiversity, energy, food system, and societal resilience objectives. Considering the profound ecological crisis society is currently facing, it is clear that the invisible hand of the free market has proven inept, and cannot be solely relied upon for a just and successful energy transition.

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The first author conceptualized this article in the framework of his doctoral thesis, and wrote the article. The second author, his thesis director, advised on content and carried out textual revisions.

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Bibliography

Aerts, R., & Honnay, O. (2011). Forest restoration, biodiversity and ecosystem functioning. *BMC Ecology*, *11*(1), 29. https://doi.org/10.1186/1472-6785-11-29

Aladro-Prieto, J.-M., García-Casasola, M., Castellano-Bravo, B., Ostos-Prieto, F. J., & Ponce Ortiz De Insagurbe, M. (2022). Lo agrícola, lo defensivo y lo antropológico: Claves culturales para una gestión sostenible del patrimonio en el contexto rural. *ACE: Architecture, City and Environment*, *17*(50). https://doi.org/10.5821/ace.17.50.11381

Almadhhachi, M., Seres, I., & Farkas, I. (2022). Significance of solar trees: Configuration, operation, types and technology commercialization. *Energy Reports*, *8*, 6729–6743. https://doi.org/10.1016/j.egyr.2022.05.015

An era of renewable energy growth and development | McKinsey. (2022). Retrieved March 26, 2023, from https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/renewable-energy-development-in-a-net-zero-world

Approximately 100 million households rely on rooftop solar PV by 2030 – Analysis. (2022). IEA. Retrieved March 31, 2023, from https://www.iea.org/reports/approximately-100-million-households-rely-on-rooftop-solar-pv-by-2030

Ardani, K., Denholm, P., Mai, T., Margolis, R., O'Shaughnessy, E., Silverman, T., & Zuboy, J. (2021). U.S. Department of Energy - Office of Energy Efficiency & Renewable Energy. *Solar Futures Study*.

Aronescu, A., & Appelbaum, J. (2017). Design optimization of photovoltaic solar fields-insight and methodology. *Renewable and Sustainable Energy Reviews*, *76*, 882–893. https://doi.org/10.1016/j.rser.2017.03.079

Artificialisation des sols -: Les critères d'exemption des installations photovoltaïques en consultation. (2022, June 5). Banque des Territoires. Retrieved March 26, 2023, from https://www.banquedesterritoires.fr/artificialisation-des-sols-les-criteres-dexemption-des-installations-photovoltaiques-en

Azqueta, D., & Sotelsek, D. (2007). Valuing nature: From environmental impacts to natural capital. *Ecological Economics*, *63*(1), 22–30. https://doi.org/10.1016/j.ecolecon.2007.02.029

Berney Needleman, D., R. Poindexter, J., C. Kurchin, R., Peters, I. M., Wilson, G., & Buonassisi, T. (2016). Economically sustainable scaling of photovoltaics to meet climate targets. *Energy & Environmental Science*, *9*(6), 2122–2129. https://doi.org/10.1039/C6EE00484A

Caffrey, K. (2010). The House of the Rising Sun: Homeowners' Associations, Restrictive Covenants, Solar Panels, and the Contract Clause. *Natural Resources Journal*, *50*(3), 721–759.

Deng, R., Zhuo, Y., & Shen, Y. (2022). Recent progress in silicon photovoltaic module recycling processes. *Resources, Conservation and Recycling*, *187*, 106612. https://doi.org/10.1016/j.resconrec.2022.106612

Dupraz, C., Marrou, H., Talbot, G., Dufour, L., Nogier, A., & Ferard, Y. (2011). Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes. *Renewable Energy*, *36*(10), 2725–2732. https://doi.org/10.1016/j.renene.2011.03.005

EIA projects nearly 50% increase in world energy usage by 2050, led by growth in Asia. (n.d.). Retrieved March 25, 2023, from https://www.eia.gov/todayinenergy/detail.php?id=42342

Energy Efficiency 2020 – Analysis. (2020). IEA. Retrieved March 25, 2023, from https://www.iea.org/reports/energy-efficiency-2020

Espino Hidalgo, B. D., & Horeczki, R. (2022). Innovative and Sustainable Cultural Heritage for Local Development in the Face of Territorial Imbalance. *ACE: Architecture, City and Environment*, *17*(50). https://doi.org/10.5821/ace.17.50.11374

Fountain, H. (2022, June 3). Carbon Dioxide Levels Are Highest in Human History. *The New York Times*. Retrieved March 25, 2023, from https://www.nytimes.com/2022/06/03/climate/carbon-dioxide-record.html

France, Ryan. (2022). *Triple-Junction III-V Solar Cells with 39.5% AM1.5G and 34.2% AM0 Efficiencies.* https://www.osti.gov/biblio/1877360

George, Z. S. (2022, July 13). Can Planting a Trillion New Trees Save the World? *The New York Times*. Retrieved March 25, 2023, from https://www.nytimes.com/2022/07/13/magazine/planting-trees-climate-change.html

Gholami, H., Nils Røstvik, H., & Steemers, K. (2021). The Contribution of Building-Integrated Photovoltaics (BIPV) to the Concept of Nearly Zero-Energy Cities in Europe: Potential and Challenges Ahead. *Energies*, *14*(19), Article 19. https://doi.org/10.3390/en14196015

Goel, M. (2016). Solar rooftop in India: Policies, challenges and outlook. *Green Energy & Environment*, *1*(2), 129–137. https://doi.org/10.1016/j.gee.2016.08.003

Haegel, N. M., Atwater, H., Barnes, T., Breyer, C., Burrell, A., Chiang, Y.-M., De Wolf, S., Dimmler, B., Feldman, D., Glunz, S., Goldschmidt, J. C., Hochschild, D., Inzunza, R., Kaizuka, I., Kroposki, B., Kurtz, S., Leu, S., Margolis, R., Matsubara, K., … Bett, A. W. (2019). Terawatt-scale photovoltaics: Transform global energy. *Science*, *364*(6443), 836–838. https://doi.org/10.1126/science.aaw1845

Harris, D. R., & Fuller, D. Q. (2014). Agriculture: Definition and Overview. In C. Smith (Ed.), *Encyclopedia of Global Archaeology* (pp. 104–113). Springer New York. https://doi.org/10.1007/978-1-4419-0465-2_64

Hosseini, S. E., & Wahid, M. A. (2020). Hydrogen from solar energy, a clean energy carrier from a sustainable source of energy. *International Journal of Energy Research*, *44*(6), 4110–4131. https://doi.org/10.1002/er.4930

Integrated Photovoltaics—Fraunhofer ISE. (n.d.). Fraunhofer Institute for Solar Energy Systems ISE. Retrieved April 2, 2023, from https://www.ise.fraunhofer.de/en/business-areas/photovoltaics/photovoltaic-modules-and-power-plants/integrated-photovoltaics.html

Lipcaneanu, N. (2022). Nature-positive renewables. European Environmental Bureau. Retrieved March 25, 2023, from https://eeb.org/wp-content/uploads/2022/09/Summary_Nature-positive-renewable-energy_final.pdf

Ludin, N. A., Mustafa, N. I., Hanafiah, M. M., Ibrahim, M. A., Asri Mat Teridi, M., Sepeai, S., Zaharim, A., & Sopian, K. (2018). Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: A review. *Renewable and Sustainable Energy Reviews*, *96*, 11–28. https://doi.org/10.1016/j.rser.2018.07.048

Macknick, J., Hartmann, H., Barron-Gafford, G., Beatty, B., Burton, R., Seok-Choi, C., Davis, M., Davis, R., Figueroa, J., Garrett, A., Hain, L., Herbert, S., Janski, J., Kinzer, A., Knapp, A., Lehan, M., Losey, J., Marley, J., MacDonald, J., … Walston, L. (2022). *The 5 Cs of Agrivoltaic Success Factors in the United States: Lessons from the InSPIRE Research Study* (NREL/TP-6A20-83566, 1882930, MainId:84339; p. NREL/TP-6A20-83566, 1882930, MainId:84339). https://doi.org/10.2172/1882930

Mah, D. N., Wang, G., Lo, K., Leung, M. K. H., Hills, P., & Lo, A. Y. (2018). Barriers and policy enablers for solar photovoltaics (PV) in cities: Perspectives of potential adopters in Hong Kong. *Renewable and Sustainable Energy Reviews*, *92*, 921–936. https://doi.org/10.1016/j.rser.2018.04.041

Maitra, S., Hossain, A., Brestic, M., Skalicky, M., Ondrišík, P., Gitari, H., Brahmachari, K., Shankar, T., Bhadra, P., Palai, J., Jena, J., Bhattacharya, U., Duvvada, S., Lalichetti, S., & Sairam, M. (2021). Intercropping system-A low input agricultural strategy for food and environmental security. *Agronomy*, *11*, 343. https://doi.org/10.3390/agronomy11020343

Mamun, M. A. A., Dargusch, P., Wadley, D., Zulkarnain, N. A., & Aziz, A. A. (2022). A review of research on agrivoltaic systems. *Renewable and Sustainable Energy Reviews*, *161*, 112351. https://doi.org/10.1016/j.rser.2022.112351

Martín-Arroyo, J. (2022, January 7). *Atrapados en la lluvia de megaparques renovables*. El País. Retrieved March 25, 2023, from https://elpais.com/economia/2022-01-07/atrapados-en-la-lluvia-de-megaparques-renovables.html

McCall, J., Macdonald, J., Burton, R., & Macknick, J. (2023). Vegetation Management Cost and Maintenance Implications of Different Ground Covers at Utility-Scale Solar Sites. *Sustainability*, *15*(7), Article 7. https://doi.org/10.3390/su15075895

Meadows, D. H. (1972). *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind*. Universe Books.

Montoya, J. M., Donohue, I., & Pimm, S. L. (2018). Planetary Boundaries for Biodiversity: Implausible Science, Pernicious Policies. *Trends in Ecology & Evolution*, *33*(2), 71–73. https://doi.org/10.1016/j.tree.2017.10.004

Novel design for east-west solar parks reduces soil deterioration. (2021, August 9). Pv Magazine International. Retrieved March 25, 2023, from https://www.pv-magazine.com/2021/08/09/novel-design-for-east-west-solar-parks-reduces-soil-deterioration/

Pascaris, A. S., Schelly, C., & Pearce, J. M. (2020). A First Investigation of Agriculture Sector Perspectives on the Opportunities and Barriers for Agrivoltaics. *Agronomy*, *10*(12), Article 12. https://doi.org/10.3390/agronomy10121885

Phuang, Z. X., Lin, Z., Liew, P. Y., Hanafiah, M. M., & Woon, K. S. (2022). The dilemma in energy transition in Malaysia: A comparative life cycle assessment of large scale solar and biodiesel production from palm oil. *Journal of Cleaner Production*, *350*, 131475. https://doi.org/10.1016/j.jclepro.2022.131475

Rhodes, C. J. (2019). Only 12 years left to readjust for the 1.5-degree climate change option – Says International Panel on Climate Change report: Current commentary. *Science Progress*, *102*(1), 73–87. https://doi.org/10.1177/0036850418823397

Rössler, M. (2006). World Heritage cultural landscapes: A UNESCO flagship programme 1992 – 2006. *Landscape Research*, *31*(4), 333–353. https://doi.org/10.1080/01426390601004210

Sandesh, K., & Ujwal, P. (2021). Trends and perspectives of liquid biofuel – Process and industrial viability. *Energy Conversion and Management: X*, *10*, 100075. https://doi.org/10.1016/j.ecmx.2020.100075

Sisser, J. M., Nelson, K. C., Larson, K. L., Ogden, L. A., Polsky, C., & Chowdhury, R. R. (2016). Lawn enforcement: How municipal policies and neighborhood norms influence homeowner residential landscape management. *Landscape and Urban Planning*, *150*, 16–25. https://doi.org/10.1016/j.landurbplan.2016.02.011

Stubbs, M. (2014). Congressional Research Service. *Conservation Reserve Program (CRP): Status and Issues*. Retrieved April 2, 2023, from https://crsreports.congress.gov/product/pdf/R/R42783

Sturchio, M. A., Macknick, J. E., Barron-Gafford, G. A., Chen, A., Alderfer, C., Condon, K., Hajek, O. L., Miller, B., Pauletto, B., Siggers, J. A., Slette, I. J., & Knapp, A. K. (2022). Grassland productivity responds unexpectedly to dynamic light and soil water environments induced by photovoltaic arrays. *Ecosphere*, *13*(12), e4334. https://doi.org/10.1002/ecs2.4334

Toledo, C., & Scognamiglio, A. (2021). Agrivoltaic Systems Design and Assessment: A Critical Review, and a Descriptive Model towards a Sustainable Landscape Vision (Three-Dimensional Agrivoltaic Patterns). *Sustainability*, *13*(12), Article 12. https://doi.org/10.3390/su13126871

Trommsdorff, M., Kang, J., Reise, C., Schindele, S., Bopp, G., Ehmann, A., Weselek, A., Högy, P., & Obergfell, T. (2021). Combining food and energy production: Design of an agrivoltaic system applied in arable and vegetable farming in Germany. *Renewable and Sustainable Energy Reviews*, *140*, 110694. https://doi.org/10.1016/j.rser.2020.110694

Vollprecht, J., Trommsdorff, M., & Hermann, C. (2021). Legal framework of agrivoltaics in Germany. *AIP Conference Proceedings*, *2361*(1), 020002. https://doi.org/10.1063/5.0055133

Wikoff, H. M., Reese, S. B., & Reese, M. O. (2022). Embodied energy and carbon from the manufacture of cadmium telluride and silicon photovoltaics. *Joule*, *6*(7), 1710–1725. https://doi.org/10.1016/j.joule.2022.06.006

Willey, R. W., & Osiru, D. S. O. (1972). Studies on mixtures of maize and beans (Phaseolus vulgaris) with particular reference to plant population. *The Journal of Agricultural Science*, *79*(3), 517–529. https://doi.org/10.1017/S0021859600025909

Williams, E., Sekar, A., Matteson, S., & Rittmann, B. E. (2015). Sun-to-Wheels Exergy Efficiencies for Bio-Ethanol and Photovoltaics. *Environmental Science & Technology*, *49*(11), 6394–6401. https://doi.org/10.1021/es504377b

Williams, M. (2003). *Deforesting the Earth: From Prehistory to Global Crisis*. University of Chicago Press.

Yan, X., & Wang, S. J. (2019). Infrastructure-Integrated Photovoltaic (IIPV): A boost to solar energy's green credentials? *Energy Procedia*, *158*, 3314–3318. https://doi.org/10.1016/j.egypro.2019.01.973

Zalamea-León, E. F., Mena-Campos, J. D., Moscoso-Cordero, M. S., Barragán-Escandón, E. A., & Méndez-Santos, P. (2018). Perspectivas de cubiertas fotovoltaicas y arquitectura en contextos urbanos patrimoniales. *ACE: Architecture, City and Environment*, *13*(38), 185–210. https://doi.org/10.5821/ace.13.38.5369