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Net-Zero Energy Farm Buildings: A New Era of Sustainable Agriculture

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Modern agriculture is becoming increasingly dependent on energy intensive buildings, from climate controlled greenhouses to mechanized livestock houses, and this dependence is raising concerns about cost, emissions, and long term resilience. Net-zero energy (NZE) farm buildings aim to balance the energy consumed on site with energy generated from renewable sources, primarily solar photovoltaics, so that operations approach an annual energy balance of zero. Across controlled environment agriculture, greenhouse production, and poultry housing, researchers have explored passive design, energy efficient technologies, and renewable integration as pathways toward this goal. At the same time, large scale assessments show that energy intensities vary enormously across facility types and crops, and that achieving full renewable self sufficiency can require land areas far larger than the building footprint itself. This article brings together insights on the technologies, opportunities, and limitations associated with net-zero energy farm buildings, highlighting both the promise of solar integrated greenhouses and energy optimized livestock housing, and the practical challenges of cost, climate dependence, and land use that will shape how widely such designs can be adopted in the future of farming.

Introduction

Agriculture has moved indoors in many parts of the world, with mechanized greenhouses and enclosed plant factories now used to grow crops under tightly controlled conditions, a practice broadly described as controlled environment agriculture (Mills, 2025). While this approach is often promoted as a route to greater sustainability, it also consumes substantially more energy than open field cultivation, and on a national scale it has the potential to expand to a meaningful share of total energy demand (Mills, 2025).

A similar pattern is visible in livestock housing, where poultry production for meat and eggs is among the fastest growing segments of the livestock sector and is associated with significant greenhouse gas emissions and other environmental impacts (Li et al., 2022). Infrastructure and the energy used to operate poultry housing can together represent as much as half of the non-renewable energy consumed in poultry production, and a substantial share of its life cycle environmental impacts (Li et al., 2022).

Against this backdrop, the concept of the net-zero energy building (NZEB) has emerged as a strategy for reducing the energy footprint of buildings of all kinds, including those used in agriculture (Wang et al., 2024). A net-zero energy building is one that, over the course of a year, generates as much renewable energy on site as it consumes from non-renewable sources, typically through a combination of energy efficient design and on site renewable energy systems such as solar photovoltaics (Wang et al., 2024). For greenhouses specifically, integrating solar technology directly into the structure has been proposed as a way to offset the high energy demand associated with conditioning the growing space (Ravishankar et al., 2020).

This article examines how the net-zero energy concept is being applied to farm buildings, drawing on recent research covering controlled environment agriculture, greenhouse integrated photovoltaics, poultry housing design, and the broader technology base of zero energy buildings. It considers both the opportunities these approaches offer for reducing the environmental footprint of food production and the practical constraints, particularly around land use, cost, and climate dependence, that will determine how far net-zero energy farm buildings can realistically be scaled.

The Energy Challenge in Controlled Environment Agriculture

Controlled environment agriculture, which includes both greenhouses and fully enclosed plant factories, is often promoted as a way to reduce land and water use, protect crops from environmental hazards, and extend growing seasons (Mills, 2025). However, a large scale meta-analysis covering 116 studies across 40 countries found that while this form of agriculture provides less than one percent of crops grown in the United States, it already consumes more energy than all open field cultivation combined, and could expand roughly tenfold to account for around seven percent of national energy use (Mills, 2025).

Energy intensity varies enormously depending on facility type, crop, and geography, spanning five orders of magnitude in the compiled data (Mills, 2025). Greenhouses were found to be the least energy intensive facility type, with a median of around twenty seven megajoules per kilogram of yield, while plant factories required far more energy, particularly for crops such as cannabis, which emerged as the most energy intensive crop by a wide margin (Mills, 2025). By contrast, open field crops required only around one megajoule per kilogram on average, underlining the scale of the energy penalty associated with moving cultivation indoors (Mills, 2025).

Improvements in energy efficiency, such as the use of LED lighting, heat pumps, or improved insulation, were found in around half of the studies reviewed, yet facilities with these measures showed only marginally lower energy intensities than those without, suggesting that many other factors, including climate, crop choice, and operational practices, strongly influence overall energy outcomes (Mills, 2025).

Solar Integration in Greenhouse Structures

One proposed solution to the high energy demand of greenhouses is to integrate solar power generation directly into the greenhouse covering itself, using semitransparent organic solar cells that allow light to reach crops while also generating electricity (Ravishankar et al., 2020). Because the absorption spectrum of organic solar cells can be tuned through material selection, they can be designed to capture wavelengths of light that are less important for plant growth while allowing photosynthetically useful light to pass through to the crop canopy (Ravishankar et al., 2020). Using a detailed energy balance model applied across the United States, researchers found that greenhouses integrated with semitransparent organic solar cells could achieve an annual surplus of energy in warm and moderate climates, effectively reaching net-zero energy status while still allowing sunlight to reach the crops (Ravishankar et al., 2020). The study also found that with appropriate design, the reduction in sunlight reaching the growing area could be minimized, supporting the conclusion that organic solar cells represent a promising option for diversifying renewable energy generation within agricultural structures (Ravishankar et al., 2020).

These findings are consistent with the broader meta-analysis of controlled environment agriculture, which similarly identified greenhouses, rather than plant factories, as the facility type best positioned to achieve favorable energy outcomes due to their comparatively lower baseline energy intensity (Mills, 2025).

The Land Use Trade-Off of Renewable Self-Sufficiency

While solar integration can move individual greenhouses toward net-zero energy status, achieving full on site renewable self sufficiency across controlled environment agriculture more broadly introduces a significant land use trade-off (Mills, 2025). Analysis of solar photovoltaic area requirements found that, across the facilities studied, the ground mounted array needed to meet all on-farm energy needs always exceeded the building footprint itself, averaging around four times the footprint for food producing greenhouses, around forty eight times for food producing plant factories, and as much as one hundred and twenty two times for cannabis producing plant factories (Mills, 2025).

Even in the most favorable cases, highly energy efficient greenhouses located in an ideal solar climate required a solar array area roughly equal to the building footprint, but such outcomes were described as rare (Mills, 2025). This means that one of the often cited benefits of controlled environment agriculture, namely sparing land compared to open field cultivation, can be substantially reduced or even reversed once the land required for renewable energy generation is taken into account (Mills, 2025). By contrast, open field cultivation that is fully electrified would require only a minor fractional expansion of land area to achieve net-zero emissions using solar photovoltaics, since its baseline energy intensity is already so much lower (Mills, 2025). This contrast highlights why the design of the building envelope and the choice of facility type are central to the feasibility of net-zero energy farm buildings, since they directly determine how much renewable generation capacity, and therefore how much land, will ultimately be required (Wang et al., 2024).

Energy Efficient Building Envelopes and Systems

Reducing the underlying energy demand of a building before adding renewable generation capacity is widely regarded as the first and most important step toward achieving net-zero energy status (Wang et al., 2024). Energy efficient measures for buildings include improving the thermal performance of the building envelope, integrating phase change materials that can absorb and release heat to reduce temperature fluctuations, and upgrading heating, ventilation, and air conditioning systems, which together can account for forty to sixty percent of total building energy consumption (Wang et al., 2024).

Research on phase change materials has shown that their integration into building envelopes can reduce heating energy consumption by around seventeen and a half percent in dry climates and just over ten percent in semi-arid climates, while also improving indoor thermal comfort satisfaction (Wang et al., 2024). However, the effectiveness of these materials depends on climatic conditions as well as their thickness and placement within the envelope, with different installation positions recommended for hot versus cold climates (Wang et al., 2024).

Once energy demand has been minimized through such measures, the deployment of on site renewable energy technologies, most commonly solar photovoltaic systems, becomes the next priority and is often the most cost effective way to close the remaining gap toward net-zero energy status (Wang et al., 2024). Solar photovoltaic systems can be installed as building attached systems on rooftops or walls, or as building integrated systems that form part of the structure itself, with the latter approach offering the added benefit of saving on conventional building materials while generating electricity (Wang et al., 2024). Beyond solar energy, other renewable sources such as geothermal, wind, and biomass energy can also contribute to net-zero outcomes, each with different characteristics; geothermal energy is comparatively stable and less affected by weather, wind energy is more variable but environmentally favorable in suitable locations, and biomass energy can provide a steady supply as long as raw material is available (Wang et al., 2024).

Designing Net-Zero Energy Poultry Housing

Livestock housing presents a distinct set of challenges for net-zero energy design compared to crop production, since the welfare and physiological needs of the animals must be balanced against energy saving measures (Li et al., 2022). A review of insights from residential and commercial net-zero energy buildings found that strategies generally fall into three categories: reducing direct energy use through building design, improving the energy efficiency of active technology systems, and installing renewable energy generation systems appropriate to the local context (Li et al., 2022). However, not all passive design strategies that work well in residential or commercial buildings translate directly to poultry housing. For example, maximizing glazed areas to capture natural light, a common passive design strategy, may be less applicable in poultry housing where photoperiod, meaning the timing and duration of light exposure, must be carefully controlled for the birds (Li et al., 2022). Within conventional poultry housing, heating during heating seasons and ventilation during cooling seasons were identified as the two largest contributors to direct energy use, although their relative importance varies considerably depending on geography and climate (Li et al., 2022). Because of the high ventilation rates required to maintain air quality in confined poultry housing, heating, ventilation, and air conditioning systems were highlighted as a priority area for energy efficiency improvements (Li et al., 2022).

At the same time, the review emphasized that any modifications to poultry housing technology must be grounded in the physiological requirements of the birds, including ambient temperature, air quality, and access to feed and water, as well as in local climatic conditions and the technical and economic feasibility of available alternatives (Li et al., 2022). This reflects a broader theme in net-zero energy design for agriculture: energy performance cannot be optimized in isolation from the biological needs of the crops or animals housed within the building (Li et al., 2022). Among the renewable energy options considered for net-zero energy buildings more broadly, solar photovoltaic and solar thermal systems are the most commonly applied, particularly for meeting domestic hot water needs, while geothermal systems are often connected to radiant heating systems such as heated floors (Li et al., 2022). These same categories of technology, suitably adapted to the operational requirements of poultry housing, form the basis for the renewable energy component of net-zero energy designs in this sector (Li et al., 2022).

Towards Zero-Energy Communities in Agriculture

Beyond individual buildings, researchers have begun to extend the net-zero energy concept to the scale of entire communities, an idea that has direct relevance for agricultural settings where multiple farm buildings, such as greenhouses, livestock housing, and storage facilities, often operate together on the same site (Wang et al., 2024). The European Union has introduced the concept of Positive Energy Districts as a model for renewable energy communities, consisting of energy efficient buildings that not only achieve zero emissions through renewable energy use but also intelligently manage energy storage systems across the group of buildings (Wang et al., 2024).

Extending zero energy status from a single building to a community introduces additional complexity, since the energy flows between multiple energy producing and consuming buildings must be coordinated, and a wider variety of energy consuming equipment must be balanced against available renewable generation and storage capacity (Wang et al., 2024). For agricultural operations that already involve multiple energy intensive buildings on a single site, this community scale approach to energy management may offer a more practical pathway to overall net-zero status than attempting to achieve it building by building (Wang et al., 2024). This community level perspective also connects to the land use findings from controlled environment agriculture, since pooling renewable generation and storage across several buildings on a farm could, in principle, make more efficient use of the available land than installing separate, smaller scale systems at each individual structure (Mills, 2025).

Conclusion

Net-zero energy farm buildings represent a meaningful step toward more sustainable agriculture, offering a framework in which the substantial energy demands of greenhouses, plant factories, and livestock housing can be balanced through a combination of energy efficient design and renewable energy generation. Technologies such as semitransparent solar cells integrated into greenhouse coverings, improved building envelopes, phase change materials, and efficient heating and ventilation systems all contribute to reducing the baseline energy demand that renewable systems must offset. At the same time, the evidence shows that this transition is far from straightforward. Energy intensities vary enormously across facility types and crops, the land required to achieve full renewable self sufficiency can far exceed a building's footprint, and the unique physiological needs of crops and livestock place real limits on which design strategies can be applied. Looking ahead, extending the net-zero energy concept from individual buildings to entire farm sites or agricultural communities, supported by careful facility design and realistic land use planning, offers a promising direction for ensuring that the move toward energy self sufficient agriculture genuinely supports, rather than undermines, broader sustainability goals.

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