



Energy Crisis and Climate Change in Agriculture: Impacts, Renewable-Energy Pathways and Climate-Smart Solutions

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Abstract

Agriculture depends on reliable energy for land preparation, irrigation, fertilizer production, harvesting, processing, storage and transport. Rising fuel and electricity costs, supply disruptions and climate-related stresses therefore affect farm profitability and food security simultaneously. This review examines the energy-climate-agriculture nexus and identifies practical pathways for reducing vulnerability. Direct farm energy use remains strongly linked to diesel and electricity, while substantial indirect energy is embedded in fertilizers and other inputs. Climate change compounds these pressures through heat stress, erratic rainfall, drought, flooding, altered pest and disease dynamics and declining soil resilience. A transition based on energy efficiency, solar-powered irrigation, renewable electricity, improved machinery, precision input management and climate-smart agronomy can reduce fossil-fuel dependence while

strengthening adaptation. Digital tools and artificial intelligence can further optimize irrigation, machinery operation and energy scheduling when supported by reliable data and farmer-oriented extension. Effective transition requires affordable finance, enabling infrastructure, policy continuity and locally suitable technologies. Integrating energy management with climate-smart agriculture offers a practical route toward productive, low-carbon and resilient farming systems.

Introduction

Modern agriculture is both an energy user and a climate-sensitive production system. Energy is required directly through diesel, electricity and heat, and indirectly through the manufacture of fertilizers, pesticides, machinery and other inputs. A review of open-field agriculture in the European Union showed that fertilizer production and on-farm diesel use are among the largest energy-demanding components, illustrating why fuel and input-price shocks can

rapidly raise production costs (Paris *et al.*, 2022). At the same time, climate change is altering temperature, rainfall and the frequency of extreme events, with consequences for crop growth, water availability, pests, soil processes and farm income (Malhi *et al.*, 2021).

The present energy crisis is not a single shortage but a combination of price volatility, geopolitical risk, infrastructure constraints and the challenge of shifting from fossil fuels to lower-carbon sources. Energy-market disruptions can expose agriculture because irrigation, machinery, cold chains and fertilizer supply are closely linked to energy systems. Bilan *et al.* (2023) and Hussain *et al.* (2023) emphasize that energy security, affordability and sustainability must be addressed together during the green transition. For agriculture, this means reducing unnecessary energy use while expanding reliable renewable options and improving resilience to climate shocks.

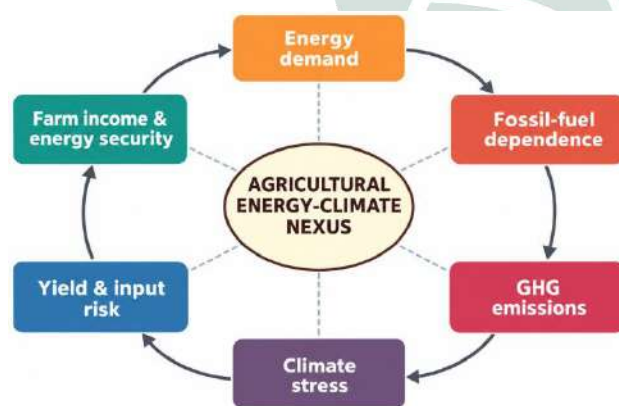


Figure 1. Interconnected feedbacks linking farm energy use, climate change and agricultural vulnerability.

Where Agriculture Uses Energy

Farm energy demand occurs at several stages. Tractor operations consume liquid fuels;

irrigation relies on electricity or diesel; drying and storage require mechanical and thermal energy; and post-harvest handling depends on transport and cold-chain infrastructure. Indirect energy can be even less visible. Paris *et al.* (2022) reported that a large share of energy associated with open-field agriculture is embodied in upstream inputs, particularly fertilizers. Consequently, energy-efficiency strategies should not focus only on tractor fuel. Nutrient-use efficiency, improved fertilizer management, reduced unnecessary passes, appropriate machinery sizing and efficient irrigation all contribute to lowering the total energy footprint.

Energy efficiency is particularly important during periods of high prices because every avoided unit of fuel or electricity reduces production cost immediately. Farghali *et al.* (2023) reviewed a broad range of energy-saving strategies and highlighted efficiency, renewable energy, intelligent control and electrification as complementary measures. On farms, the same principle can be applied through preventive machinery maintenance, correct tyre pressure, field-operation planning, efficient pumps, variable-speed drives, improved water conveyance and scheduling irrigation according to crop demand rather than fixed routines.

Climate Change Intensifies Agricultural Energy Risk

Climate change increases energy demand in several indirect ways. Higher temperatures can raise crop water requirements and increase pumping hours. Drought reduces surface-water availability, forcing deeper groundwater extraction and greater pumping energy. Heat can increase cooling requirements in livestock

facilities and storage systems. Intense rainfall and flooding may damage energy and irrigation infrastructure, while variable seasons can require additional field operations. These stresses occur alongside direct biological impacts on photosynthesis, phenology, reproductive development and yield (Malhi *et al.*, 2021).

Pest, disease and weed pressures are also climate-sensitive. Warmer conditions may expand the suitable range or seasonal activity of some pests and pathogens, while shifts in rainfall and humidity can alter disease risk. Poorly adapted responses may increase pesticide, machinery and labour requirements. Climate-smart agriculture therefore aims not merely to maintain yield, but to combine productivity, adaptation and mitigation. Zhao *et al.* (2023) describe climate-smart agriculture as an integrated approach that links improved water management, resilient cropping systems, technology, information services and risk-management practices.

Renewable Energy Options for Farms

Renewable energy can reduce exposure to volatile fossil-fuel prices when technologies are matched to local conditions. Solar photovoltaic systems are especially relevant for irrigation because daytime electricity generation often coincides with pumping demand. Solar pumping can replace or supplement diesel and grid electricity, particularly in remote areas. Tiwari *et al.* (2022) reviewed solar photovoltaic pump-operated micro-irrigation systems and identified the combination of solar pumping and micro-irrigation as a promising water- and energy-efficient option for agriculture.

Solar systems are most effective when pump capacity, well yield, irrigation requirement and

distribution efficiency are designed as one system. Oversized pumps or unrestricted pumping can waste both water and capital. Pairing solar energy with drip or sprinkler systems, storage tanks, soil-moisture information and water-use rules can therefore improve both energy and water outcomes. Other farm-scale renewable options include biomass residues for thermal energy, biogas from animal wastes, small-scale wind systems in suitable locations and renewable electricity for cold storage, processing and charging of electric equipment.

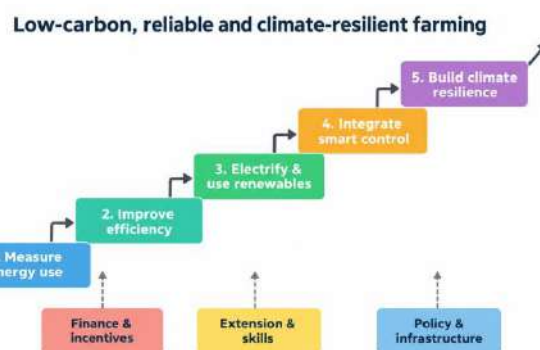


Figure 2. A phased farm-energy transition roadmap combining efficiency, renewable energy, digital control and enabling support.

Energy-Efficient and Climate-Smart Farming Practices

A farm-energy transition should begin with efficiency before adding new generation capacity. The first step is to identify major energy uses by operation and season. The second is to remove avoidable demand through efficient pumps and motors, timely field operations, reduced tillage where agronomically suitable, improved nutrient management and better irrigation scheduling. The third step is to replace part of the remaining fossil-energy demand with renewable electricity or fuels. This sequence

reduces the size and cost of renewable systems and improves payback.

Climate-smart agronomy strengthens this transition. Conservation agriculture, crop diversification, residue management, agroforestry, improved cultivars, efficient nutrient use and water-saving irrigation can increase resilience while reducing some energy-intensive operations. Zhao *et al.* (2023) note that climate-smart agriculture is context specific: practices should be selected according to local climate, soils, crops, water resources and livelihood needs. The objective is not to promote one technology everywhere, but to build combinations that improve productivity and adaptive capacity while limiting emissions where feasible.

Digital Technologies and Artificial Intelligence

Digital tools can help farms use energy at the right time and place. Sensors can monitor soil moisture, pump performance, fuel use and weather conditions. Variable-rate systems can reduce unnecessary application of water, fertilizer and pesticides. Artificial intelligence can support demand forecasting, irrigation scheduling, machinery routing, fault detection and integration of renewable energy with storage or grid supply. Farghali *et al.* (2023) identify artificial intelligence and smart-grid approaches as useful tools for improving energy efficiency and managing renewable-energy variability.

However, digitalization is not automatically energy efficient or farmer friendly. Benefits depend on reliable connectivity, appropriate sensors, interoperable equipment, local calibration and clear recommendations. Extension support is essential so that data lead to

practical decisions rather than additional complexity. Low-cost tools that solve a specific farm problem, such as detecting pump inefficiency or avoiding unnecessary irrigation may provide greater value than highly complex platforms that are difficult to maintain.

Economic, Policy and Adoption Considerations

The main barrier to farm-energy transition is often not technical feasibility but initial cost, financing and uncertainty. Renewable-energy systems can have low operating costs but require upfront investment. Smallholders may also face fragmented land, insecure access to electricity networks, limited technical service and difficulty obtaining credit. Hussain *et al.* (2023) show that affordability and energy poverty are important dimensions of the green transition, while Farghali *et al.* (2023) emphasize that technology must be supported by policy and social measures.

Policy instruments can improve adoption through capital subsidies, low-interest credit, energy-service models, reliable net-metering or feed-in arrangements where appropriate, support for efficient pumps and motors, and training for technicians and farmers. Programmes should also avoid incentives that encourage excessive groundwater extraction. Linking renewable-energy support with water budgeting, micro-irrigation, crop planning and groundwater governance can produce more durable benefits. Public investment in rural grids, storage, repair networks and extension services is equally important because farm technology is only as reliable as the system that supports it.

Post-Harvest Energy and Decentralized Rural Systems

Energy challenges continue after harvest. Drying, milling, cooling, storage, packaging and transport determine whether harvested produce reaches consumers with acceptable quality. Where electricity supply is unreliable, farmers and rural enterprises may depend on diesel generators or may avoid cold storage and mechanical processing altogether. Energy planning should therefore extend beyond field operations to village-level and value-chain infrastructure. Efficient motors, insulated cold rooms, solar-assisted drying, renewable-powered pack houses and appropriately sized decentralized electricity systems can reduce operating costs and improve reliability. Farghali *et al.* (2023) emphasize that energy efficiency and renewable supply are strongest when they are planned together rather than treated as separate interventions.

Decentralized systems can also improve resilience during grid failures or fuel shortages, but they require realistic load assessment, maintenance arrangements and financial planning. A solar system designed only from installed pump horsepower may be oversized if irrigation efficiency is poor, while a system designed without considering seasonal peaks may fail when it is most needed. The transition roadmap in Figure 2 therefore starts with measurement and efficiency, followed by renewable-energy integration and smart control. This sequencing is consistent with the broader evidence that demand reduction lowers the capacity and cost required from new energy infrastructure (Paris *et al.*, 2022; Farghali *et al.*, 2023).

Farm-Level Implementation Priorities

For practical adoption, farmers and extension agencies can begin with a simple energy audit that records fuel, electricity and irrigation use by operation. High-cost operations should then be checked for avoidable losses: inefficient pumps, leakage, excessive irrigation, repeated tillage, poor machinery matching or unnecessary fertilizer application. Measures with low investment and quick savings can be implemented first. The resulting lower energy demand provides a sound basis for selecting solar pumping, renewable electricity, storage or other technologies. This approach reduces the risk of investing in equipment that is larger or more complex than the farm actually needs.

Training and after-sales support are as important as hardware. Solar pumps, sensors and smart controllers can underperform when installation, calibration or maintenance is weak. Extension programmes should therefore combine technical guidance with agronomic advice, water budgeting and basic financial evaluation. Tiwari *et al.* (2022) show the value of integrating solar pumping with efficient irrigation, while Zhao *et al.* (2023) stress that climate-smart technologies must be adapted to local conditions and supported by information services. A farmer-centered transition should consequently prioritize reliability, repairability, understandable decision rules and measurable savings rather than technological complexity alone.

A Practical Pathway for Resilient Agriculture

A practical farm-level pathway is to measure current energy use, identify the most expensive

or inefficient operations, implement low-cost efficiency measures, and then assess renewable-energy options based on the reduced demand. Water and energy planning should be integrated because irrigation is often a major variable load. At the same time, climate-risk assessment should identify the crops, seasons and operations most exposed to heat, drought, flooding or energy interruptions. The resulting plan can combine agronomic adaptation with energy transition instead of treating them as separate projects.

This integrated approach also avoids a common limitation of energy-transition discussions: replacing one energy source without reconsidering the production system. Bilan *et al.* (2023) frame modern energy crises as a challenge requiring structural responses rather than short-term supply fixes. In agriculture, structural resilience comes from lower energy intensity, diversified energy supply, efficient water use, resilient cropping systems, better information and stronger institutions. These measures reduce exposure to both market shocks and climate variability.

Conclusion

The energy crisis and climate change are closely connected challenges for agriculture. Farms require reliable and affordable energy, yet dependence on fossil fuels and energy-intensive inputs exposes producers to price volatility and supply disruptions. Climate change adds further pressure by increasing heat, water stress, extreme-weather risk and biological threats. The most effective response is an integrated transition that begins with energy efficiency, expands suitable renewable energy, improves water and nutrient management, and embeds these changes within climate-smart agronomy.

Solar irrigation, efficient pumps, precision input use, resilient cropping systems and digital decision support can contribute substantially when they are locally appropriate and supported by finance, infrastructure, extension and sound resource governance. The goal is not simply to substitute diesel with electricity or fossil electricity with solar power. It is to create farming systems that produce more reliably with less avoidable energy, lower emissions and greater capacity to withstand climate and market shocks.

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