Food and Agriculture Organization of the United Nations

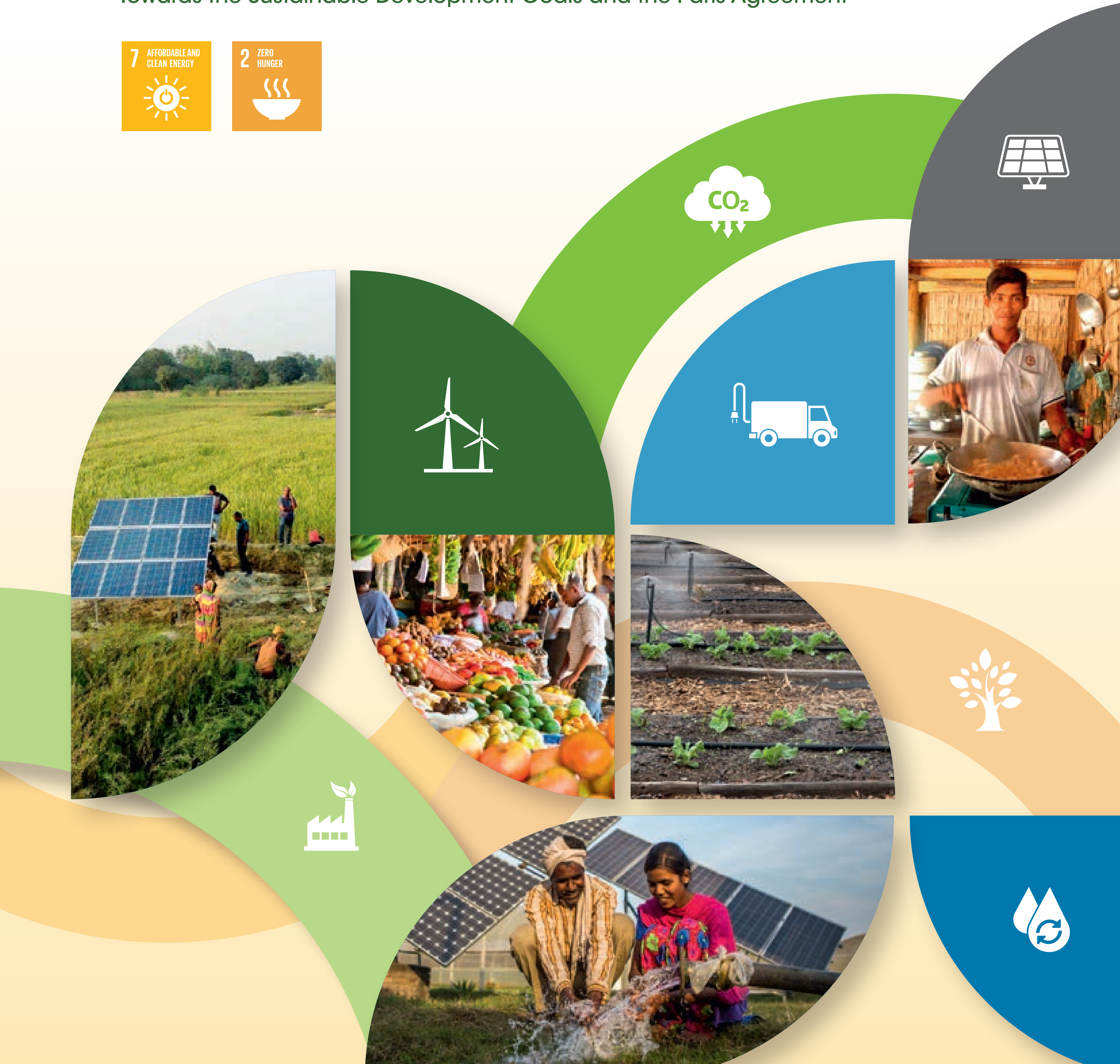
IRENA
International Renewable Energy Agency

Renewable energy for agri-food systems

Towards the Sustainable Development Goals and the Paris Agreement

7 AFFORDABLE AND CLEAN ENERGY

2 ZERO HUNGER



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Renewable energy for agri-food systems

Towards the Sustainable Development Goals and the Paris Agreement

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FOREWORD

Energy and food systems are deeply entwined. About 30% of the world's energy is consumed within agri-food systems. Energy is also responsible for a third of agri-food systems' emissions of greenhouse gases. Both systems must be transformed to meet current and future demand for food and energy in a fair, environmentally sustainable, and inclusive manner. A joint approach to the energy transition and to the transformation of agri-food systems is crucial to meet the Sustainable Development Goals (SDGs) and the Paris Agreement on Climate Change.

The latter half of 2021 has several important events. In September, the Secretary-General of the United Nations convened the UN Food Systems Summit and the High-Level Dialogue on Energy to advance dialogue and action to transform how the world produces, consumes and thinks about food and energy. In November, governments will gather in Glasgow for the United Nations Climate Change Conference (COP26) to commit to more ambitious climate action under the Paris Agreement. These deliberations take place against the backdrop of a global COVID-19 pandemic that has disrupted lives and economies, worsened inequality and threatened progress on key development objectives, including poverty alleviation.

Recognising a common thread between these global events, the International Renewable Energy Agency and the UN Food and Agriculture Organization have prepared this report on the role of renewable energy in agri-food systems. From primary production, to processing and storage, to cooking, energy is essential to raising productivity and incomes, cutting food losses, enhancing climate resilience for farmers and agri-enterprises, and improving cooking conditions. However, the current pattern of energy use is both unsustainable, owing to high dependence on fossil fuels and inefficient biomass use, and insufficient, due to poor access to energy in the rural areas of developing countries where agriculture is the main source of livelihood.

Renewable energy solutions and integrated food-energy systems can directly advance energy and food security, while also contributing to job creation, gender equality and climate resilience and adaptation. As presented in this report, the growing evidence for these benefits presents a compelling case for decision makers across sectors to devise policies and measures to accelerate the adoption of renewable energy in agri-food systems.

This opportunity is not without its challenges, such as siloed policy making, a lack of forward market linkages, a dire shortage of affordable financing for consumers and enterprises, and concerns about sustainability. This report sheds light on those challenges and offers recommendations on how to overcome them in an eight-point action agenda.

The solutions are within our grasp. They will require ambition and action-oriented partnerships at the local, national and global levels. We are convinced that this report will help light the path to achievement of the SDGs on food and energy in support of the 2030 Agenda and the Paris Agreement.

The report is an outcome of an agreement signed by IRENA and FAO in January 2021 to accelerate the deployment of renewables in the agri-food, fisheries and forestry chains, and in sustainable bioenergy. Our organisations are committed to working together to engage governments, development partners, the private sector and financing institutions in forging a common vision of inclusive and sustainable food systems, energy systems, and societies for better production, better nutrition, a better environment and a better life for all, leaving no one behind.

Qu Dongyu
Director-General
UN Food and Agriculture Organization

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International Renewable Energy Agency

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EXECUTIVE SUMMARY

The world's energy and food systems must be transformed to cope with growing demand; to become more inclusive, secure, and sustainable; and to come into alignment with the 2030 Agenda for Sustainable Development and the Paris Agreement on Climate Change. The transformation pathways of the two systems are deeply entwined: Agri-food systems consume about 30% of the world's energy, and a third of agri-food systems' emissions of greenhouse gases stem from energy use. The energy transition will directly affect the food system, and vice versa.

Food and energy systems also have a profound impact on society, economies and the environment, making them central to meeting multiple Sustainable Development Goals. Over 2.5 billion people worldwide rely on agriculture for their livelihoods making the sector a key driver for development. Energising the agri-food system by ensuring that reliable, affordable and environmentally sustainable energy is available for primary production, post-harvest processing, storage and cooking is a key enabler of higher yields, increased incomes, lower losses and greater climate resilience. However, present patterns of energy use in agri-food systems point to regional disparities, lack of access to modern energy (especially in the developing world) and continuing dependence on fossil fuels.

The structure of energy consumption in food systems varies significantly between developing and developed countries. In the latter, about a quarter of total energy use occurs in the production stage (crop, livestock and fishery), 45% in food processing and distribution, and 30% in retail, preparation and cooking. In developing countries, a smaller share of energy is used on the farm and a greater share for cooking. In fact, about 35% of the population still used wood fuel for cooking in 2019, leading to health and environmental damage that is disproportionately borne by women and children.

Worldwide, energy consumption in agri-food systems increased by more than 20% between 2000 and 2018. A key driver of that growth was mechanisation in Asia in the form of irrigation pumps, farm machinery, processing equipment and inputs such as fertilisers. Energy use in Africa, which hosts around 15% of the global population and faces growing food demand, has remained largely constant, accounting for only about 4% of global energy consumption in agri-food systems. Limited access to energy at each step of the agri-food system limits the ability of farmers and agri-enterprises to raise productivity, cut losses and cope with a changing climate and other shocks.

Renewable energy for agri-food systems

As agri-food value chains modernise, alternatives to fossil fuel energy sources are needed to ensure that food systems are built on secure, environmentally sustainable and resilient foundations.

Renewable energy can play a critical role in meeting needs for electricity, heating, cooling and transport needs of food systems in both developed and developing countries. In so doing, it can advance efforts to end hunger, reduce drudgery, lower greenhouse gas emissions, increase the adaptive capacity of farmers and agri-enterprises, raise incomes, and lessen the environmental impact of the food sector. At the same time, it can contribute to gender equality and youth employment.

Various renewable energy applications being deployed along agri-food chains are demonstrating the benefits of such solutions. **Solar irrigation**, among the most mature applications, is being widely adopted to improve access to water, thus enabling multiple cropping cycles and increasing resilience to changing rainfall patterns. The use of solar irrigation pumps has raised farmers' incomes by 50% or more in India compared to rain-fed irrigation. In Rwanda, smallholder farmers' yields have grown by about a third. The use of solar irrigation also displaces current and future fossil fuel use as the land area under irrigation expands. In so doing, it lowers emissions. Bangladesh's Nationally Determined Contribution under the Paris Agreement, for example, identifies solar irrigation as a key measure to mitigate climate change. Life-cycle emissions for solar-powered water pumping are estimated to be 95% to 98% lower than for pumps powered by grid electricity or diesel fuel.

Renewables-based agro-processing systems, stand-alone or based on mini-grids, offer an increasingly cost-effective alternative to fossil fuels, one with the added benefits of reducing environmental impact, promoting decentralised processing infrastructure and reducing labour-intensive processing activities. Despite their high potential across several value chains, however, adoption of renewables for agro-processing remains at an early stage. In the case of solar-powered grain milling – a key value chain in Sub-Saharan Africa – business models and technologies are still in the pilot phase and have not yet been commercially deployed at scale. Mini-grids are being used to power post-harvest processes, including milling, oil-pressing and ice-making – but usage can and should be greatly expanded. In Sierra Leone, a 250-kW hydro-based mini-grid powers a palm oil pressing plant, which also improves the financial case for the mini-grid buying a third of the electricity generated. Geothermal energy, too, is being used to meet thermal and electricity needs for agri-processing. The Mokai geothermal field in New Zealand, for example, supplies steam from two of its wells to a dairy factory that processes more than 250 million litres of milk each year. Demonstration projects are also being supported to create agro-processing hubs powered by renewables in rural areas – for example, the Kamwenge district of Uganda, where a biomass gasification plant produces electricity and heat for agro-processing.

Cold storage and refrigeration are a necessity at every stage of the agri-food chain to increase shelf life, cut losses, and maintain the quality of products from crops, livestock and fisheries. Losses disproportionately occur in the "first mile" between harvesting and processing; such losses are estimated to account for 37% of the food products lost in Sub-Saharan Africa. Improving access to refrigeration could prevent spoilage of up to a quarter of the perishable foods currently produced in countries with less-developed cold storage infrastructure. Further, global cold chain activities already account for around 5 percent of food-system emissions – a figure expected to rise. Renewables-based solutions offer several advantages, including decentralised cold storage capable of reaching smallholder farmers and remote fishing communities, and the power to transition existing infrastructure to more environmentally friendly and affordable energy solutions in developing and developed countries alike. In Kenya, for instance, decentralised renewables-based cold storage infrastructure reduces losses and improves market access for farmers, providing up to 30% additional income through aggregation and shortening of the value chain. Various technological options are available; these need to adapted to the local context and cooling needs.

Sustainable bioenergy is an important renewable energy resource that can meet needs for electricity, heat and transport fuels within the agri-food sector and beyond. Biomass by-products from agri-food activities can be used to produce energy for processing, storage and cooking. Residues generated from crop production and livestock can be an important source of bioenergy while considering the competing end uses (*e.g.* as animal feed). Manure and agro-processing materials can be utilised to produce biogas at various scales and for different purposes, including for cooking and lighting and in commercial and industrial establishments. An estimated 125 million people use biogas for cooking globally – the majority in countries in Asia such as China, Nepal, Viet Nam, India and Bangladesh. Bagasse – a waste product from sugarcane processing – is widely used in cane-producing countries such as India, Brazil, Thailand, the Philippines and Viet Nam, enabling sugarcane mills to approach or achieve energy self-sufficiency for raw sugar production and potentially to generate exportable electricity. In Thailand, the cassava industry uses both solid and liquid wastes to produce biogas and generate power. Biogas power plants operate in several sectors of the economy, including sugarcane, cassava, slaughterhouses and food processing. In Myanmar, where rice production is an important agricultural activity, rice husks (a by-product of milling) can be used to bridge the energy access gap in rural areas through combustion or gasification, yielding electricity and heat to expand productive activities, including value-added rice products.

Bioenergy and agricultural systems are closely linked at several levels related to the source of the biomass feedstock. Because of these links, it is critical to identify the location- and context-specific approaches that maximise food and energy benefits while minimising potential negative impacts. Country-specific bioenergy pathways, such as the one presented for Zambia in this report, must be plotted out in detail to ensure an adequate supply of feedstock and increase access to energy sustainably across sectors.

The discussion of these applications highlights the importance of a holistic approach that identifies energy gaps at each stage of agri-food value chains and informs the design of targeted energy interventions that can unlock the full spectrum of social and economic benefits for all stakeholders. In Ethiopia, for instance, analysis of six value chains covering grains, high value crops and the dairy sector finds that the electrification of agri-food systems' activities could generate revenue streams worth USD 4 billion between 2020 and 2025. Across the three value chains, productive end-use technologies could also create about 190 000 jobs by mechanising tasks and expanding production capacity. Integrated food-energy systems, which fully account for the nexus of energy, food and water will optimise land use and advance circularity in energy-food linkages, recognising and addressing trade-offs and harnessing synergies among the sectors.

Several common challenges exist for scaling up renewable energy applications in food systems. Silo-ed policy making and planning is chief among them. Another common obstacle is a techno-centric approach to the deployment of renewable energy, as opposed to a value-chain approach that considers factors such as forward and backward market linkages, data limitations, lack of access to end-user and enterprise financing, insufficient technical and management capacity among agri-enterprises, poor awareness, and the particular difficulties that women-led enterprises have in accessing solutions.

Recommendations for decision makers

Scaling up renewable energy use in agri-food systems to jointly advance energy and food security, as well as action towards the Sustainable Development Goals and the Paris Agreement, will require concerted action by decision makers in government, the private sector, international organisations, financing institutions, academia and nongovernmental organisations. As the global community convenes for the United Nations High-Level Dialogue on Energy, the Food Systems Summit and COP 26, this report offers a set of recommendations for decision makers, summarised below and illustrated in S Figure 1.

- **Improve the data and information base** through existing and new tools to guide renewable energy investments in food systems and inform policy makers. The effort should include mapping optimal locations to boost the benefits that renewable energy investments can bring to food systems, complemented by comprehensive cost-benefit analyses that consider the environmental, social, economic and gender aspects of those investments.

- **Improve access to finance** both for enterprises (the supply side of the energy equation) and, most importantly, for end users in food systems (the energy demand side). Various examples of tailored financing solutions, including climate finance, on which to build are increasingly available. Unlocking local capital will be key for scale in the long term and designing products for enterprises and end-users.

- **Facilitate the development of holistic approaches** such as integrated food-energy systems (*e.g.* agri-voltaic systems) and the water-energy-food nexus to minimise competition and leverage synergies in water and land use.

- More broadly, **mainstream cross-sector perspectives** into national and regional strategies for transforming the energy and food systems through a stable and supportive enabling environment. That environment must include 1) dedicated policies and plans; 2) cross-sectoral co-ordination that includes government, the private sector civil society and end-users, both nationally and subnationally.

- **Prioritise low-risk, high-impact action in the near term**. Examples include reducing food losses, enhancing circular economy effects, and strengthening the links between *energy for food* and *energy for health* as part of the green recovery.

- **Promote innovation in the development of technologies and energy efficient appliances** through dedicated high-risk innovation funds and multi-stakeholder partnerships between energy supply and demand actors to develop or repurpose existing technologies, pilot them for operational viability, and establish supply chains to deliver solutions (which must include long-term operational and maintenance services).

S.1. Advancing energy and food security to meet the Sustainable Development Goals

1 INTRODUCTION

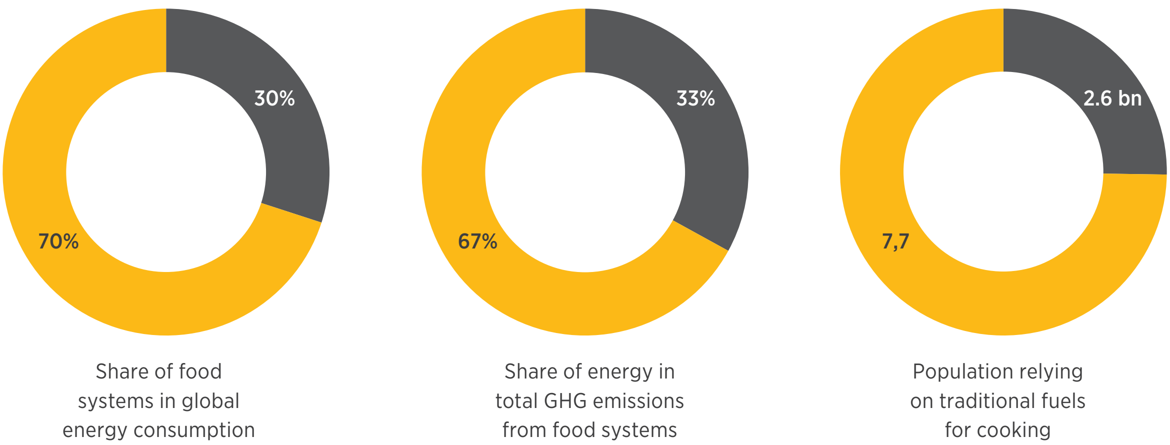
The global energy and food systems are at an important crossroads. Both must cope with growing demand for energy and food from a growing population; both must transform to become more inclusive, secure and sustainable; and both must come into alignment with the 2030 Agenda for Sustainable Development and the Paris Agreement. The pathways to transformation of the two systems are deeply entwined.

Energising agri-food systems has been an essential feature of agricultural development throughout history and is a prime factor in helping to achieve food security. Energy improves yields, reduces drudgery and losses, adds value and raises incomes, particularly for smallholder farmers and small and medium agri-food enterprises. Energy also fuels innovations in food systems. With over 2.5 billion people worldwide deriving their livelihood from agriculture, shortages of reliable, affordable and sufficient energy impede development and reduce resilience to shocks related to the climate and, more recently, Covid-19.

The current use of energy in the food system is unsustainable for several reasons. First, millions of people and small and medium-sized agri-food enterprises lack access to sustainable, reliable and affordable energy to produce, store, process and consume food, resulting in significant food losses in post-harvest stages. Around 14% of food produced globally is lost before even reaching the market (FAO, 2020a). Too often, the quality of food and cooking conditions are sub-optimal. Over 2.6 billion people lived without access to clean cooking fuels and technologies in 2019 at significant costs, borne disproportionately by women and children.

Second, agri-food chains account for about 30% of global energy consumption, most of it in post-harvest stages and in the form of fossil fuels (Figure 1). About 30% of that energy is wasted through food losses at one point or another in the value chain (FAO, 2011).

Figure 1. Energy use in agri-food systems: a snapshot



Source: Crippa *et al.* (2021); IEA, IRENA, UNSD, World Bank and WHO (2021).

Finally, energy use is responsible for about one-third of the greenhouse gas (GHG) emissions from food systems. The share of energy-related carbon dioxide (CO_2) emissions occurring in food systems rose to 21% of total CO_2 emissions in 2015, an increase of 31% over 1990. Food processing and distribution, which includes retail, packaging and transport, saw the biggest increases. All these stages increased their emissions shares substantially (by one-third to three times) compared with 1990 (Crippa *et al.,* 2021).

However, energy can also be part of the solution to climate change-food system links. This can be achieved through: 1) the use of renewable energy in agri-food systems; 2) the production of renewable energy from agri-food system residues; 3) reductions in GHG emissions embedded in food loss and waste; and 4) carbon sequestration in energy crops and soils using biofertilisers derived from biogas production and biochar from gasification of solid biomass. Having sufficient energy in food chains can also contribute to climate change adaptation by increasing resilience to changing weather patterns (*e.g.* powered irrigation compared with rainfed agriculture) and potentially increasing incomes through product and services diversification, value-added activities and local job creation.

Modern bioenergy[1] is poised to play a critical role in advancing the energy transition. Its share in final energy consumption is estimated to rise to 18% in 2050 from 3% in 2018 (IRENA, 2021a). Integrated food-energy systems – based on food crops, residues or agri-voltaics – are likely to play a central role in scaling up sustainable use of bioenergy across sectors. This important feature of food systems is often overlooked in discussions and programmes on the scaling up of renewable energy development.

The challenge is to decouple the use of fossil fuels in food-system transformation and related innovations without compromising food security. With growing demand for energy and food, the transformation of both systems is necessary to align them more closely with global climate and sustainability goals. Linkages between sectors are such that a transformation in one will have a profound effect on others. In particular, the energy transition will directly affect and be affected by changes in food systems – and vice versa.

Food and energy systems also contribute immensely to the Sustainable Development Goals. For example, renewable energy solutions deployed for food systems can increase incomes for farmers and other actors in the value chain, strengthen poverty alleviation efforts, improve health outcomes (through reduced use of traditional fuels for cooking and better access to water), and support gender empowerment and climate resilience and mitigation (IRENA, 2016a).

Effectively managing these interlinkages and maximising benefits requires a holistic approach that advances food and energy security while also addressing climate change and sustainability. This joint report from the UN Food and Agriculture Organization (FAO) and the International Renewable Energy Agency (IRENA) highlights key opportunities to integrate renewable energy within food systems. It discusses obstacles to scaling up adoption as well as ways to overcome those obstacles. As the global community convenes in 2021 for the United Nations High-Level Dialogue on Energy, the United Nations

[1] "Modern bioenergy" can be used efficiently for electricity generation (combined with heat or CCS), heating for industrial applications and productive activities, cooking in efficient wood and pellet stoves and boilers, and the production of biofuels for transport. Meanwhile, traditional uses of biomass refer to local solid biofuels (wood, charcoal, agricultural residues, and animal dung) being burned via basic techniques using, for example, traditional open cookstoves and fireplaces. Owing to their informal and non-commercial nature, it is difficult to estimate the energy consumed by such practices, which remain widespread in households in the developing world. Even though biomass as it is traditionally used is, in principle, renewable, policy attention should focus on encouraging the adoption of more efficient renewable heating and cooking technologies (IEA, IRENA, UNSD, World Bank and WHO, 2021).

Food Systems Summit and COP26, it is time to break down sectoral silos and pursue a holistic approach that can deliver optimal outcomes for people, economies and the planet. To this end, the report presents recommendations for decision-makers to scale up the use of renewables in agriculture in a manner that maximises socio-economic and envrionmental benefits.

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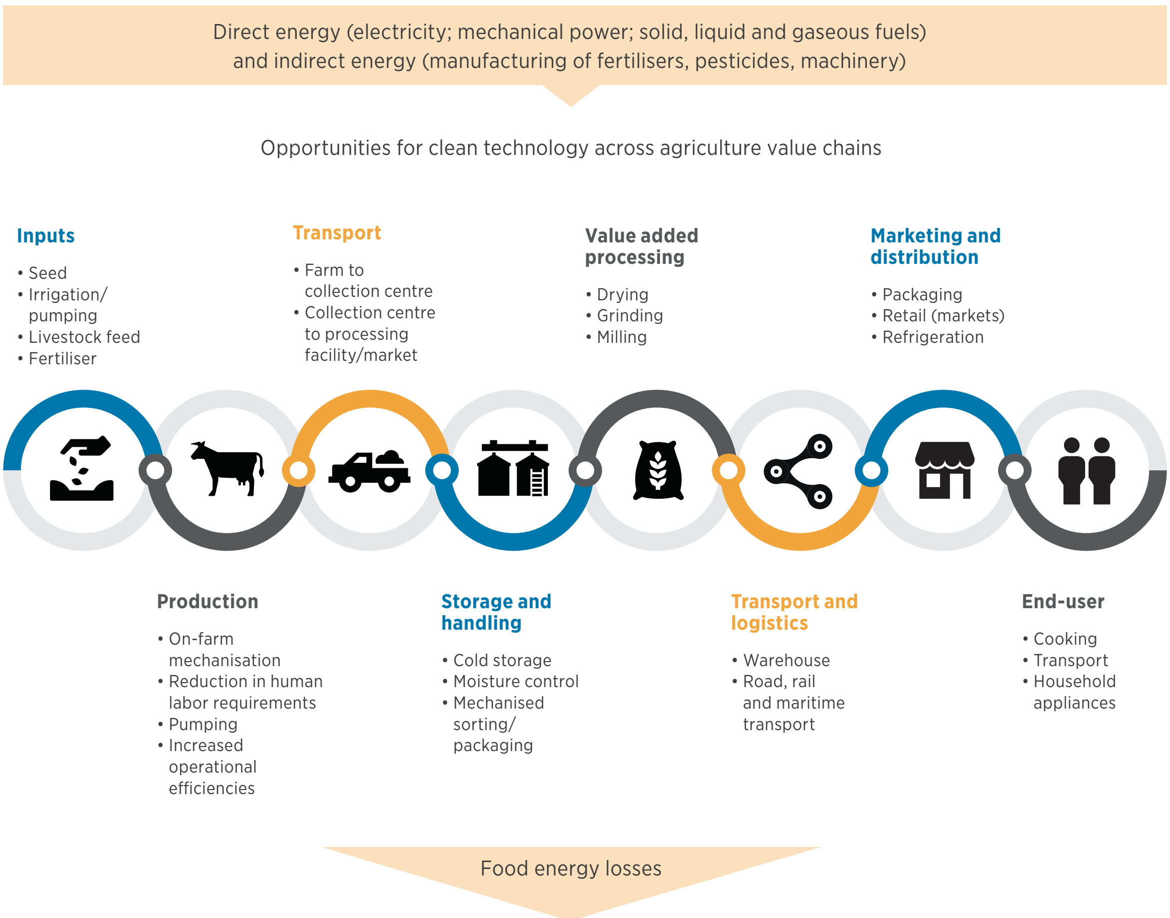
2 RENEWABLE ENERGY FOR FOOD SYSTEMS TRANSFORMATION

Energy plays a fundamental role in food systems. It is consumed not only in primary production, but also in secondary activities, such as drying, cooling, storage, transport and distribution (Figure 2) (Taghizadeh-Hesary, Rasoulinezhad and Yoshino, 2019). It is needed at all steps along the agri-food chain, both directly (for production, processing and transport) and indirectly (for manufacturing of fertilisers, agro-chemicals and machinery). Agri-food systems are responsible for about 30% of the world's total energy consumption (FAO, 2011).

Figure 2. Energy flows in agri-food systems



Source: FAO and USAID.

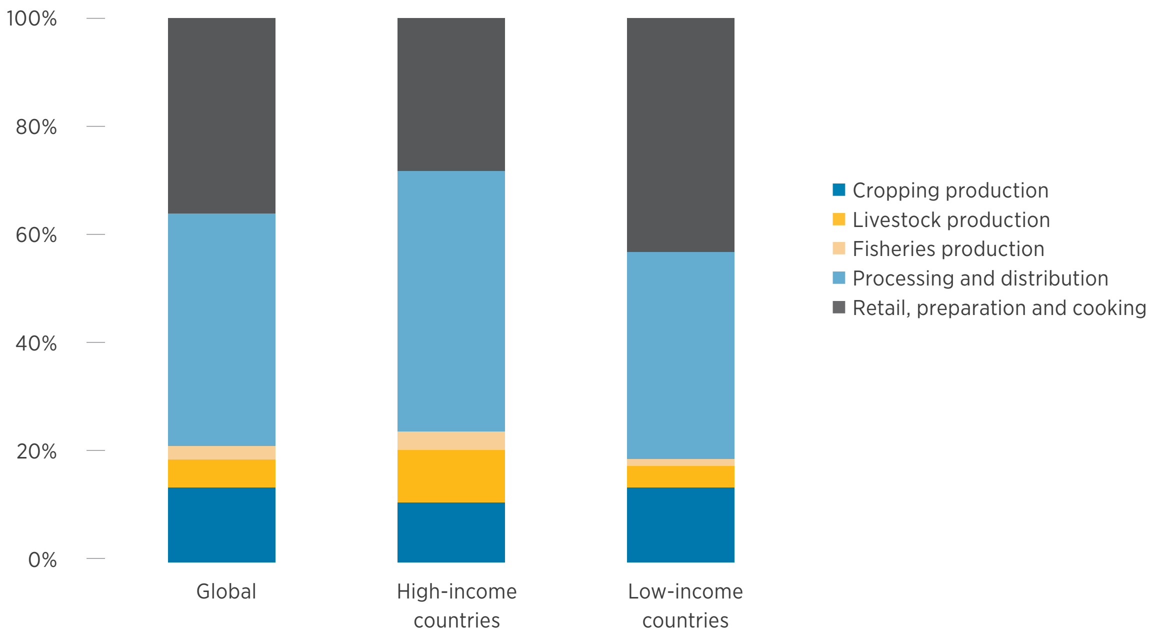
2.1 Energy consumption in food systems

The pattern of energy consumption in food systems varies significantly between developing and developed countries. In the latter, about a quarter of the total energy is consumed during the production stage (crop, livestock and fishery), 45% in food processing and distribution, and 30% in retail, preparation and cooking (Figure 3). In developing countries, a smaller share of energy is used on the farm and a greater share for cooking (FAO, 2011).

In the **primary production stage**, energy is consumed chiefly to fuel tractors and machinery, operate irrigation infrastructure, produce fertiliser and feed, operate greenhouses and other forms of protected cropping, and carry out fishing and aquaculture. Across each of these activities, one finds major variations in energy needs depending on the scale of the enterprise and on the type of food being produced. In the **post-harvest processing and storage** stage, produce may undergo drying, cutting, threshing, milling, winnowing, or other forms of processing before distribution. This stage may also involve refrigeration to reduce post-harvest losses. Energy for electricity, heating and cooling, and transport is required at this stage, and its availability plays a crucial role in value addition as well as food and income loss reduction for various actors in agri-food systems. The **transport and distribution** stage primarily involve food commodities reaching markets, local or distant. Energy consumption in this stage can vary significantly depending on the structure of supply chains and the mode of transport, but the almost exclusive reliance on fossil fuels makes transportation costs vulnerable to fuel price fluctuations.

Finally, energy use during the **retail, preparation and cooking** stage essentially involves food storage and inputs for cooking meals using various cooking appliances.

Figure 3. Share of total energy consumption globally and in high- and low-income countries, by segment of agri-food chain



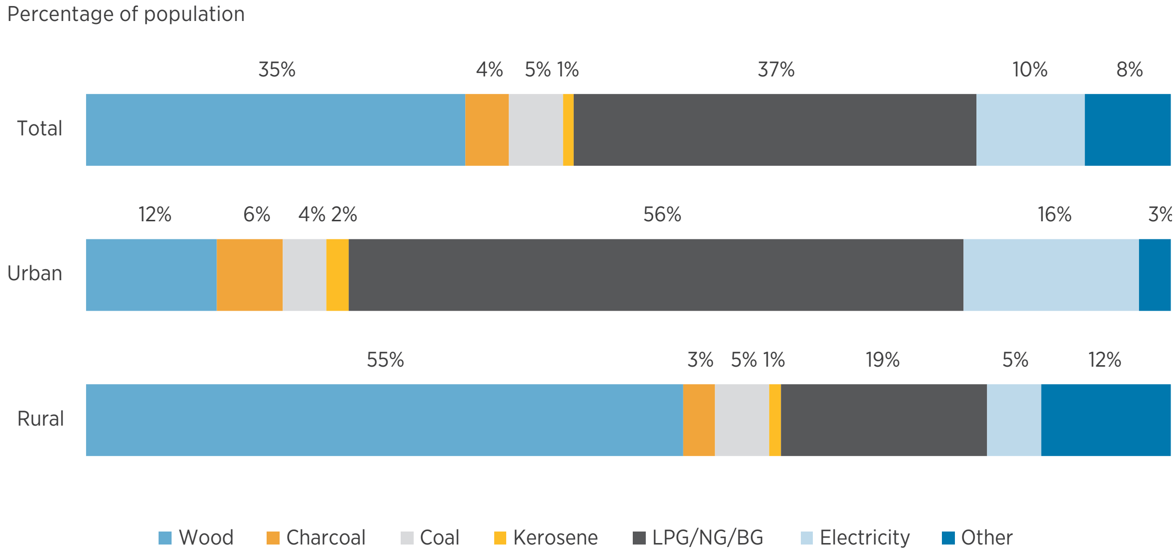
Source: FAO (2011).

As regards household level, globally, about 35% of the population use wood fuel for cooking in 2019, with 37% relying on liquefied propane gas (LPG), natural gas or biogas and 10% on electricity (ESMAP, 2020). Significant variations exist between regions and urban and rural areas (Figure 4). The use of traditional fuels for cooking (wood, charcoal, etc.) tends to be higher in rural areas across regions that have a clean-cooking deficit. The share of the population without access to clean cooking is highest in Sub-Saharan Africa and lowest in Latin America and the Caribbean. In absolute terms, Sub-Saharan Africa has seen an increase in the use of biomass, driven by population growth.

In recent decades, traditional forms of energy have been largely displaced by fossil fuels as agri-food systems have become more industrialised and farming and food processing more intensive – a process continuing in many countries. Hence, the provision of modern[2] energy services – like heating, cooling, transport, water pumping, lighting, animal welfare, and mechanical power – have become largely dependent on fossil fuels. For agriculture (crops and livestock), fishing, and forestry production, energy consumption has been steadily rising in recent decades, with the main energy inputs being electricity and diesel fuel and just a small share of renewables.

Energy consumption in agriculture is not evenly distributed across regions (Figure 5).

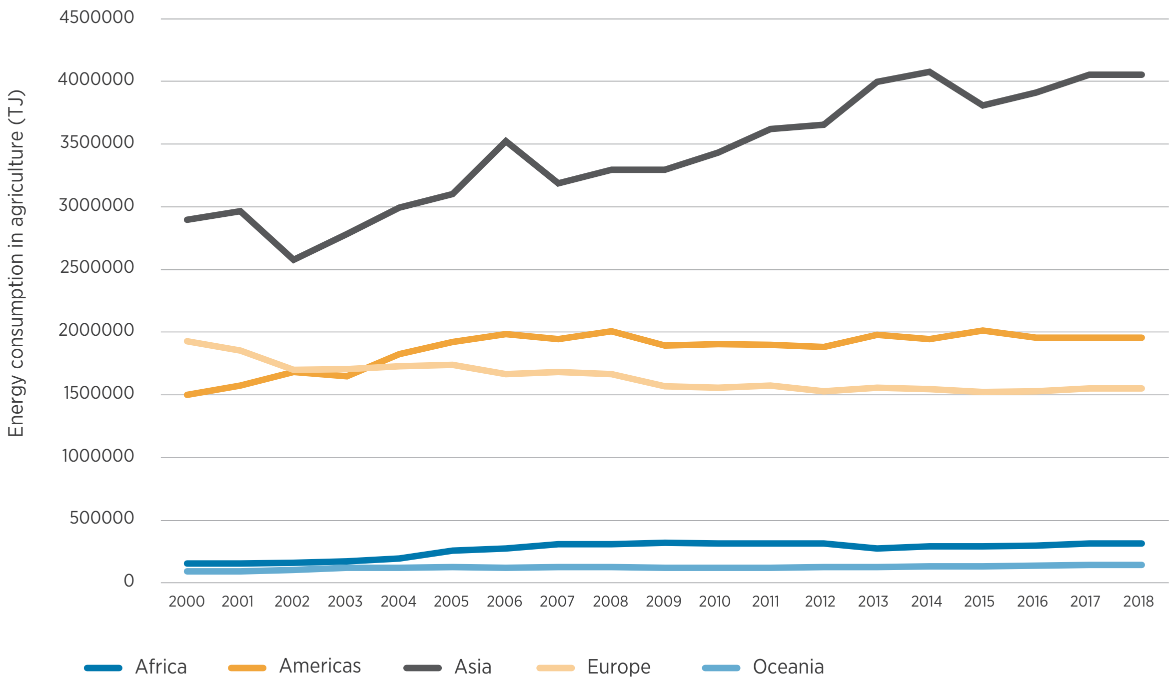
Figure 4. Global cooking fuel mix, total and by urban and rural areas



Source: ESMAP (2020).
Note: LPG = liquefied propane gas; NG = natural gas; BG = biogas

[2] There is no single internationally accepted and adopted definition and measurement method of access to modern energy. The IEA defined modern energy access as "a household having reliable and affordable access to clean cooking facilities, a first connection to electricity and then an increasing level of electricity consumption over time to reach the regional average". ESMAP-led Multi-Tier Framework aimed to redefine energy access from a traditional binary count to a multi-dimensional definition as "the ability to avail energy that is adequate, available when needed, reliable, of good quality, convenient, affordable, legal, healthy and safe for all required energy services". Beyond connections, the new mehtoodlogy also considers other aspects, including reliability and affordability. Meanwhile, the Global Bioenergy Partnership (GBEP) defines modern energy services based on two criteria: energy efficiency and safety to human health. Where modern energy services rely on the combustion of fuels, the fuels (whether solid, liquid or gaseous) must be burned in efficient and safe combustion chambers, improved cookstoves or fuel cells. Efficiency is meant here as the energy output as a percentage of the heating value of the fuel. Safety refers to the absence of indoor air pollutants and low amount of pollutants released in the open air by the energy system (GBEP, 2011).

Figure 5. Energy consumption in agri-food systems, by region, 2000-2018



Source: FAOSTAT, 2021.

Over the past two decades, energy consumption in Asia has grown as agriculture has become more mechanised with irrigation pumps, farm machinery, processing equipment and inputs such as chemical fertilisers. In the Americas and Europe, it has remained stable, even as production has grown, thanks to increased efficiencies and agronomic progress. In Europe, between 2000 and 2012, energy intensity in agriculture fell by 20%, while slight reductions were seen in North America and Asia. Across the African continent, which hosts around 15% of the global population and faces growing food demand, energy consumption has remained constant.

The disparity in energy use across regions points to a large energy gap, particularly on the African continent. That gap will have to be met to raise productivity, strengthen supply chains, reduce food and income losses, and improve food security. At the same time, continuing to meet energy needs through fossil fuels across continents poses significant problems in terms of accessibility, affordability, resilience to supply and price shocks, and environmental effects, particularly climate change.

Demand for food and non-food products continues to grow globally, reflecting dietary changes driven by population growth, higher incomes and urbanisation (FAO, 2018a). By 2050, food production will need to grow by 70%, primarily through yield increases, to meet expanding demand. While fossil fuel use in agri-food systems has facilitated farm mechanisation, boosted fertiliser production and improved food processing and transportation, it has introduced risks for food security and left behind a large proportion of the agricultural community, particularly in emerging economies (FAO, 2011).

A significant challenge for global food systems is to deliver food security and nutrition for all in a sustainable way – that is, in a way that does not compromise the economic, social and environmental bases for food security. Food systems must be profitable (economic sustainability); they must yield broad-based benefits for society (social sustainability); and they must have a positive or neutral impact on the natural environment (environmental sustainability) (FAO, 2018b). Meeting those goals will require a transition away from dependence on fossil fuels.

2.2 How renewables can transform agri-food systems

Renewable energy can play a crucial role in meeting the energy needs of agri-food systems in both developed and developing countries. In so doing, it can advance efforts to end hunger, reduce drudgery, lower GHG emissions, increase the adaptive capacity of farmers and agri-enterprises, raise incomes, and lessen the environmental impact of the agri-food sector. At the same time, it can contribute to gender equality and youth employment (IFAD, 2020).

Increasing supplies of modern energy in low-access areas

Agri-food systems in developing countries account for a large share of the livelihoods of farmers, fishers and other actors in the food value chain. Because of the still developing infrastructure of those systems, the incremental amount of energy required to increase productivity, food security and resilience to climate and other shocks will be significant. As things stand, lack of access to reliable and affordable energy in sufficient quantity poses a major constraint on agricultural production and post-harvest processing (IFAD, 2020). It is also a major reason why food chains in developing countries account for high losses even before the food reaches the market, in part due to the lack of adequate cold storage (FAO, 2020a).

With rainfall patterns increasingly erratic owing to climate change, the rainfed agricultural systems that are still dominant in Sub-Saharan Africa and parts of South Asia will need better water-management and irrigation systems and infrastructure to improve yields, productivity, food security and resilience, particularly among subsistence farmers. Land area under irrigation is still far too low, particularly in Sub-Saharan Africa. And where irrigation has expanded, fossil fuels are usually used. In India alone, more than 8.8 million fossil fuel–powered pumps are in operation (IEEFA, 2021). In Bangladesh, over 1.3 million diesel pumps consume at least a million tonnes of diesel costing USD 900 million annually (Bengal Solar, 2021). At the farm level, fossil fuel–based pumps impose high (and fluctuating) recurring costs for farmers; aggregated at the sector-level, those costs can be a severe burden for governments of states where fuel is imported or subsidised, not to mention the impact on the environment.

Presently, rural agricultural communities capture only a small proportion of the value of their produce, the majority being retained by firms closer to urban areas with more ready access to energy, facilities and infrastructure. Improving food security and raising incomes for primary producers depends on expanding access to modern energy, along with other changes such as financing, appliances, business knowledge and market access. In Ethiopia, for example, electrification of agricultural activities could save fuel costs and generate substantial new revenues for rural smallholders and small and medium agricultural enterprises. An analysis of six value chain opportunities covering grains, high value crops and the dairy sector finds that, thanks to access to modern energy, these could generate revenue streams worth USD 4 billion between 2020 and 2025 (Table 1) (Borgstein, Wade and Mekonnen, 2020). Deploying renewables-based solutions in horticulture, wheat and dairy sectors could also create about 190 000 jobs across value chains by expanding production capacity and reducing losses (Ethiopia Jobs Creation Commission, 2021).

Table 1. Value chain opportunities for electrification in Ethiopia

Sector	Description	Appliance Needs	Potential value unlocked*
Irrigating horticulture	Irrigate land with electric pumps for production of high-value crops (head cabbage, tomatoes, red pepper, onions, garlic, avocados, bananas, mangoes)	Electric pumping systems, large and small, on- and off-grid. Sprinklers, manual and automatic drip irrigation systems	USD 1.2 billion
Grain milling	Replace diesel mills with electric equivalents (maize, wheat and teff)	Electric mills; small-scale (off-grid) and large-scale (on-grid)	USD 120 million (replacing diesel-powered milling)
Injera baking	Produce high-quality injera with electric griddles (mitads)	Efficient electric injera mitads	USD 780 million**
Bread baking	Produce bread locally in bakeries to meet growing demand in rural and peri-urban areas	Dough mixers, bread baking ovens	USD 150 million
Milk cooling	Power milk collection centres that store and cool milk from rural producers	Milk collection centres with mixers and chillers	USD 1.3 billion
Coffee washing	Pump water and run coffee-washing machines electrically, replacing diesel generators and pumps	Water pumps, coffee washing stations	USD 540 million (replacing diesel-powered systems)

* Gross revenue potential from output of electric systems by 2025
** Evolving cultural practices involving the trade of bread and injera will impact revenue potential realised for the sectors.

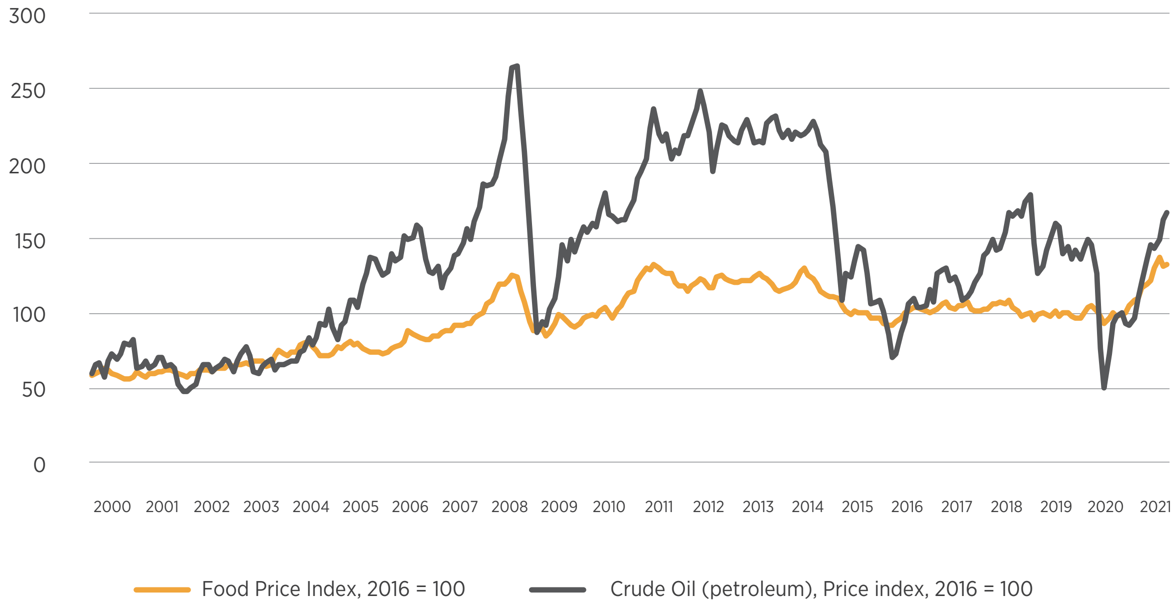
Source: Borgstein, Wade and Mekonnen (2020).

Decentralised renewable energy can play a fundamental role in strengthening modern energy access in areas where supply is presently lacking or unreliable and expensive. Their distributed nature allows them to tap into locally available resources and deliver tailored energy services – from electricity to heating/cooling and transport – across diverse agri-food value chains.

Minimising dependence on the volatility of fossil-fuel prices

As noted, transforming food systems and improving food security depend on more widespread use of modern forms of energy in agri-food systems. However, the unfettered use of fossil fuels to meet growing energy needs for electricity, heating, cooling and transport in the agri-food sector is not an option for several reasons. First, food prices are vulnerable to sudden changes in fossil fuel supply and price. The Food Price Index, an average of five commodity group indices (meat, dairy, cereals, vegetable oil and sugar), closely follows the price of oil, showing significant volatility (Figure 6). With the growing energy intensity of agriculture, rising energy prices translate into higher costs of production, processing and transport, which could means higher costs for consumers. More recently, disruptions caused by the Covid-19 pandemic have made charcoal and LPG scarcer and more expensive in countries such as Kenya (World Bank, 2021).

Figure 6. Evolution of the Food Price and Oil Price index, 2000-2021



Source: IMF Commodity Price Database.

These trends point to the need to diversify energy use in agri-food systems, in order to depend less on price-volatile and transport-dependent sources of energy. Diversification will promote both energy and food security in the long-term.

Reducing costs and losses along the agri-food chain through access to energy

In the developing world, around 14% of food is lost before reaching the market (FAO, 2019b). A significant share of the total energy used by agri-food systems is embedded in these losses, 30 to 40% according to FAO (2011). In developing countries, most food losses occur during harvest and storage.[3] It is estimated that on-farm losses for fruits and vegetables in Sub-Saharan Africa are as much as 50%; for cereals and pulses, as much as 18% is lost. In countries with high levels of food insecurity, reducing losses early in the supply chain is likely to do the most to increase food security. Here, renewables can play an important role.

The causes of food loss range from poor handling, inadequate transport and storage, and lack of cold chain capacity. Sustainable cold chains and cooling technologies could play a crucial role in reducing losses, particularly close to the farm. But these require reliable and affordable access to energy. Today, renewables-based cold storage using decentralised infrastructure located close to the farm is being deployed to reduce losses (see Box 17 in chapter 4) on a new effort to tackle food loss through investments in storage infrastructure in rural areas of Africa.

[3] Food loss is the decrease in the quantity or quality of food resulting from decisions and actions by food suppliers in the chain, excluding retailers, food service providers and consumers. Food waste refers to the decrease in the quantity or quality of food resulting from decisions and actions by retailers, food service providers and consumers (FAO, n.d.)

Converse to what occurs in developing countries, in high-income countries, food waste is more important than food losses as it concerns the food quantity and quality in the retailing, preparation, cooking and consumption stages of the food supply chain. Many countries deal with the growing demand for food by increasing production without reducing food loss and waste, thereby raising pressure on the environment and increasingly scarce natural resources.

Reducing the environmental impacts of energy used in agri-food systems

The food sector is a major contributor to GHG emissions[4] while also being deeply affected by climate change. Energy-related activities within agri-food systems contribute to around one third of emissions from the food sector (Crippa *et al*, 2021). Production stages (in fisheries, aquaculture, and agriculture, as well as emissions from inputs such as fertiliser) account for the largest share (39%). On-farm emissions arising from energy use increased globally by 25% from 1990 to 2018 (Tubiello *et al.,* 2021).

Mitigation strategies will require energy efficiency and decarbonisation in all segments of the food value chain. In developed countries, significant opportunities to improve energy efficiency can be found in production activities. In developing countries, by contrast, the focus should be on post-harvest energy use (Bajan, Mrówczy´nska-Kami´nska and Poczta, 2020). Complementing energy efficiency, greater use of low-carbon renewable energy could support mitigation, while meeting needs for energy in primary production, processing, storage, distribution, retail and cooking. This is increasingly recognised in countries' Nationally Determined Contributions (NDCs) submitted under the Paris Agreement on Climate Change (Box 1). Beyond mitigation, integration of renewables in agri-food systems also strengthens adaptation, adding resilience to the extreme weather events and resource shortages caused by climate change.

Meeting the clean cooking challenge

As noted earlier, about 35% of the population was still using wood fuel for cooking in 2019, with 37% relying on LPG, natural gas or biogas, and 10% on electricity (ESMAP, 2020). The health and environmental impact (degradation and biodiversity loss) of the continued use of traditional fuels for cooking is significant – and borne disproportionately by women. At least 2.6 billion people were without access to clean cooking in 2019, and slow progress means that an estimated 2.4 billion people will remain without access in 2030, the target year for reaching universal access under SDG 7 (IEA, IRENA, UNSD, World Bank and WHO, 2021).

Several cultural, economic and social factors influence the uptake of clean cooking solutions. However, several options are available to rapidly scale up adoption in a manner that is environmentally sustainable and brings several co-benefits. Renewable options such as improved biomass stoves, biogas, ethanol and solar cookers already contribute to expanded access, and renewables-enabled electric cooking has begun to play a role as well (REN21, 2021).

Biogas-based solutions have long been deployed to expand access to clean cooking, to improve the management of agricultural waste (including waste from livestock), and to produce fertiliser. In Africa, where a large share of smallholders keep livestock, between 5% and 20% are potentially business-oriented, with incentives to significantly expand and upgrade their livestock production (World Bank

[4] The world's food systems are responsible for more than one-third of global anthropogenic GHG emissions.

Box 1. How agri-food systems figure in Nationally Determined Contributions

Agri-food systems are diverse and can be highly complex. Finished items sold to consumers generally draw on the production of crops, livestock, forestry, fisheries and aquaculture, along with the utilisation of their by-products. Due to the systemic nature of value chains, they cannot be classified under a standard IPCC sector designation used to report on GHG emissions; instead, they are cross-sectoral, which is also reflected in the way references to them appear under different sectors and areas in the NDCs.

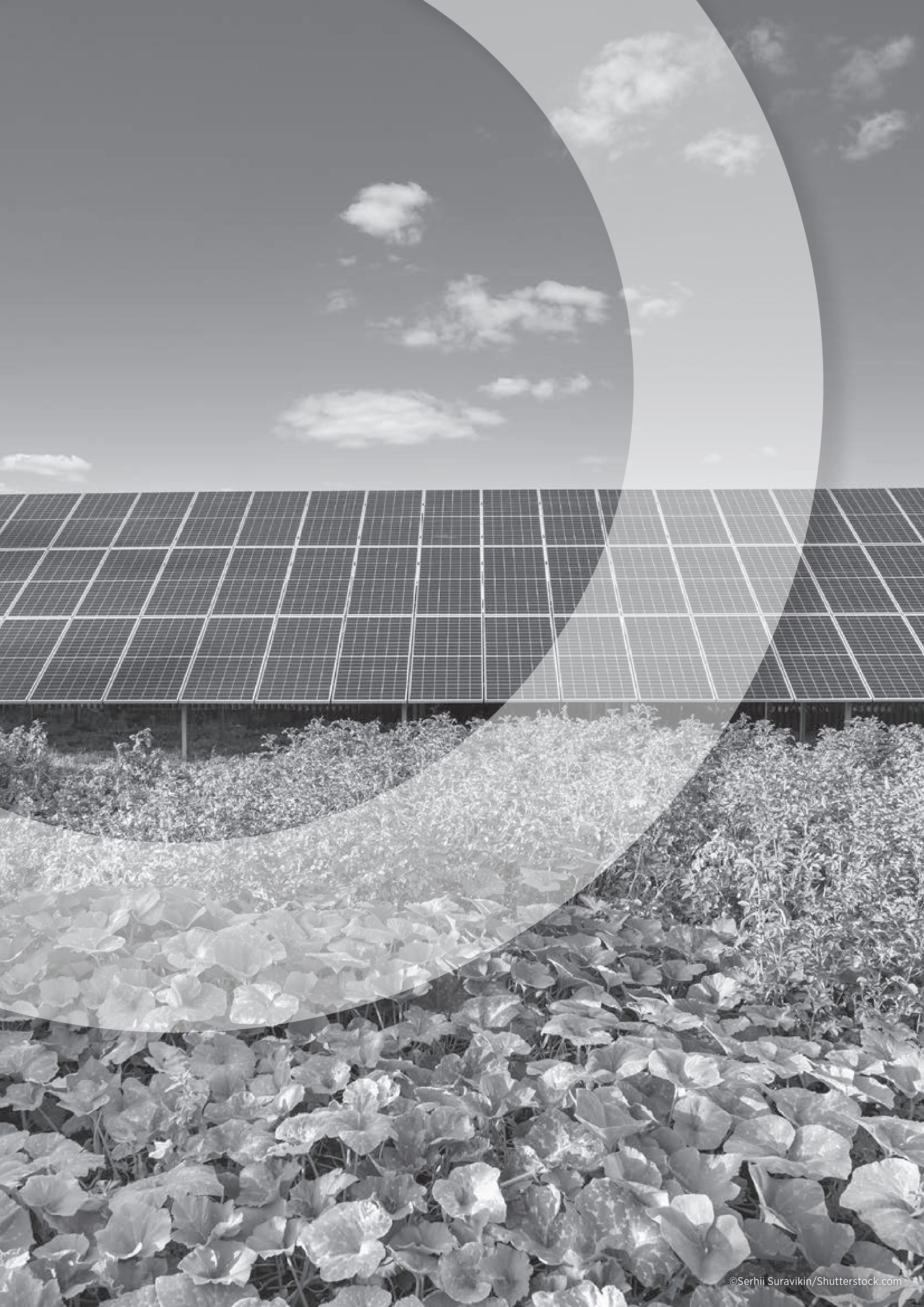
An analysis of 163 NDC submissions found that 55% of them refer to various aspects of food value chains, predominantly among the least-developed countries and Small Island Developing States, many in Sub-Saharan Africa. Several stressed in their NDCs the goal of strengthening specific agri-food value chains using renewable energy or other means. Kenya's NDC emphasises the need to enhance the resilience of the agriculture, livestock and fisheries value chains by promoting climate-smart agriculture and livestock development. Rwanda aims to give 100% of its farmers access to services for post-harvest treatment and storage of food crops and to reduce post-harvest losses to no more than 1% by 2030 – from 10.4%, 27.4% and 8.3% in 2014 for maize, beans and rice, respectively. The use of solar energy in warehouses is highlighted to be actively promoted.

Source: FAO (2019a).

and FAO, 2014). Although the technical potential for household biogas digestors across the continent is about 40 million, existing installations are still less than 150 000, even as biogas production increased by 28% between 2015 and 2020 (REN21, 2021). The Africa Biogas Partnership Programme has facilitated the installation of over 72 000 digestors across Burkina Faso, Ethiopia, Kenya, Senegal, Tanzania and Uganda since 2009. In Viet Nam, the biogas programme for the animal husbandry sector facilitated the construction of more than 290 000 biogas digestors, improving living conditions for over 1.7 million people while addressing needs for livestock waste management, biofertilisers and clean cooking fuels. Over its 18-year lifetime, the programme also has resulted in over 20 000 person-years employment in some 250 biodigester enterprises. These are discussed further in the next chapter.

Electric cooking is also increasingly viable for many people connected to national grids and some mini-grids. Linking renewables-based power to efficient cooking appliances, such as electric pressure cookers (which consume less electricity than traditional electric hotplates), and better demand-side management can improve their viability in decentralised settings. Globally, more than four million solar cookers had been distributed by early 2021, providing clean cooking to an estimated 14 million people (REN21, 2021). Several obstacles remain, notably high upfront equipment costs.

Some intriguing innovations combine cooking with lighting and device-charging deliver more value for money and thus have improved adoption rates – for example, in India (Wilson, *et al.,* 2018).



3 RENEWABLE ENERGY APPLICATIONS IN AGRI-FOOD CHAINS

This chapter discusses renewable energy applications across agri-food chains and highlights the importance of a holistic approach to identify energy gaps at each stage and to design interventions that can unlock the full spectrum of social, economic and environmental benefits for all stakeholders. Specific applications of renewable energy – for irrigation, agro-processing, cold storage and sustainable bioenergy – will also be discussed, with a primary focus on developing countries.

3.1 Strengthening agri-food chains with renewables

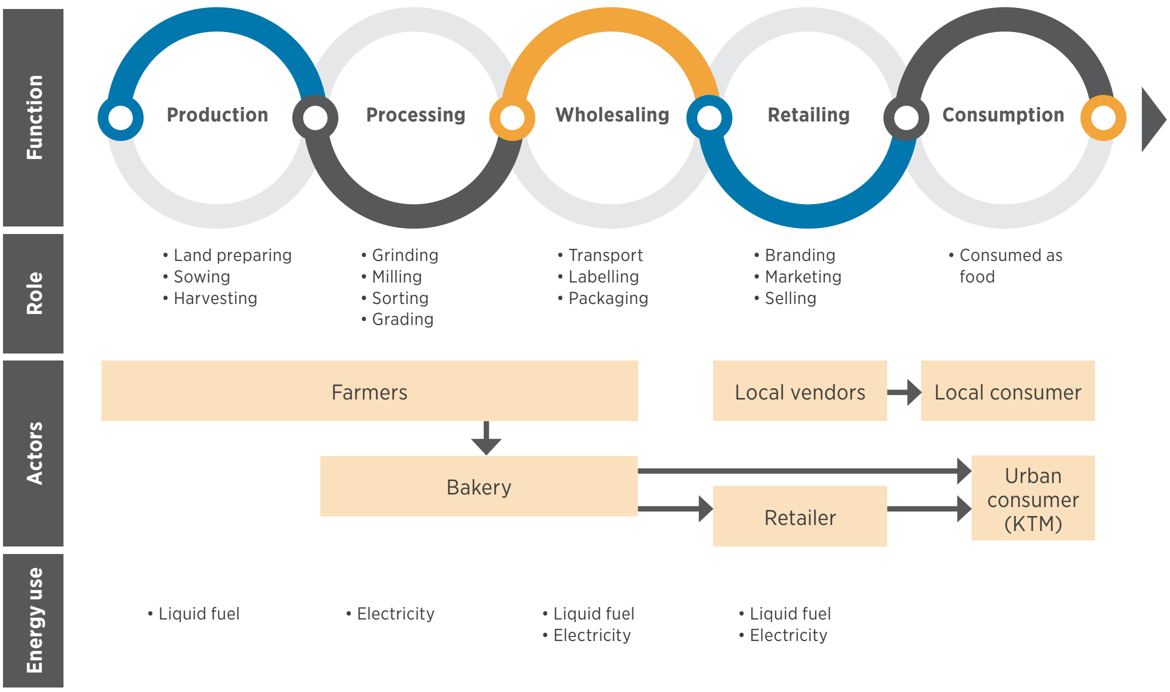
Agri-food chains link production, aggregation, processing, distribution, retail and consumption. Their structures are diverse and can be highly complex, involving multiple actors and interactions with varying products involving crops, livestock, forestry, fisheries and aquaculture (FAO, 2019a). Food value chains are often linear, comprising units of enterprises that interact closely with one another through products and services, exchange of information and pursuit of shared interest (Springer-Heinze, 2018). FAO (2014) defines sustainable food chains as the "full range of farms and firms and their successive coordinated value-adding activities that produce particular raw agricultural materials and transform them into particular food products that are sold to final consumers and disposed of after use, in a manner that is profitable throughout, has broad-based benefits for society, and does not permanently deplete natural resources".

Using a value chain approach to assess energy needs and gaps offers several advantages. First, it enables the identification of energy needs and gaps at each stage, making possible a "whole-of-system" intervention design to unlock maximum value and benefits. Second, a value chain perspective considers the enterprises and stakeholders operating at each stage, offering insights into where incentives already exist and where they can be most useful in encouraging the use of renewable energy. For example, adopting renewables-based cooling and water pumping within the milk value chain will directly benefit dairy farmers; additional value may also occur for milk processors, transport businesses and retailers from reduced losses and improved quality (FAO, 2018c). In Kenya, a major dairy processor has partnered with an off-grid solar technology provider to provide solar-powered irrigation to support fodder crops and water access for cattle, thus boosting milk production (Lukhanyu, 2021). The multiplier effects of improved access to modern energy tend to be more significant in longer value chains (such as that for milk chain) as compared with rice or vegetable chains (FAO, 2018c). Third, value chain mapping makes it possible to trace the path of a product, as well as financing and information, between actors, thus helping to identify suitable delivery models and the points at which non-energy-related challenges (*e.g.* access to financing and gaps in awareness and skills) need to be addressed.

In recent years, a number of projects and programmes have applied a value chain approach to analyse renewable energy opportunities. The Renewable Energy and Energy Efficiency Partnership, in collaboration with GIZ's Powering Agriculture programme, analysed dairy value chains in India and Kenya to identify potential applications for renewable energy at each stage of milk production, collection, processing and retailing. Mapping the dairy value chains in both countries found important differences. In Kenya, many dairy farmers lacked access to cooling infrastructure in rural areas leading to milk spoilage before reaching a collection centre or processing plant. Such a condition makes many producers sell to neighbours or traders in the informal market. In India, village milk collection centres usually are equipped with cooling equipment with a strong role played by farmer-owned co-operatives; savings are likely passed down to farmers, incentivising investments in renewable energy technologies (REEEP, 2018).

IRENA, the International Centre for Integrated Mountain Development and SELCO Foundation are undertaking an assessment of the viability of decentralised renewable energy in the value chains for buckwheat, yak, potato and vegetables (gundruk) in the high-altitude communities of the Hindu Kush Himalayan region (see Box 2). The analysis begins by mapping key entry points across value chains and stakeholders, primary data gathering to understand existing energy flows and opportunities to deploy renewable energy, and cost-benefit analysis to assess the viability of renewables-based solutions. In the buckwheat value chain (Figure 7), for example, renewables-based irrigation pumps, weeding machines, insecticide sprayers, threshers, winnowers and graders are found to be important ways to address energy gaps. The analysis also finds the need for customisation of renewable energy solutions to the mountain context by bringing efficiency and mechanisation to production, processing, quality-assurance and marketing. Relatively short mountain value chains, largely subsistence in nature, can be made more robust by diversifying products and adding value, both of which will translate into

Figure 7. The buckwheat value chain in Nepal



Source: IRENA, SELCO Foundation and ICIMOD. KTM = Kathmandu.

Box 2. Renewable energy to improve agri-food value chains in the Hindu Kush Himalayan region

IRENA, the International Centre for Integrated Mountain Development and SELCO Foundation have partnered to assess energy needs across three agri-food value chains in the Hindu Kush Himalayan region, which encompasses mountain communities in Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal and Pakistan. The analysed value chains are of economic importance across the region. However, due to the difficulty of entering the area during the pandemic, the study relied on primary data collected from Bhutan and Nepal. The value chains included in the analysis are:

- **Buckwheat**, a very common crop in the region, is grown primarily for human consumption. It is a short-season crop and does well on low-fertility or acidic soils. In Nepal, buckwheat is counted as the sixth staple food crop; in Bhutan, over 70% of the marginal farmers depend on it.
- **Yak** is the main animal source of livelihood for high-altitude populations, particularly those where climate and terrain make farming difficult. Yaks provide milk, fibre, meat, and associated by-products.
- **Potato** is widely grown across the region, mainly in hilly areas at relatively lower altitudes. Particularly in Nepal and Bhutan, potatoes are grown as a short-duration crop offering high yields in cool climates. They are well suited to the production of seed tubers for sale at lower altitudes.
- **Vegetables** are commonly grown across the region both for subsistence and for selling. Leafy vegetables, particularly fermented and sun-dried (gundruk), are highly popular food in Nepal.

Across each value chain, the analysis identifies decentralised renewable energy applications to improve energy access, reduce losses and drudgery, and raise incomes. A preliminary cost-benefit analysis has been undertaken to assess the viability of various solutions. Some of the most viable, according to the assessment, include renewables-based weeding, threshing and winnowing machines (buckwheat), cold storage (yak milk, potatoes and vegetables), pumped and drip irrigation systems (potatoes and vegetables), and butter churners and cream separators (yak milk).

Source: IRENA, SELCO Foundation and ICIMOD Viability Assessment of Decentralised Renewable Energy Solutions in Food Value Chains in Hindukush-Himalayan Region.

increased energy demand. Delivering renewables-based solutions will require a three-pronged lens of technology, cash-flow based financial models and business cases that are aligned with existing social capital and ownership structures.

3.2 Integrated food-energy systems

Scaling up the use of renewable energy in alignment with international and national goals on climate change and sustainable development will have implications for land use. The land intensity of energy technologies vary. Both quantitative aspects (*e.g.* area required per installed capacity) and qualitative aspects (*e.g.* duration of impact, changes to land quality) across the energy entire life cycle (extraction and processing, installation, production and decommissioning) must be considered (IRENA, 2015). While the long-term qualitative impact on land of certain renewable technologies, such as solar photovoltaic (solar PV) and wind, is limited, increased deployment may conceivably compete with other uses (and end users) in certain contexts. Integrated food-energy systems address this problem by combining the production of renewable energy and food.

With respect to bioenergy, integration can be achieved in two ways (Table 2):

- By optimising land use through cropping systems that integrate energy and food crops (*e.g.* agro-forestry systems where trees are used for bioenergy, agri-voltaic systems)

- By optimising the use of biomass by employing by-products or residues of food or energy production as inputs in the production process of other outputs (*e.g.* biogas from manure).

A third type of integrated food-energy system is not based on bioenergy but agri-voltaics, or the combinations of agriculture and the generation of solar power. Solar technologies offer opportunities for mixed, multi-purpose land use. Globally, over 2.8 GW of agri-voltaics have been installed (Fraunhofer ISE, n.d.-a). In general, ground-mounted solar PV, when deployed in areas with high insolation, requires less land than surface-mined coal.[5]

Increasingly, special structures are being deployed involving rows of PV panels mounted above ground and arranged at intervals wide enough to admit plenty of sunlight for photosynthesis and leave space for agricultural machinery (though it also makes cleaning the panels more difficult). The layout of an agri-voltaics plant dictates its effectiveness in terms of electricity generation and crop cultivation (NSEFI, 2020). In Mali and the Gambia, a multi-year agri-voltaic programme has been launched to test the techno-economic viability of integrated food-energy-water systems through four demonstration projects (Fraunhofer ISE, n.d.-b). In Chile, pilot projects have also been realised in Curacaví to investigate the impact of agri-voltaics on crops in arid areas with high solar radiation (Weselek *et al.*, 2019).

In Japan, the concept of co-production of food and energy (known as “solar sharing”) was first developed in 2004. In 2019, some 1 900 agri-voltaic projects were operating across Japan, with the major crops being mioga ginger, Japanese cleyera, paddy rice, mushrooms and blueberries. In Germany, the production of potatoes under agri-voltaic conditions decreased overall yield by up to 18%; however, the share of tubers with a large diameter (35-50 mm) increased, raising the marketable yield. Land-use efficiency improved between 60% and 90%, suggesting significant potential in land-scarce regions. Given its shading feature, agri-volatic has also significant potential with shade tolerant/loving crops in arid or semi-arid zones.

[5] The land used by onshore wind is higher in terms of total area. But, as with solar PV, most of the land on a windfarm can be put to other uses.

Table 2. Examples of integrated food energy systems

Example	Brief description	Notes
Type 1: Integrated food-energy systems that optimise land use		
Intercropping pigeon peas with maize on the same field (Mozambique)	Integration of drought-resistant pigeon peas in maize fields increases resilience and profitability in smallholder systems by allowing the simultaneous production of food (pods), fodder (leaves), fuel (wood) and fertiliser (nitrogen fixation from pigeon peas).	Intercropping pigeon peas with maize is a low- risk, low-input integrated food-energy system with a self-reinforcing and synergistic positive effect on the availability, accessibility and security of food, fodder, fuel and green fertiliser. It is climate-smart in that (i) it reduces the need to collect wood for cooking through the use of pigeon pea trunks,: thus reducing forest degradation; and (ii) the pigeon pea, a perennial crop, stores carbon. This integrated food-energy system has a high potential for country-wide replication among small-scale farmers. Agreements between exporting and importing countries ensure a secure market for pigeon peas. One example is the agreement between Mozambique (exporter) and India (importer).
Jatropha boundary planting around smallholder food crop fields (Mozambique)	Integration of a non-edible energy crop (*Jatropha curcas*) as live fencing protects food crops from free roaming animals and increases food security in smallholder farming systems. Furthermore, the oil from jatropha fruits, pure or blended with petroleum, can be used to fuel engines in locations not serviced by the national grid. For example, jatropha provided energy to a teacher training centre in Bilibiza before the grid reached the town. A Mozambican company produces jatropha-based fuel to power maize mills for higher quality maize flour production in remote areas. Detoxified seedcake from the processing of jatropha oil can be used as bio-fertiliser.	The commercial potential lies in (i) the possibility of selling jatropha seeds to biodiesel plants and (ii) the production of soap from jatropha oil after removing undesirable compounds from the seedcake through a combination of solar irradiation and ozonation. The soap has a guaranteed local market and, if made in sufficiently high quality, has a niche market for export. This integrated system is climate-smart because the production and use of biodiesel reduce the need for fossil fuel.
Type 2: Integrated food-energy systems that optimise biomass use		
Palm oil processing utilising oil palm residues for thermal energy generation (Ghana)	Use of unused crude palm oil processing by-products (fibre and palm kernel shells) as fuel generates thermal energy for processing activities. Industrial processors use fibre and palm kernel shells to fuel a furnace that produces steam (i) to sterilise fresh fruit and (ii) to power turbines that generate the electricity needed in factory offices and to run the processing machinery. Artisanal processors utilise fibre or fibre-kernel pastes as their sole fuel for boiling operations during processing.	The prospects for this integrated food-energy systems are as follows: In semi-intensive systems: palm kernel shells can be used in a top-lit, updraft micro-gasifier stove for home cooking. In artisanal systems, empty palm bunches can be used for boiling in the oil processing chain. The stove tested by the ASA Initiative produces a charred residue (a by-product of burning the oil palm biomass) that can be used as bio-fertiliser.
An integrated greenhouse system (China)	A pigsty and a biogas digester fuelled by pig dung come together to provide lighting, heat and organic manure (*i.e.* fermented waste) for a vegetable greenhouse.	The use of pig manure to produce biogas reduces methane emission from manure and supports vegetable production.

Source: FAO, 2018d.

In the South-Western United States, three common plants (chiltepin pepper, jalapeño and cherry tomato), representative of three different dryland environments, were planted beneath PV panels. During the three-month growing season, light levels, air temperatures and relative humidity were monitored. While impacts varied by plant type, agri-voltaic systems showed promise (NREL, 2019; Barron-Gafford *et al.*, 2019). Chiltepin fruit production was three times greater in the agri-voltaic system compared with the baseline. Cherry tomato production doubled. Water-use efficiency for the jalapeño was 157% higher in agri-voltaic system and 65% greater for cherry tomato. Soil moisture remained up to 15% higher due to reduction in direct sunlight exposure beneath agri-voltaic panels. Agri-voltaic panels were about 9°C cooler during the daytime, yielding better performance compared with traditional arrays.

The trade-off between the extra costs imposed by the agricultural activities carried out below the solar panels and the additional revenue from those activities has yet to be thoroughly quantified. The major constraints for developers so far are the cost of erecting and cleaning elevated panels. Dedicated policies will also be needed to accelerate the adoption of agri-voltaic systems. In India, the KUSUM (Kisan Urja Suraksha Utthan Mahabhiyan) scheme foresees the installation of agri-voltaic systems with a capacity ranging from 500 kW to 2 MW for simultaneous electricity generation and cash-crop production (PIB, 2021). To scale-up adoption, policy measures are needed to facilitate pilot projects, introduce appropriate land-use classification, improve technical norms and quality standards, and tailor financial incentives to the cost structures of agri-voltaic systems (NSEFI, 2020).

3.3 Selected renewable energy applications in agri-food systems

Renewable energy applications are emerging across the agri-food systems. This section provides an in-depth analysis of four examples – solar pumping for irrigation, cold storage, agro-processing and sustainable bioenergy – that have experienced growth in adoption in recent years. For each application, the status of adoption is discussed, along with delivery and financing models being used to accelerate deployment. The analysis also presents key enablers of accelerated growth.

Solar pumping for irrigation

Rainfed agriculture provides the largest share of global food production. In Sub-Saharan Africa, more than 80% of cropland is low-input rainfed production, while only 3% of land is irrigated (FAO, 2020b). Farmers, particularly smallholders, have limited influence on the amount and timing of water made available to crops. When rain does not come, farmers either resort to manual means of crop irrigation or fossil fuel powered pumps – leaving them overburdened physically and financially (GOGLA, 2019). Meanwhile, climate change is disrupting rainfall patterns. More frequent droughts and water shortages pose significant risks to livelihoods and food security, particularly of the most vulnerable populations in the least developed parts of the world.

Combined with measures to improve water harvesting and conservation,[6] irrigation can improve yields, reduce vulnerability to changing rainfall patterns and enable multiple cropping practices. Solar-powered irrigation, in particular, offers the opportunity to meet energy needs for water pumping in a decentralised

[6] Improved managed of rainwater in rainfed systems can play an important role in enchaning water access, while also tackling challenges associated with excessive runoff and soil erosion. Even in water-constrained areas, there is usually sufficient rainfall quadruple yields in some cases but rquire investments to maximise rainfall infiltration and the water-holding capacity of soils (IWMI, 2010; IWMI, n.d.)

and environmentally friendly manner (IRENA, 2016b). In fact, energy-efficient and affordable solar water pumps have the potential to improve the lives of many of the more than 500 million smallholder farmers worldwide (Efficiency for Access, 2019). Moreover, solar-based irrigation provides a clean and cost-effective alternative to fossil fuels (FAO and GIZ, 2018).

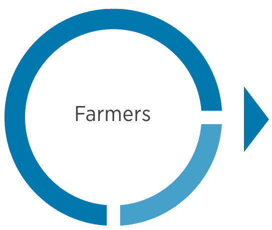
Policies and programmes to promote solar irrigation must adopt a cross-sectoral "nexus approach". Why? Because the risk of groundwater depletion exists regardless of the energy source (FAO and GIZ, 2018), and the low operational costs of solar irrigation pumps may contribute to over-extraction under specific conditions (GOGLA, 2020; IWMI, 2020). To address this risk, tools and measures such as sales of extra energy to the national grid through feed-in tariffs, are being deployed and adopted to ensure expansion of irrigation services through renewables, while also guaranteeing sound management of surface and groundwater.

Status and potential of solar-powered irrigation

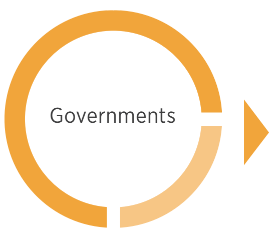
Solar-powered irrigation has been practised since the 1970s (FAO and GIZ, 2018). With recent improvements in efficiency and innovations in delivery and financing models, its attractiveness has grown – and so has deployment. In Asia, India has led the field with the deployment of over 272 000 systems as of December 2020 (MNRE, 2021a). In Bangladesh, some 1 500 systems have been deployed, with a target of reaching 10 000 by 2027 (IDCOL, n.d.). In 2019 and 2020, over 40 000 solar water pumps were sold, primarily in India and East Africa (chiefly Kenya, Uganda and Senegal) (GOGLA, 2021).

The technical potential for solar water pumps on smallholder farms (less than 1 hectare) is at least 130 million across West, Central and East Africa, and 33 million units in South Asia (GOGLA, 2020). In Sub-Saharan Africa, irrigated areas are expected to more than double by 2050, benefiting millions of small farmers (FAO, 2020b). And those figures do not include the opportunity of solar water pumps to replace existing diesel-fuelled or grid-connected pumps.

Figure 8. Benefits of solar pumping solutions for farmers and governments



- Supply of energy and improved access to water for irrigation
- Improved crop yields and increased incomes
- Reduced manual work and improved expenditure of time
- Enhanced crop resilience and food security
- More income generating opportunities by complementing staple foods with high-value crops
- Additional benefits for health, education and poverty alleviation



- Reduction in electricity and fuel use
- Subsidy savings
- Reduced fuel imports
- Creation of small businesses/employment across the value chain
- Improved reliability of power systems
- Increased agricultural economic output
- Emissions reductions

Source: IRENA, 2016b.

Box 3. Solar-powered irrigation in Rwanda

The Rulindo district of Rwanda is known for growing crops such as cassava, maize and beans, with most water needs being met from the Yanze River. Traditionally, farmers have irrigated using manual treadle pumps, which require at least three people to peddle.

The FAO, through the Knowing Water Better (KnoWat) project – solar-powered irrigation systems have been deployed to increase efficiency, reduce manual labour and support livelihoods in the district. Three portable solar pumps were delivered to farmers belonging to the Yanze vegetable growers' co-operative. The 500 W systems supply 40 litres of water per minute, irrigating fields more than four kilometres from the water source (a dam), and dramatically reduce manual labour, freeing up time and raising farm productivity.

Source: FAO (2021a).

The drivers of solar-based irrigation solutions are multi-fold and vary for different stakeholders and contexts (Figure 8). Farmers dependent on increasingly erratic rainfall patterns or fossil fuel–based pumping options see improved yields, incomes and resilience, while they and the larger community share the benefits of environmental sustainability and greater food security (IRENA, 2016b). In India, nearly half of the farmers using solar pumps reported an increase of 50% or more in their annual incomes compared with rain-fed irrigation (GOGLA, 2019). In Rwanda, smallholder farmers adopting solar irrigation pumps improved their yields by about a third higher. Many were able to grow crops in the dry season for the first time (Energy4Impact, 2021a). Significant differences in profitability emerge depending on the type of crops grown and the seasons of cultivation. For example, revenues generated from staple crops, such as maize and beans (USD 130 to 270 per hectare), was lower than revenues from cash crops such as watermelons, green beans and chili peppers (USD 1 500 to 4 000 per hectare) (Energy4Impact, 2021). Solar irrigation also reduced manual labour and drudgery (Box 3).

Payback periods vary. In Tanzania, solar irrigation systems are seen to have a payback period of around 2.6 years, without accounting for environmental benefits (Elico Foundation, 2020). In Rwanda, they are estimated to be between six months and three years depending on the crops grown and number of crop cycles (Energy4Impact, 2021a). In Chile, solar irrigation pumps to meet rising water needs for wine production during the dry period led to savings of up to USD 40 000 per year with a payback period of less than three years (Lorentz, 2012).

Socio-economic development objectives are strengthened as farmer incomes grow, and subsidies for electricity or fuels drop. Some countries are also promoting solar irrigation within the framework of national action plans on climate change as a way to reduce emissions and improve resilience within the agri-food sector. Bangladesh's NDC, for example, identifies solar irrigation as a key mitigation measure (UNFCCC, 2021). Life-cycle emissions for solar-powered water pumping (in CO_2 equivalent per kWh) are estimated to be of 95% to 98% lower than for pumps operated with grid electricity and diesel pumps (GIZ, 2016a).

Delivery and financing models

The delivery and financing model is a key determinant of how accessible solar pumping technologies can be for various types of farmers (subsistence, smallholder, commercial). The high upfront capital cost of solar pumps (compared with that of diesel or petrol pumps) is known to be a key barrier to adoption.[7] Because most subsistence and smallholder farmers have constrained cash flows that are closely linked to cropping seasons, they have little to invest in capital-intensive technologies in the absence of special financing programmes. Commercial and large-scale farmers may be more equipped economically to afford solar-based irrigation methods and are more likely to own a dedicated water extraction and pumping system (*e.g,.* borewells).

A suitable delivery model should reflect local irrigation practices and needs. Multiple approaches are often needed to cater to different market segments. As an example, average farm sizes and irrigation practices vary widely. Smallholder farms in Bangladesh and Viet Nam average 0.24 and 0.32 hectares, respectively, compared with 0.47, 0.9 and 5 hectares in Kenya, Ethiopia and Nicaragua (FAO, 2015a). In general, farms in Asia are irrigated, while African agriculture is dominantly rain-fed. As a result, various irrigation models have emerged, ranging from community-, government- and farmer-led approaches (World Bank, 2020).

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7 The uptake of solar irrigation relies heavily on water access (e.g. borehole, river, dam, well) which requires careful assessment especially under a scenario of large-scale adoption. Tapping into groundwater may require additional spending on borehole digging, which may be too costly for farmers, thus requiring targeted support within irrigation programmes (Mercy Corps, 2020).

Smallholder farmers often organise themselves into co-operatives to procure necessary systems or secure water-as-a-service from farms within the vicinity or from mobile pump operators. The evidence from Zimbabwe, Benin and India (Tiwary, 2012) demonstrates that community models have been effective. But a scale-up by way of such an approach will require a careful examination of socio-cultural norms; existing water user associations, ownership, operation and management; and the prevailing financing system (Mitra *et al.*, 2014).

Small-scale farmers are often enthusiastic participants in the irrigation service market, since many have surplus pump capacity and are under pressure to recover investments by earning additional income. In some cases, entrepreneurs are procuring systems on an annual lease – as in the case of the salt pan workers in Kutch, India – and delivering irrigation services (IRENA, 2016b). Such a service market need not be monopolistic; several small entrepreneurs working in the same area can compete to ensure competitive pricing, as well as provide quality services.

However, the different scales of farming and existing irrigation practices (grid-connected, fuel-based and rainfed) need to be considered. The competitiveness of solar irrigation can vary, as farmers with smaller landholdings may choose smaller, less capital-intensive options, such as petrol- or diesel-based pumps, or may opt to pay for irrigation services (SNV, 2014).

Reflecting the variety in local conditions, solar irrigation solutions are being deployed through several different delivery models.

A key element of those involving direct ownership of irrigation pumps is making the systems affordable for farmers. Individual solar pumps can be up to ten times more capital-intensive than conventional pumps of a similar size, although life-cycle costs are likely to be lower (CEEW, 2018). In Rwanda, for example, the optimum solution costs around USD 2 000 for four farmers, compared to annual earnings of between USD 600 and 750 for a typical smallholder farmer with a 0.5 hectare holding (Energy4Impact, 2021a).

Therefore, a combination of financial instruments, including grants and concessional loans, is needed to address the initial capital cost requirements. In India, for example, under the PM-KUSUM (Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan) Scheme, which aims to solarise pumps for more than 3.5 million farmers, grants are available to cover up to 80% of a standalone solar irrigation system (Government of India, n.d.). In Nepal, the renewable energy subsidy policy includes a provision for 60% subsidy for irrigation pumps (AEPC, 2016). These subsidies may be economically justified in some cases based on the benefits associated with reduced fossil fuel subsidies and saved generation capacity – and on their immediate effect on deployment. However, they can and should be designed to be smarter and more results-based to ensure cost-effectiveness, quality and after-sale service, and to consider the water-energy-food nexus (IRENA, 2016b). When markets are reasonably large, public procurement programmes for solar pumping systems can reduce costs by tapping into economies of scale and ensuring timely delivery and sustainable operation. The International Solar Alliance, for example, led the price discovery for a project for 272 000 solar pumps by aggregating demand from 22 countries, reducing prices by half (Bhaskar, 2019).

A grant-only approach, however, often poses problems for sustainable market development. If end users must bear the cost not covered by the grant, a financing element may have to be built in for inclusiveness. Capital subsidies must often be complemented by enhanced access to credit, as in Bangladesh.

In Bangladesh, the Infrastructure Development Company Limited (IDCOL) has facilitated the deployment of over 1,515 solar irrigation pumps as of March 2021, with an installed capacity of around 40 MWp (IDCOL, n.d.). The target is 10 000 pumps by 2025. IDCOL uses both the ownership and fee-for-service models. Under the former, a combination of grant and debt is offered to farmers through a network of partner organisations. The grant component is usually 50%, followed by collateralised debt (35%) offered on ten-year terms with a two-year grace period (IDCOL, 2020).

As awareness of benefits among farmers improves and the cost of system deployment falls, the need for subsidies is likely to drop, thus ensuring more equitable access to systems for poorer farmers (Energy4Impact, 2021a). In East Africa, the pay-as-you-go ecosystem offers farmers payment plans to acquire solar irrigation systems. In Kenya, "pay-as-you-grow" models adapted to farmers' income cycles are being deployed to improve accessibility and affordability (EEP Africa, 2021). With systems as small as 75 to 370 Watt peak (Wp) being marketed primarily in Sub-Saharan Africa, the pay-as-you-go model offers advantages in the absence of other end-user support (IFC, 2020). However, ownership-oriented models are not always suitable, particularly for more marginalised farmers whose landholding patterns and income streams may not be sufficient to allow them to invest in solar irrigation.

An alternative has been the water-as-a-service model. In Tanzania, ELICO Foundation and Mott Foundation, is pioneering the use of water-as-a-service model whereby farmers pay for irrigation services (Elico Foundation, 2020). In Bangladesh, majority of the pumps deployed have been under a "fee-for-service" model serving multiple farmers, making it possible to build a larger system – typically around 25 kWp. The project sponsor receives grants and concessional loans, enabling it to sell irrigation services to farmers for a per-hectare fee (IFC, 2020). Such support can be supplemented with incentives, such as tax exemptions, to lower the installed system costs still further. Country experience demonstrates that while each of these instruments has advantages and shortcomings, a combination can be effective in meeting deployment and development goals.

Solar irrigation pumps tend to be used only during the growing season. Incentivising multiple uses for pumps can improve overall economics while meeting a wider range of socio-economic development objectives. In India, under the PM-KUSUM scheme, the government is promoting grid-connected agricultural pumps by offering a performance-based incentive for pump-generated electricity exported to the grid by farmers (Government of India, n.d.). In Bangladesh, excess electricity generated by pumps is used for agricultural mechanisation, including husking machines, threshing machines, cold storage, and aquaculture (IDCOL, 2020).

Promoting adoption on a wider scale

The benefits of solar irrigation are well established in a growing number of contexts, representing a cost-effective and environmentally sustainable option to expand and energise irrigation infrastructure. However, several steps are needed to scale up adoption, maximise benefits and ensure sustainability from the perspective of the water-energy-food nexus. These include actions to improve distribution channels, forward market linkages, financing, awareness and capacity. Careful attention to the nexus and an integrated approach to programme design are also needed. Each of these is considered in turn.

Distribution channels are necessary to deliver solar irrigation in rural areas and provide maintenance to ensure long-term operation. Establishing a distribution network depends on partnering with local farmer organisations and enterprises – and on building local skills so as to minimise response times and provide maintenance, if needed, locally.

Solar irrigation solutions are not a panacea for agri-food system transformation, but rather fit into a broader portfolio of solutions to improve water supply and management for crop and livestock production which in turn contribute to enhanced yields, resilience and incomes so long as market linkages exist. Forward market linkages[8] are important for farmers to derive full benefits from solar irrigation solutions. Increased yields and the capacity to diversify agri-produce enable farmers to raise their income, in turn enhancing the economic case for investments in solutions such as solar irrigation pumps.

To raise incomes, partnerships with off-takers need to be strengthened, particularly for subsistence farmers. In Tanzania, the ELICO Foundation, in partnership with the Mott Foundation, has engaged with suppliers of agricultural inputs and extension services, as well as companies that source fresh organic vegetables and green beans, to improve market linkages for smallholder farmers adopting solar irrigation (Elico Foundation, 2020). Over time, off-takers can also take on the important role of pre-funding inputs and contributing to the capital costs of solar irrigation systems.

But affordability will remain a problem, given the high upfront capital costs involved. A combination of end-user financing, such as grants, long-term credit, and tax exemptions, can help make systems more affordable. Depending on local contexts, these can be integrated into existing rural financing networks and community organisations (*e.g.* co-operatives).

Capital subsidies in early stages of market development, when affordability is constrained and the ecosystem for access to debt financing is not fully mature, should be carefully set to increase affordability, while also providing adequate incentives for technology innovation, cost reduction and long-term market development. How subsidies are disbursed is important; slow delivery or low accessibility increases transaction costs and creates liquidity issues among distributors (Energy4Impact, 2021a).

Engaging local financing institutions is a crucial part of unlocking financing. Those with a history of agricultural lending can be encouraged to develop tailored loan products for solar irrigation systems, with the equipment held as collateral. First-loss risk guarantees during early stage of market development can also provide lending institutions the comfort they need to increase exposure to the sector on favourable terms for farmers (GIZ, 2020). There is also a cultural dimension. In some communities, farmers may prefer to borrow from family and friends (Energy4Impact, 2021a).

Public financing is also necessary to build an enabling ecosystem for solar irrigation. In Rwanda, for example, the government has offered financial support for inputs and agronomic training (Energy4Impact, 2021a).

[8] Strengthening market linkages entails physical infrastructure investment to support on-farm production (irrigation, energy, transportation, pre- and post-harvest storage), efficient trading and exchange (telecommunications, covered markets), value addition (agro-processing and packaging facilities), and improved transportation and bulk storage. Technologies that facilitate farmers' access to local information about weather, water consumption, diseases, yield, and input and output prices also need to be facilitated (Ringler *et al.*, 2021).

Enterprise financing for suppliers and distributors must be strengthened. Access to debt remains limited, and although positive steps have been taken in this direction, such as the recent syndicated debt facility for SunCulture (EEP, 2021), greater efforts are needed to unlock local enterprise financing. Crowdfunding has also been a relevant source of fund-raising for enterprises. Futurepump, a manufacturer of solar irrigation pumps for smallholder farmers, raised over USD 1 million from 1,200 investors in a matter of weeks (IWMI, 2021).

In several markets where substantial financial support has been proposed for solar pumping uptake has been slow owing to reluctance to embrace new technologies in general. A key component to developing the market for solar pumping in rural areas is to raise awareness and demonstrate the viability and reliability of the technology. Awareness raising should target multiple stakeholders, ideally starting with demonstration sites, followed by small meetings with farmers, larger education events, and radio shows (Energy4Impact, 2021a). In addition, it is essential to consider capacity building to ensure long-term operability, and to target the various stakeholders that cover the entire value chain, from policy and programme formulation to design and installation of solar and complementary technologies, as well as financing, operation and maintenance.

To ensure attention to the water-energy-food nexus, financial support can be linked with preconditions, such as the use of drip irrigation, but such preconditions in the absence of a holistic approach may also undermine the ability of farmers to access solar pumping technology.[9] Several programmes and initiatives are taking measures to reduce the risks posed by solar irrigation pumping systems. These range from linking energy with water-conservation techniques (*e.g.* drip irrigation), to adaptations in delivery models (*e.g.* selling excess generation to the grid at a premium tariff), and utilisation of remote systems to monitor behavioural changes resulting from the switch to solar-based irrigation (FAO and GIZ, 2018).

Given their cross-sectoral nature, solar pumping programmes should include the three sectors of water, energy and agriculture to ensure that potential trade-offs are managed, particularly related to groundwater sustainability as adoption grows (Efficiency for Access and IWMI, 2021). An integrated assessment of unmet demand for water and energy near agricultural lands would be useful when designing systems so as to maximise socio-economic development (IRENA, 2016b). For example, solar pumps can act as anchor loads, encouraging investments in access to electricity for surrounding communities. Moreover, for rural smallholders who most lack water and food security, irrigation design should consider the multiple uses of water (Ringler *et al.*, 2021).

When effectively designed and implemented, solar-powered irrigation programmes have the potential to contribute to multiple Sustainable Development Goals.

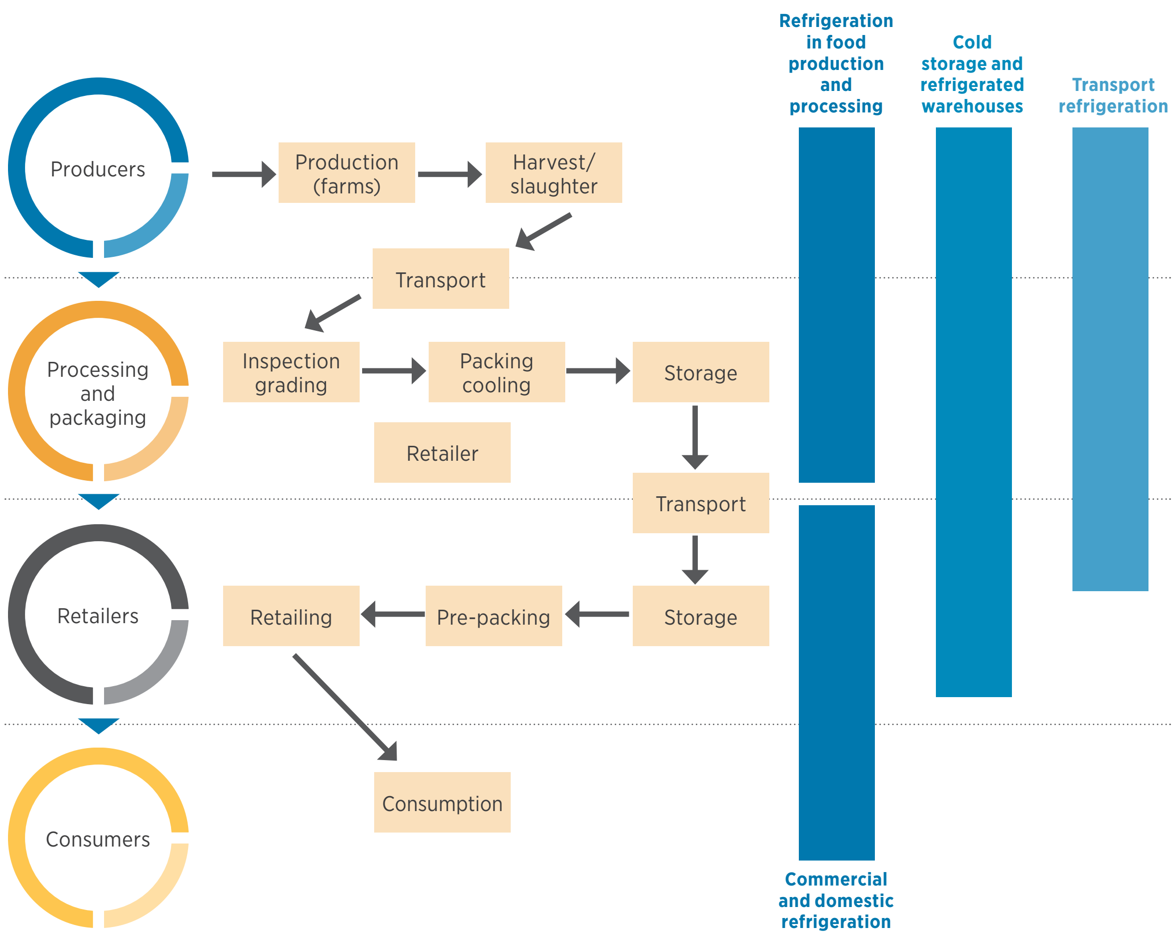
[9] Shifting to drip irrigation, in particular for smallholders, requires a substantial behavioral change. Drip systems are often expensive and difficult to manage, requiring advanced skills. In addition, overpumping and salinity may actually reduce efficiency if the drip network is not adequately cleaned and maintained. Therefore, the technology should be customised to adapt to local conditions, especially with respect to capacity building across the value chain. Drip irrigation, while increasing the efficiency of water and energy use, may also increase overall consumption owing to the expansion or irrigated areas or increases in the intensity of cropping and irrigation.

Renewables-based cold storage

Cold storage and refrigeration are needed at each stage of the agri-food chain to increase shelf life, cut losses, and maintain the quality of products made from crops, livestock and fisheries (Figure 9). The cold chain also makes it possible to expand markets beyond local buyers, raising incomes for farmers, processors, distributors and retailers (USAID, 2020).

While agri-food chains exist in all countries, they differ in their technological development. For example, at the distribution and retail stage of the agri-food chain, less-developed countries often store food in rudimentary rooms instead of modern warehouses or cold stores. These differences are evident in the pattern of GHG emissions from the agri-food systems of developing and developed countries. In the latter, the post-harvest stages of value chains are energy intensive and contribute around half of the agri-food system's total emissions. In developing countries, the corresponding share is about a quarter (Crippa *et al.*, 2021). However, as countries develop, their agri-food chains will also advance and employ more modern technologies at each step of the value chain.

Figure 9. Components of the agri-food cold chain



Source: Judith Evans and IIR in Guilpart (2018).

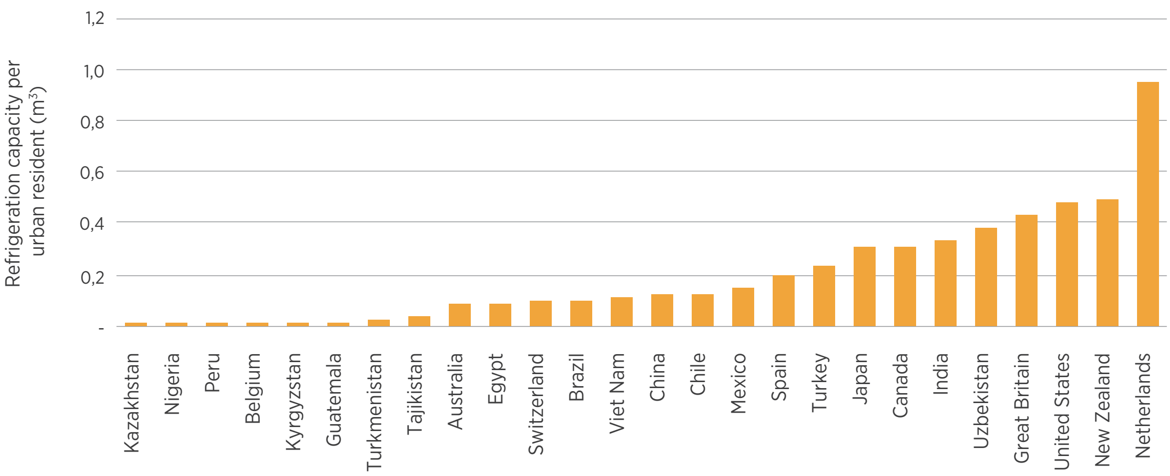
Cold storage is one such technology that is expected to expand. While cold storage is the norm in developed countries, the same cannot be said for developing countries (GIZ, 2016b). How large is the cold storage deficit? Data on cold storage demand and current capacity are scant. However, one estimate of cold storage capacity per urban resident shows great divergence among countries (Figure 10).

A key factor behind the limited availability of cold storage technology in developing countries is the lack of electricity in rural areas where majority of the food is produced. In Sub-Saharan Africa, only about 25% of the rural population had access to electricity in 2019 compared to over 90% in Central and Southern Asia and Latin America.

In the absence of adequate cold storage, the handling, storage and sale of perishable food commodities often takes place entirely outside of temperature-controlled environments, particularly in rural areas. Globally around 14% of food produced is lost between the post-harvest and retails stages of the value chain (FAO, 2020a). Losses disproportionately occur within the "first mile" between harvesting and processing – estimated at 37% of the food products lost in Sub-Saharan Africa (World Bank, 2018). Improving access to refrigeration could prevent spoilage of up to a quarter of the perishable foods currently produced in countries with less-developed cold storage infrastructure (Lange, Priesemann, Geiss and Lambrecht, 2016). Food losses are particularly high in perishable products like fruits, vegetables and dairy due to the lack of proper cold storage (SEforAll, 2021). In Rwanda, for example, more than half of tomatoes are lost along the value chain – the lack of cold storage being a major factor. As shown in Figure 11, globally, losses are highest for roots and tubers as well as fruits, and vegetables, followed by meat, and other animal product.

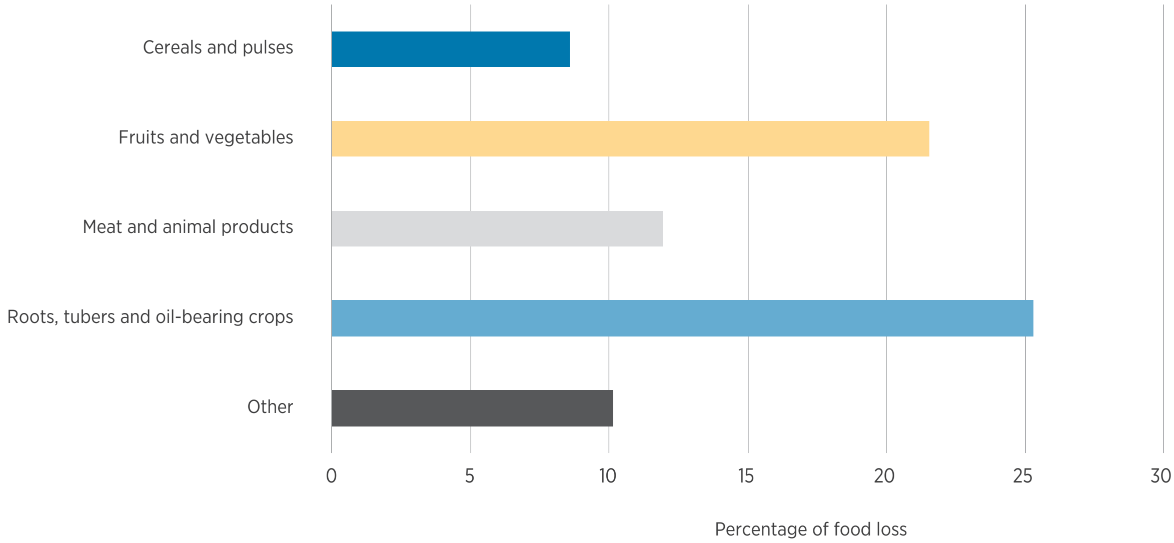
Lack of access to cooling not only means direct economic losses for farmers; it also reduces their negotiating capacity because they are forced to sell their produce soon after harvest, often at a lower cost to avoid loss due to rotting. The availability of optimal storage facilities allows farmers to better time when to sell their crop and thus receive fair prices. The additional storage time also enables consumers to make more informed consumption decisions.

Figure 10. Refrigeration warehouse capacity in selected countries, 2018



Source: GCCA (2018).

Figure 11. Losses from post-harvest to distribution, by food group



Source: FAO (2019b).

Cooling is an energy-intensive process. This presents both a challenge and an opportunity. The cold chain, including industrial and domestic refrigeration, already accounts for 5% of global GHG food-system emissions and its importance in total emissions is likely to increase (Tubiello *et al.*, 2021). If the increase in future cold storage capacity were to come from fossil fuels–based systems, the resulting increase in GHG emissions would further exacerbate climate change. However, advances in renewables-based and efficient cooling systems present an opportunity to expand cold storage capacity in a way that is environmentally sustainable and more accessible, particularly in rural areas.

A cross-section of cold storage technologies

Several cold storage technologies are deployed around the world. These can broadly be divided into three types: 1) passive cooling; 2) ab- and adsorption systems; and 3) compression systems. The three systems vary in the type of energy they require, the scale at which they can operate and the extent to which technical capacity is required to build and operate them. Vapor compression systems and cooling with ice need electricity to operate, while the others do not.

Passive cooling systems are rudimentary systems that often exploit the cooling effect resulting from evaporation of water, in which case they are called evaporative cooling systems. As temperatures rise, water begins to evaporate which absorbs heat from the surrounding air, producing a cooling effect. Given their passive nature, such a system is limited in the amount of cooling they can produce; they work best in semi-arid climates. Even under the best conditions, evaporative cooling is unable to reduce temperatures more than 10-15°C below the ambient temperature.

Evaporative cooling is suitable primarily for fruit and vegetables that need to be stored for a few days after harvest, especially tropical or subtropical crops. It is not suitable for produce requiring low temperatures such as dairy products, fish, or milk. The benefits of the technology are that it does not need access to any form of energy, can be manufactured with locally available materials and requires

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no advanced technical knowledge to construct. It is also the cheapest of all the cooling technologies. The manufacturing cost of the system can vary depending on local labour costs as well as the cost of material. In India, an evaporative cooling chamber with a capacity of 100-200 kg can be built for as little as 1 USD per kg of capacity. In Ghana or Tanzania costs are 4-6 times higher (GIZ, 2016b).

Sorption cooling is a thermally driven cooling system that can work with or without electricity. Thermally driven cooling systems are particularly suitable where sources of thermal energy are readily available. Sorption cooling combines a refrigerant with an absorbent or adsorbent. Under low pressure, the refrigerant evaporates at ambient temperatures, absorbing heat and creating a cooling effect. Once evaporated, the gaseous refrigerant interacts with the ad- or absorbent, reducing pressure in the evaporator, causing further evaporation of the refrigerant and producing higher cooling.

Sorption cooling systems can produce high levels of cooling similar to those of compression systems. They can be installed where waste heat is available or where heat can be generated using other thermal processes. Thermal energy from solar energy systems (both parabolic and evacuated tube) can also be used. They are generally of mid- to large scale. However, they are technically more complex than either evaporative or compression systems.

Sorption cooling systems have higher capital costs than evaporative and compression systems. However, their operating cost is lower than that of compression systems. Adsorption specifically is still expensive compared with conventional technologies; it is mainly used for specialist medical refrigeration applications (GIZ, 2016b). But an absorption solar refrigerator (Bisolar Tech Fridge) deployed in Cameroon prevented losses of up to 50% for local food products, including onions and tomatoes (SEforAll, 2021).

Compression cold storage is the most widely used cold storage technology. Energy is required to power a mechanical compressor that produces cooling. The technology is mature and can easily be sized for small- to large-scale cooling requirements. Vapor compression cooling systems require less initial investment than sorption systems but have high running costs. Compression cooling can be sized for different uses, including household refrigerators and mobile applications, *e.g.* in trucks or vans. One limitation of compression systems is that they depend on reliable electricity, which rules out many rural areas around the world. However, the growth of distributed renewable energy may change all that judging by their growth over the past five to seven years.

Solar-powered cold stores are constructed around a box the size of a shipping container on which solar panels and compression cooling equipment are installed. To reduce energy use, the walls of the store are well insulated. The cost of solar cold stores depends on size and can range from USD 20 000 to USD 30 000 for 3-5 tonnes of capacity. Biogas plants are also deployed to power cooling infrastructure, particularly in the dairy sector.

A farmer in Africa holding cassava plant harvest. ©Simplice/Shutterstock.com

Box 4. A pay-as-you-go model for cold storage: The case of Kenya

In Kenya, post-harvest losses in horticulture can reach 40% owing to poor aggregation and lack of first-mile cold storage infrastructure. To reduce losses and improve farmer incomes through fair value chains, a private entity (SokoFresh Solutions) has set up cold storage infrastructure in areas with high concentrations of crop cultivation that could benefit from aggregated cold storage.

The initiative began with mango, avocado and French beans, allowing farmers to store produce for a fee of USD 0.2 per kilo, with 1-3 days as the average storage cycle. Market linkages are also facilitated for aggregated produce, allowing buyers to collect products from the cold storage facilities at preferential pricing. Co-operatives and other aggregators can also utilise cold storage for a monthly access fee of USD 800. The objective has been to unlock additional income (up to 30%) for farmers by negotiating through an aggregator and shortening the value chain.

Given the seasonal nature of agriculture, low utilisation rates and the high upfront capital cost of cold storage facilities, the business model for farmers' groups to invest in cold storage is not yet strong enough and tailored financing products are not yet available. In this context, the fee-for-service model is preferred, though it comes with long payback periods (up to eight years) for the enterprises offering such services. Further, building farmers' trust and continuous engagement takes time, requiring enterprises to have access to patient, long-term capital.

A key challenge has been the units' viability in the context of smallholder farming and the lack of aggregators (intermediaries) to ensure optimum use of the assets. In response, several entities have begun to offer cold storage as a service to farmers, while also playing the role of aggregator to negotiate better prices for agri-commodities (Box 4).

In addition to these technologies, there are other ways in which access to cooling can be increased along the agri-food systems. One way is to use ice for cooling, especially when transporting perishables like fish, meat and milk. Solar ice-making machines are useful in scenarios where access to the grid is limited. In Indonesia, for example, the small-scale fishers who make up four-fifths of the nation's fishing force struggle to compete with large industrial fisheries owing to their lack of access to cold chains and large markets (GIZ, 2021). This results in a significant proportion of the catch being dried or lost, both of which entail income loss. To address this, solar-powered efficient cooling technologies were deployed, with each plant producing up to 1.2 tonnes of block ice per day, resulting in savings of some 14 000 litres of diesel per year and associated emissions reductions. Importantly, solar-based cooling systems allow even the most remote regions to develop infrastructure for preserving fresh catches and accessing markets. Furthermore, where organic wastes are available, biogas can be produced and used to generate the electricity need to run a cold store or biogas chiller. In Pakistan, four biogas plants were installed on three farms with around 100 cows each and one community comprising several villagers with smaller cattle holding. Power generated from the biogas plants operated milk chillers, along with other farm equipment (*e.g.* fodder cutters). Interestingly, while farmer paid part of the biogas plant costs, the processor provided the electric generators and milk chillers, along with other incentives, on the condition that farmers continue supplying milk (Wisions, 2014).

Where do we go from here?

The expansion of cold storage facilities is critical for the development of robust agri-food value chains that can reduce food losses, preserve produce quality and widen market access for farmers. To provide the energy to operate such facilities, renewables-based technologies offer several advantages. These include decentralised cold storage capable of reaching smallholder farmers and remote fishing communities, and the power to transition existing infrastructure to more environment-friendly and affordable energy solutions in developing and developed countries alike.

Renewables-powered active cooling and evaporative cooling can be very useful in modernising the agri-food sector where grid electricity is unavailable or unreliable. Obstacles must be overcome, however. Access to affordable finance is a key bottleneck. The fragmented nature of farming activity in developing countries complicates the viability and affordability of cold storage infrastructure. Where clusters of farms or aggregators (*e.g.* co-operatives) are present, sufficient demand can be generated to make decentralised cold storage viable. Most enterprises presently meeting that demand have adopted a services-based model. Given the investment scale and rather long payback periods, however, long-term growth capital is needed to make these technologies more widely available. Banks generally hesitate to finance such systems, as they are deemed to have a high probability of default. Many countries have policies in place to incentivise the uptake of solar PV, but most of the incentives are targeted at utility-level use of PV or home lighting. Few targeted incentives exist for deploying solar PV for productive use in the agri-food chain.

Dedicated policy support for renewables-based food storage and processing systems are needed to accelerate adoption of this low-carbon solution to the pressing need for an effective food system's cold chain.

Renewables-based agro-processing

Processing is an important stage in the agri-food value chain, strongly influencing the capacity of food systems to add value, reduce post-harvest losses and increase socio-economic benefits for farming communities. Improving processing represents a central pillar of the agri-food systems transformation priorities that are high on government and donor agendas (World Bank, 2019). It will require energy.

Agro-processing needs vary depending on the products and enterprises involved, the depth of value chains, and market access. But for small and marginal farmers, some processing must be done to realise the value of their products (SELCO Foundation, 2018). Across Sub-Saharan Africa, for example, communities relying on grains and cassava for their main staple food crop must have access to milling facilities. In East Africa, maize accounts for 75% of the total annual harvest, with smallholder farmers in off-grid areas producing most of it (Efficiency for Access, 2020). Similarly, farmers in regions with significant paddy production often rely on local processing facilities for hulling and polishing, leaving them few opportunities to add value. Many rural communities rely on diesel-powered milling equipment to process staple crops to meet food, and animal and poultry feed needs. Others engage in manual, labour-intensive processing or sell produce to centralised processors, thereby forgoing opportunities to add value themselves.

Fossil fuel-based agro-processing equipment traditionally has had low capital costs (compared with electricity-based equipment) and established distribution and maintenance channels. However, operational costs can be high and volatile due to fluctuations in fuel costs, which are often passed on to farmers. The reliability of such systems can be low and their environmental footprint high. Electric and thermal agro-processing equipment powered by renewable energy, whether standalone systems or mini-grids, offers an increasingly cost-effective alternative, one with the added benefits of reducing environmental impact, promoting the development of decentralised processing infrastructure and reducing labour-intensive processing activities.

Agro-processing facilities powered by mini-grids, particularly micro-hydro or biomass-powered mini-grids, have had a longer track record compared with standalone processing systems. But with innovations in technology design (notably the rising efficiency of direct-current processing equipment) and in delivery and financing models, emerging pilots show a high potential for scalability. A key parameter is to place end users' needs at the centre of the ecosystem. Renewables-based systems must be able to match or exceed the outputs of traditional systems in terms of cost and other benefits.

Talti village in Dhading district in Nepal: a new micro hydropower plant has made it possible to open an agro-processing plant. ©The World Bank

The status and drivers of renewables-based agro-processing

Agro-processing of staple and cash crops is an area of growing interest for governments looking to increase local value creation. Renewables-based solutions, particularly distributed energy technologies, offer the potential to decentralise processing activities to increase incomes of small-scale actors (World Bank, 2019). In Indonesia, 80% of surveyed farmers using solar PV-powered mills saw incomes grow due to value addition (Powering Agriculture, 2020). Milled flour and fruits can be dried and stored for up to one year, particularly for situations when electricity or diesel fuel may not be available.

Although the use of renewables for food processing shows high potential across several value chains, adoption remains at an early stage for specific technologies. In the case of solar-powered grain milling – a key value chain in Sub-Saharan Africa – business models and technologies are still in the pilot phase and not yet deployed at scale. Obstacles associated with high upfront costs, delivery channels and the need to match the output of fossil fuel-based systems remain. That said, the potential for solar mills and threshers is significant – 940 000 units in Sub-Saharan Africa alone (IFC, 2020). Beyond solar milling, specialised applications can also be found in the value chains of oil, poultry, dairy, and coffee.

Linkages between agro-processing activity and renewables-based mini-grids have been more common. Mini-grids are increasingly used to power food processing, including milling, oil-pressing, egg incubation and ice-making. In Sierra Leone, for example, a 250-kW hydro-based mini-grid powers a palm oil pressing plant, which also improves the financial case for the mini-grid buying a third of the electricity generated (Power for All, 2020). The Mae Muk Waterfall micro-hydro project in Myanmar, for example, includes tailored tariffs for enterprises engaged in productive uses, including those involving agro-processing such as rice mills, fruit processing, lime baking and corn thrashers (Vaghela, 2019). In Nepal, micro-hydro plants were initially established for mechanical agro-processing and later energised to power consumptive and productive loads, including local mills (Shakya, 2015). This replaced labour-intensive manual processing, freeing up time and supporting a larger number of income-generating activities.

Geothermal-based energy is also increasingly used to meet thermal and electricity needs for agri-processing (Van Nguyen *et al*, 2015). The Mokai geothermal field in New Zealand, for example, supplies steam from two of its wells to a dairy factory to process more than 250 million litres of milk each year (IRENA, 2019a). Iceland has harnessed its abundant geothermal resources for fish farming and drying, making it among the largest global producers of dried fish. In Kenya, pilot projects have been launched to utilise geothermal heat to pasteurise milk, heat aquaculture ponds and dry grain. Substantial potential also exists in meat and honey processing, and in postharvest crop preservation (IRENA, 2019a).

The delivery and financing models involved in the deployment of renewables to support processing activities are diverse and evolving. A key determinant is the structure of value chains – that is, their scale and distribution, their level of aggregation, and the logistical infrastructure involved.

Many off-grid rural communities lacking access to reliable grid service may have to transport produce over long distances to reach centralised processing sites that are likely to be fossil fuel–based, thus imposing significant costs to farmers. In response, decentralised renewables-based processing is being deployed to reduce transportation costs and enable value addition at the farm- or community-level (Box 5). Such interventions are facilitated through programmes initiated by development organisations in partnership with the private sector and other entities, including farm produce aggregators. These partnerships are playing a crucial role in devising new delivery and financing models, as well as technology improvements.

Demonstration projects are also being supported to create renewables-powered agro-processing hubs in rural areas. In the Kamwenge district of Uganda, a biomass gasification plant produces electricity and heat for agro-processing. Local farmers bring their produce to the hub, where it is sorted, dried and processed. Residues are used as fuel in the hub. The electricity thus produced powers agro-processing and other local economic activities, as well as local households (EEP Africa, 2018). In the Sittilingi Valley in the Indian state of Tamil Nadu, tribal communities that had traditionally practised rain-fed subsistence farming established a producers' organisation – the Sittilingi Organic Farmer's Association – reliable electricity and equipment were needed to create value-added products from millet, pulses and other crops. In partnership with a local foundation, the organisation established a solar-powered food processing centre that includes a flour mill, dal mill, grader/de-stoner, dough mixer, and weighing and packing machines. The organisation pays monthly instalments to the foundation that provided the funds, demonstrating how partnerships can be leveraged to deploy renewable energy for agro-processing (SELCO Foundation, 2018).

Generally, operators have a hard time raising capital for renewables-based agro-processing equipment. There is a strong preference for payments in instalments, either through a pay-as-you-go model, loans or leasing (Efficiency for Access, 2020). Pay-as-you-go models are being tried and tested across Sub-Saharan Africa, including Guinea, Kenya, Uganda and Tanzania (Cooper, 2018). Finding the right business model for operators is critical to optimum utilisation of equipment and recovery of investments. Multi-purpose processing equipment that offers a series of ancillary services can increase reach and improve profitability.

Box 5. Solar-powered milling in Kenya

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Milling is a crucial processing activity for communities relying on grains as staple food crop. Many communities rely on diesel-powered milling equipment which have high operational costs and can be difficult-to-access and unreliable. Renewables-powered offer a cost-effective, low-maintenance and decentralised option, reducing time and labour costs.

In Southern Kenya, a solar-powered mill was installed by an enterprise that produces fruit powders at one of its aggregation sites. A 40-foot mobile processing factory was installed which is powered by a 1.8 kW solar generator and holds a 1.3 kW mill solar mill, a solar dryer, ambulant ventilators, and processing equipment. Local farmers can utilise the processing equipment and increase their revenues by eliminating the cost of delivering their produce to distant commercial centres. The mobile processing factory creates a symbiotic relationship between the enterprise and the farmers, enabling tracing the origin and quality of products and the farmers receive training for better production and a reliable long-term buyer of their produce.

Source: Musinguzi (2021).

From the perspective of sustainable development, it is important to assess not only the financial attractiveness of an investment, but also the associated co-benefits and hidden costs (*e.g.* environmental, social) (FAO, 2019c). In the Philippines, an assessment of rice husk gasification found the solution viable in off-grid areas presently relying on diesel generators and with sufficient husk resources close to the mill sites. Further, small-scale solar-powered rice processing has high potential, particularly in off-grid and island contexts where production quantities are not high (FAO, 2019c).

The way forward

Renewables' potential for agro-processing is evident across many different value chains. However, several problems must be addressed to scale up adoption and maximise socio-economic benefits.

A key barrier is the present stock of processing equipment and the need for **greater technological innovation** to link renewable supply with efficiency improvements in agricultural machinery. Traditional agro-processing equipment, including milling machines, threshers, oil pressing machines and hullers, is relatively inefficient, requiring large systems to power. The energy intensity of many processing plants can be more than 50% higher than necessary because of outdated technologies and low energy efficiency when benchmarked against the best available technologies (FAO, 2015b). Improving energy efficiency through design and equipment changes and making equipment compatible with certain renewable technologies (*e.g.* DC solar power) could bring significant cost savings and improve viability. Prices of agro-processing equipment would drop if suppliers could increase their scale.

Other technology-specific challenges include **maintaining adequate throughput** (in terms of both volume and quality) of solar-based solutions compared with traditional solutions, particularly for milling. Technology must be adapted to local conditions and needs. For example, different types of milling machines may be needed in various regions. Fine flour demanded in East Africa require hammer mills, while coarse, whole grain flour preferred in West Africa require plate mills.

The viability and optimum utilisation of renewables-based agro-processing infrastructure depends crucially on the **degree of aggregation** that can be achieved to make activities viable and the capacity of the systems to meet the throughput expectations in a cost-effective manner vis-à-vis traditional fuels (World Bank, 2019). For example, farmers' co-operatives have been engaged to improve volumes and viability in cassava grating in Côte d'Ivoire. Distance to markets and processing centres can also strongly influence the suitability of agro-processing infrastructure (Khoza *et al.*, 2018).

Forward market linkages must also be established to realise the full benefits of processing for local farmers and micro-enterprises. In the case of dairy, for example, energy interventions offer an opportunity for farmers to produce value-added products from cow's milk, such as yogurt and cheese. However, selling these products requires market access, usually in urban areas. The lack of transport options limits demand for improved dairy products in rural areas (USAID, 2018).

As with solar irrigation, a key barrier to the use of renewables-based agro-processing is the lack of **financing for initial capital costs** (World Bank, 2019). Despite benefits associated with lower operational costs and opportunities to add value and reduce losses, uptake is slow owing to the lack of end-user financing. To address this, innovations in pay-as-you-go and leasing models enable end users to finance their system through periodic payments to development organisations, foundations and, in some cases, private sector intermediaries. Scaling up will depend on unlocking local financing in the form of long-term, concessional credit (*e.g.* five years or more) complemented by instruments such as grants and training, **capacity building** and market access.

Existing distributors and aggregators in the agri-food sector could also play an important role in financing renewables-based agro-processing systems. Targeted debt facilities and other financing options may be required for distributors offering consumer credit to meet working capital needs (Efficiency for Access, 2020).

From the energy user side, renewables-based processing appliances must become more competitive than those powered by fossil fuels. A 2020 study found that the purchase price of solar mills was double that of diesel mills (USD 2 000 vs. USD 1 000) (Energy4Impact, 2020). The monthly expenditure on powering an electric mill is also twice that of a diesel mill for a typical mini-grid tariff in Tanzania unless the operator offers a reduced tariff. Diesel mills also set the standard for operational throughput – the amount of grain milled per hour. But with collaboration and the involvement of national manufacturers to ensure customisation, the throughput of solar energy maize mills in Tanzania was improved by 50%, making them four times more efficient than diesel-powered alternatives (Next Billion, 2020).

Given the nascent stage of development of renewables-based agro-processing solutions, significant efforts are needed to **improve awareness among end users**, from farmers to processing plant operators. Demonstration and pilot projects, better access to data and information on available systems, and informative specifications can help prospective customers assess the viability of competing systems. In the specific case of geothermal energy for agro-processing, high-quality geological data on resource availability and conditions of fluids (*e.g.* temperature, pressure) can be crucial to map and identify overlaps between geothermal resource availability and demand for low-, medium- or high-temperature heat from nearby economic activities. In new and emerging markets, accurate feasibility studies could be supported through public funding or technical assistance programmes. The results of these assessments can also help attract investors or raise debt finance, thereby facilitating the implementation of subsequent phases of a project (IRENA, 2019a).

Sustainable bioenergy

Bioenergy is energy generated from biomass. Produced in solid, liquid or gaseous form through a series of conversion processes or pathways, bioenergy is an important renewable energy resource that can meet needs for electricity, heat and transport fuels within and outside of the agri-food sector.

Each bioenergy pathway comprises various steps from biomass production, collection or harvesting to pre-processing, transport, and conversion to various forms of energy. The number of steps differs depending on the type, location and source of the biomass, the conversion technology, the type of energy carried, and the final energy required (IEA and FAO, 2017). Sourcing of the biomass remains a hurdle that must be cleared to realise the full potential of sustainable bioenergy, with the important exception of feedstock options that are readily available at the processing level and therefore already available for further use.

Biomass sources can be broadly classified into 1) residues and waste from other activities and product streams; 2) forest and agricultural crops; and 3) fast-growing grasses. Forests products (*e.g.*, fuelwood) continue to represent a major source of biomass for energy production, particularly for cooking and heating (IRENA, 2014; IEA and FAO, 2017). Given the significant overlap between areas lacking access to modern energy and those where agriculture is the principal livelihood's means, bioenergy is an important way to meet energy needs for residential and productive end uses, including within the agri-food sector. Given the versatility of its applications, countries have been setting bioenergy targets for their domestic heat, electricity and transport sectors. What needs to be ensured, however, is that biomass resources used as a energy source are available for further use and that production stimulates growth in the agri-food sector, thus minimising the negative impacts and addressing interlinkages.

The capability and capacity to produce bioenergy varies greatly by country and context. An important distinction must be made between traditional, modern and sustainable bioenergy options. Bioenergy continues to play a dominant role in many developing countries' energy mix, primarily through the traditional use of biomass for cooking and space heating, usually with basic and inefficient technology. In setting policy (including towards SDG 7 and targets for climate action), countries must focus on the sustainable[10] part of their bioenergy potential and on the use of efficient technologies that provide economic, environmental and social benefits. This is the type of bioenergy that should be considered within countries' renewable energy mixes and to meet NDCs and climate change efforts.

[10] In light of growing bioenergy demand, the need for sustainable production and use of biomass has gained in importance. Three key concerns are 1) food security; 2) risks that land use resulting from expanded use of bioenergy may increase carbon emissions or reduce biodiversity; and 3) obstacles to the achievement of economic competitiveness and the provision of high quality and affordable energy services (IRENA, IEA Bioenergy and FAO, 2017). To address environmental, social and economic risks, several global, regional and national standards and certification schemes have been introduced.

This section discusses the current status of bioenergy use globally and illustrates the steps required for countries to assess their sustainable bioenergy potential to ensure evidence-based policy making. It also discusses the opportunity of bioenergy use within agri-food chains to meet energy needs.

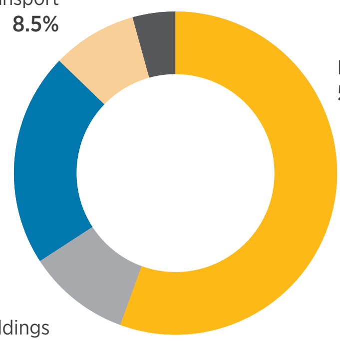
The status and drivers of bioenergy use globally and in agri-food systems

As of 2019, bioenergy accounted for over 11% of the world's final energy consumption (IEA, 2019). Heating represents the largest end-use sector (87%) (Figure 12). Traditional sources, such as firewood, animal waste and traditional charcoal, account for more than half of all bioenergy use. As of 2019, approximately 2.6 billion people still relied on such fuels for cooking, contributing to air pollution and forest degradation (Nyika et.al, 2020). More than 900 million of them lived in Sub-Saharan Africa (IEA, IRENA, UNSD, World Bank and WHO, 2021).

Electricity generation accounts for 4.3% of bioenergy use. Global installed capacity for bioenergy power plants was 127 GW in 2020 (IRENA, 2021b). The sources for electricity generation are solid biofuels at 69%; biogas at 16%, municipal waste at 13%, and liquid biofuels at 2% (IRENA, 2021b). Installed capacity is largest in Europe (42 GW), followed by Asia (41 GW), South America (18 GW) and North America (17 GW). Despite a large potential, Africa's bioenergy-fuelled generation capacity stood at 1.7 GW in 2020. Biofuels for transport, including ethanol and biodiesel, account for 8.5% of the total bioenergy consumption. By 2050, it is estimated that consumption of liquid biofuels will reach 25% of total demand for transport fuels (IRENA, 2021a).

Biomass by-products from agricultural activities can be used to produce energy for processing, storage and cooking. Residues generated from crop production and livestock provide an important source of bioenergy while considering the potential competing end uses (*e.g.* as animal feed) (FAO, 2012). Manure and agro-processing materials can be utilised to produce biogas at different scales and for different purposes, including in buildings for cooking (Box 6) and lighting and in commercial establishments to produce heat, electricity and transport fuel. Bagasse – a waste product from sugarcane processing – is extensively used to generate the heat used in processing, as well as electricity. It is widely used in cane-producing countries such as India, Brazil, Thailand, Philippines and Viet Nam, enabling sugarcane

Figure 12. Share of bioenergy consumption, by end use, 2019



Source: Based on data from IEA, World Energy Balances and Statistics.

mills to approach or achieve energy self-sufficiency for raw sugar production and potentially to generate exportable electricity (Zafar, 2020). In India, over 9.3 GW of bagasse co-generation capacity exists and opportunities to exploit rice residues are being investigated (MNRE, 2021c). Southern Africa offers the potential to expand production of bioenergy from sugarcane in the form of electricity and ethanol (IRENA, 2019b).

In Thailand, the cassava industry uses both solid and liquid wastes to produce biogas and generate power. Biogas power plants operate in various sectors of the economy, including sugarcane, cassava, slaughterhouses, and food processing (IRENA, 2017). In Myanmar, where rice production is an important agricultural activity, rice husks (a by-product of milling) can be used to bridge the energy access gap in rural areas through combustion or gasification, yielding electricity and heat to expand productive activities, including value-added rice products (Minas Mae *et al.*, 2020).

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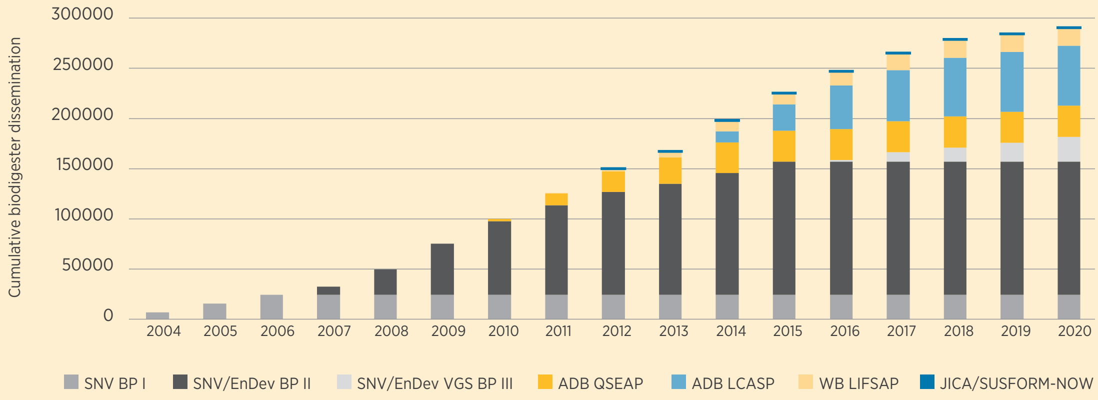
Box 6. Biogas solutions to widen access to energy and manage livestock waste

In areas where food residues or wastes are locally available, biogas can be a solution to provide sustainable fuel source for cooking, heating and electricity production. An estimated 125 million people use biogas for cooking globally – the majority in countries in Asia such as China, Nepal, Viet Nam, India and Bangladesh. In Viet Nam, the Biogas Programme for the Animal Husbandry Sector, combined with several spin-off projects, facilitated the construction of over 290 000 biogas digestors between 2003 and 2020 (Figure 13). Over 204 000 or 70% are still operational to-date, utilising livestock manure to produce biogas for cooking and, in some cases, electricity generation for income generating activities such as egg hatching and production of rice wine and tofu. Bio-slurry is produced as a by-product that can be used as fertiliser. Combined, the biodigesters result help address the waste management problem of Viet Nam's growing livestock population and improve living conditions for over 1.7 million people.

Figure 13. Biodigester installations in Viet Nam, 2003-2020 (cumulative)



Source: SNV.

In Africa, penetration remains low, but production grew 28% between 2015 and 2020. This occurred mostly in Rwanda, Senegal and the five countries covered by the Africa Biogas Partnership Programme (Burkina Faso, Ethiopia, Kenya, Tanzania and Uganda). More than 38 000 biogas digesters were installed across these countries during Phase II of the programme, implemented by Hivos and SNV between 2014 and 2019 with funding from EnDev and the Netherlands Directorate General for International Cooperation.

However, functioning of biogas digesters heavily depends on manure availability and access to comparable amounts of water (comparable to the amounts of manure, the ratio is generically 1:1). For example, the water required is approximately 50 dm^3 day−1 for each cow and 10 dm^3 day−1 for each pig providing manure to the digester and in areas with low water access this can be a key limiting factor. What is not clear is in which cases these constraints can be realistically met. Actual manure availability needs to be closely assessed to ensure that the systems have the required feedstock amounts to run on and to be able to generate the expected amounts of fuel. Maintenance and technical training for operators in the field also needs to be ensured so that systems can run and continue to be operational in the field.

Source: REN 21 Global Status Report 2021; SNV in IRENA (2021 forthcoming); FAO (2021b).

Bioenergy assessments for global and national renewable energy targets

Globally, bioenergy is expected to maintain an important role in energy supply. In fact, achieving the goal of net-zero carbon emissions will not be possible without bioenergy. IRENA's 1.5°C Scenario describes an energy transition pathway aligned with the 1.5°C climate ambition needed to fulfil the Paris Agreement on Climate Change – that is, to limit the globe's average temperature increase by the end of the present century to 1.5°C relative to pre-industrial levels. The pathway prioritises readily available technology solutions, which can be scaled up at the necessary pace to meet the 1.5°C goal.

Under IRENA's 1.5°C Scenario, modern bioenergy – solid biomass, biogas and biomethane, and liquid biofuels – will represent 18% of total final energy consumption in 2050, compared with 1.5% in 2018 (IRENA, 2021a). This will require 153 exajoules of primary biomass supply – a three-fold increase over 2018 levels. To reach this level, it will be necessary to increase sustainable production and use of biomass across the energy system without causing social, environmental or economic harm.

Countries still must define how they will implement their policies on climate, energy and the environment. Too many policies in too many countries contain targets set prior to any assessment of the types and amounts of bioenergy that can be sustainably produced. Countries need to identify how specifically and through which exact type and bioenergy supply chain they intend to meet the bioenergy components of their renewable energy target. To enable countries to transition to more sustainable pathways and define how and to what extent national targets can be met, accurate country-level assessments of bioenergy potential must be carried out. Without them, few countries are likely to be able to source the feedstock they need locally and to succeed in producing the targeted amount of sustainable bioenergy.

Using Zambia as an example, Box 7 presents the steps required to assess the national potential for sustainable bioenergy and the degree to which bioenergy can contribute to renewable energy targets.

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Box 7. Setting bioenergy strategies and meeting energy targets: Sustainable options for Zambia

Zambia is a large, sparsely populated, landlocked country rich in resources. Its economy relies heavily on agriculture and copper. Rainfall variability remains a key risk for the country's growth, affecting both agriculture and electricity generation. The country needs climate-smart solutions, such as renewable energy in various forms, to underpin long-term growth (World Bank, 2021). Agricultural growth has the potential to bring about much-needed multiplier effects on poverty and incomes.

The major source of energy in Zambia is biomass (79%), followed by hydropower (9%), imported petroleum products (9%) and coal (2%). Households are the largest users of biomass (75%), predominantly in traditional forms used for cooking and heating. Rates of access to modern forms of energy remain low – 31% for electricity and 17% for clean cooking in 2019a, with much lower rates in rural areas. The lack of access impedes socio-economic development.

The country has abundant biomass sources, including woodlands, forests, food residues and livestock waste. Forests are an important natural resource for Zambia, covering 66% of the country's total land area, but coverage has fallen over the years at a considerable pace because of forest clearing for farms and fuelwood production. The agri-food sector is dominated by small-scale farmers and productivity remains low (MoFL and CSO, 2019). A wide range of crops are produced, the most important being maize, cassava and sugarcane. Livestock – cattle, poultry, swine and goats – are widely spread throughout the country.

The government has enacted a series of policies to improve energy access. The most pertinent are the National Energy Policy (NEP 2008, 2019), the Nationally Determined Contributions (NDC, 2016), the 7NDP (2017-2021) and the Rural Electrification Master Plan (REMP) 2008–2030 (Table 3). These policies aim to reduce the use of fuelwood, produce modern renewable energy, increase access to energy in rural areas and cut fossil fuel imports. The target for access to electricity in rural areas is 50% by 2030; for clean cooking, the target is 100% in the same year (Table 4).

Table 3. Elements of Zambia's Nationally Determined Contribution

Agriculture and forestry sector	Energy targets
• Increase rural biogas plants • Increase rural biomass electricity generating facilities • Follow climate smart agriculture practices • Support natural regeneration and afforestation/ reforestation • Sustainable charcoal production with improved kilns • Promote alternative cooking fuels to reduce demand for charcoal and fuelwood	• Switch fuel use (coal to biomass) • Switch from existing isolated diesel to mini-hydro • Introduce and increase blending of biofuels with fossil fuels and where possible substitution with biofuels • Deploy off-grid renewable energy solutions in un-electrified rural areas

Source: Government of Zambia (2021).

Table 4. Energy targets for access to electricity and clean cooking solutions

	Baseline	Target
Access to electricity	National: 31.4% Urban: 67.3% Rural: 4.4% (on-grid) 7.4% (off-grid)	Urban: 90% Rural: 50.6%
Access to modern clean cooking solutions	National: 17% Urban: 38.5% Rural: 2%	Urban: 100% Rural: 100%

Source: Government of Zambia and SE4All (2021).

Biomass-based energy is viewed as playing a role in all energy sectors. What is not yet known is the extent to which the identified bioenergy pathways can supply energy to the country and expand access to energy. To obtain the answers, the following steps must be taken:

- Define the amounts of biomass available for further use without affecting agricultural activity, food security and livelihoods
- Define which bioenergy technologies can be economically viable
- Define to what degree bioenergy can support the country's energy access targets.

Biomass feedstock potential (crop residues, livestock residues and woody residues)

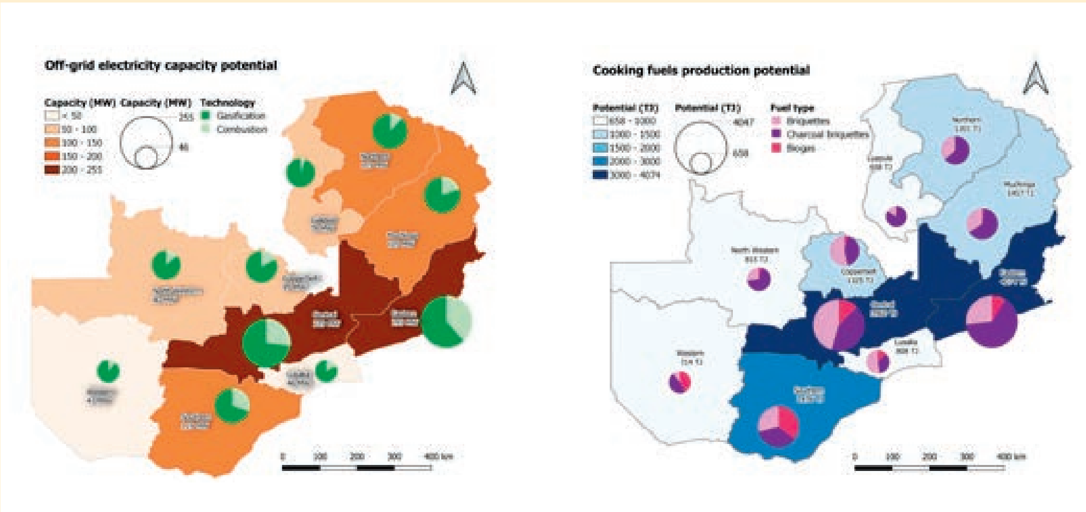
For purposes of generating electricity and producing cooking fuel, the most pertinent forms of biomass are crop residues, livestock residues and woody residues. The actual amounts available for bioenergy production depend on current food production and the current uses of residues in the country. Food residues are found both in fields and in processing plants; the distinction has a significant effect on their collection costs.

Having considered food production, current uses and needs, and the location of residues, the FAO estimated that more than 8 million tonnes per year of crop residues (from maize, cassava and cotton) are available for bioenergy production, with the largest amounts coming from the Central, Eastern, and Copperbelt provinces. On the other hand, the amount of residue generated and available from processing plants is much smaller, amounting to just 11 000 tonnes per year of rice husks. Large amounts of livestock manure are also available for bioenergy production. Cattle manure is the largest component (2 504 901 tonnes per year), followed by pig manure (572 532 tonnes per year) and chicken (layer) manure (34 643 tonnes per year). There is also a limited potential from commercial goats – about 18 718 tonnes per year. The manure is found chiefly in the Central and Southern provinces. The potential for sustainably managed forestry residues is limited, amounting to just 60 000 tonnes per year from harvesting of forest plantation residues.

Generating electricity and producing cooking fuels from biomass to meet Zambia's energy targets

From the estimated quantities of crop residue, a total of 1 192 MW could be generated across the country using a combination of gasification and combustion technologies (Figure 14). The same types of feedstocks can be used to produce cooking fuel as to generate electricity.

Figure 14. Potential for producing electricity and cooking fuels from biomass resources in Zambia



Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

Owing to differences in feedstock availability, briquetting is seen to be a more cost-effective option than biogas in Zambia. It is estimated that the total potential energy from alternative cooking fuels could be as high as 15 797 terajoules per year: 47% from charcoal briquettes, 39% from biomass briquettes, and 14% from biogas. In most parts of the country, charcoal briquettes would be in the most cost-effective option, particularly in Eastern Province. In Central Province, both biomass briquettes and charcoal briquettes would be equally effective. Only in Southern Province would biogas be the most cost-effective option.

If the total biomass available were to be used to produce electricity, 82% of the renewable electricity target for rural areas could be met from bioenergy, assuming a typical demand per rural household of 200 kWh per month (equivalent to Tier 3 in the World Bank's multi-tier framework of consumptions levels). On the other hand, if the entire biomass volume were used as a cooking fuel alternative, 12% of the country's clean cooking target in rural areas could be met.

Source: FAO and Zambia Ministry of Energy (2021).

a. https://trackingsdg7.esmap.org/time.

b. This is estimated based on all the feedstocks being used for cooking and on a household level demand of 97 mega joules per day, as reported for purposes of estimating the country's cooking target (FAO and Zambian Ministry of Energy, 2021).

Sustainable bioenergy for energy, food and climate goals

To meet the world's energy transition objective of limiting warming to 1.5°C, bioenergy will need to play a significant role. A key pillar of the transition – one expected to yield significant social, economic and environmental benefits – is to phase out the use of traditional fuels by 2030. At the same time, the use of modern bioenergy must be significantly scaled up – mainly to generate power, meet thermal needs in industry and serve as transport fuel. As well recognised, bioenergy use and agri-food systems are very closely interlinked at a number of levels, comprising the sourcing of the biomass feedstock. In this, identifying the country level and context specific food-energy approaches that maximise benefits while managing potential negative impacts will be key. Collection of the biomass, net availability of the biomass considering other needs in the agri-food sector and involvement of the farmers in the process need to play a central role in the process.

Country-specific bioenergy pathways, such as the one presented for Zambia, will have to be plotted out in detail to ensure an adequate supply of feedstock and increase access to energy sustainably across sectors. One key bottleneck to unlocking bioenergy's full potential is to ensure that all elements of the supply chain are established for a stable supply of feedbstock and support job creation and farmer livelihoods. Once the viable bioenergy options are identified, investments must be channelled to support them.

The potential to produce bioenergy depends largely on the availability and accessibility of feedstock and their geographical distribution. If that potential is to be realised, a long-term strategy is imperative. The strategy must ensure that the bioenergy produced is economically viable, sustainable and based on a dependable value chain. All key stakeholders must be involved in setting the strategy, and mechanisms to encourage the exchange of information between energy producers and biomass owners must be developed. Furthermore, policies will be required to promote the availability of mechanised equipment for the collection and pre-treatment of residues, as well as facilities for post-harvest storage. The establishment of a biomass market and supply chain would allow for easy exchanges of residues between biomass producers and bioenergy developers.

Bioenergy's potential should be considered within the wider context of renewable energy options and of the renewable energy mix. Bioenergy has proven to be an important resource to meet energy needs in agri-food systems, particularly the use of residues and waste to generate electricity, heat and fuels for processing, storage and cooking. Holistic assessments are needed to identify energy needs with precision and to guide the sustainable use of residues, where other competing uses do not exist.

3.4 Challenges for renewables in agri-food systems

This section discusses several challenges to scaling up applications of renewable energy in agri-food systems. Aspects of these obstacles have been mentioned in previous sections, but common ones are the focus here.

Making energy and agriculture policy within silos impedes the integration of renewable energy into agri-food chains. The lack of a coordinated integrated strategy limits exploitation of the substantial synergies between the energy and agri-food sectors, particularly in developing countries where agri-food chains are less developed and closely tied to socio-economic development outcomes. Renewable energy applications typically cut across multiple sectors, an example being the biogas digester programmes discussed in the section, which are relevant to institutions dealing with agriculture, livestock, energy, the environment and rural development. Effective co-ordination serves to align objectives, mobilise government support and maximise benefits. Governments will continue to play a crucial role in supporting the use of renewables in agri-food systems through public financing to facilitate deployment and by investing in an enabling ecosystem that promotes technological innovation; sets standards and ensures quality; imparts knowledge and skills; raises awareness among stakeholders and the public; and builds infrastructure for market access.

However, the implications of energy transition policies on resources such as water and land should also be closely considered and managed (McDonald *et al.*, 2009, Fritsche *et al.*, 2017). For unless renewable energy policies take into account the water-energy-food nexus, unexpected and undesirable effects may occur, for example on the uses of water and land. For this reason, solar irrigation systems that could pose the risk of groundwater over-extraction are increasingly deployed as part of a broader package to promote efficient water use. Although some renewables, such as solar PV and onshore wind, have large land requirements, their direct impact on land use over long term is minimal (compared with mining or other fossil fuel-based generation). In countries with land scarcity, significant opportunities for integrated food-energy systems exist, including the use of agri-voltaic systems as discussed in section 3.1.

To date, the discussion of renewables use in agri-food systems has focused on technology. This must change, because **a value chain approach** to deploying renewable energy along the agri-food chain is key to ensuring full socio-economic benefits to farmers and other groups. As discussed previously in this chapter of the report, robust backwards and forward market linkages are important to capture the value made possible by improved yields and diversified produce. The incentives for unlocking financing and other support (*e.g.* capacity building) for renewables in one part of the value chain can often be found at another stage – for example, when dairy processors support livestock owners and co-operatives to acquire cold storage facilities. Further, opportunities to contribute to the circular bioeconomy and the decarbonisation of food chains through use of residues to produce energy are still too often overlooked.

Data and information to guide decisions about policy and investments related to the water-energy-food nexus are extremely limited. Data on energy flows across agri-food value chains at the local level are typically unavailable; the same is true of granular spending data for farm and non-farm enterprises. Specific information is also needed to assess the viability of certain renewable energy applications. In the case of solar irrigation, for example, data are often needed on water needs, existing irrigation practices and groundwater water access[11] and availability. For agro-processing, mapping processing needs, existing infrastructure, energy use and willingness to pay could offer important guidance to the most promising renewable energy interventions (IFC, 2020). As noted in section 3.3.3, assessing the viability of geothermal use likewise requires high-quality geological data on resource availability and fluid conditions to map overlaps between resource availability and demand for low, medium or high-temperature heat from nearby economic activities (IRENA, 2019a). Such data and information are necessary to guide investments in appropriate solutions based on robust cost-benefit analysis, impact evaluation (*e.g.* effects on jobs, incomes, food security) and environmental safeguards. A holistic

[11] Solar irrigation uptake relies heavily on water access (e.g. borehole, river, dam, well) which requires careful assessment especially under a scenario of large-scale adoption. Tapping into groundwater may require additional expenditure related to borehole digging which may be beyond the affordability of farmers, thus requiring targeted support within irrigation programmes (Mercy Corps, 2020)

data-centric approach also supports cross-sectoral co-ordination and facilitates integration with long-term strategies (*e.g.* NDCs) at the sectoral and economy level.

Lack of access to **tailored end-user and enterprise financing** is a common complication across renewable energy applications in agri-food systems. The seasonal nature of farmers' incomes, coupled with the capital-intensive structure of most renewable energy investments, make affordability a problem for actors in small and medium-sized agri-food chains. The lack of access to long-term end-user financing tailored to cash flows reduces uptake, making it necessary to offer targeted financing incentives. Such incentives to support renewable energy and energy efficiency in agri-food chains are justified when the broader local economic, environmental and social benefits are taken into account (beyond traditional financial metrics), as well as the energy subsidies usually offered to the agri-food sector in many countries.

Innovations in delivery models (*e.g.* pay-as-you-go) can help close the financing gap for end users, but most do not ease the situation for enterprises. Lack of access to long-term debt and other forms of capital for suppliers and distributors remains an obstacle. Investments in cold storage and agro-processing equipment can have payback periods of up to 10 years. In developing countries, the ecosystem for lending to renewable energy firms in agriculture is often marked by a lack of tailored products, prohibitive collateral requirements and poor understanding of the water-energy-food nexus.

There is also a **lack of awareness** among end users and other stakeholders of the advantages and long-term cost effectiveness of renewables-based technologies and of the positive linkages between renewable energy and food security. In Senegal, for example, few farmers know that solar-powered irrigation systems can reduce operating costs by 40% to 50% per hectare relative to diesel-powered equipment and can increase farmers' income by at least 15% per hectare (Energy4Impact, 2021b). The lack of awareness marks all stages of food-system transformation, including energy for agricultural inputs (fuel for machinery, fertilisers, and pesticides), food processing (biomass waste to power processing devices) and transport (fossil fuel use; cooling to cut food loss during transport). These limitations are often compounded by a **lack of technical and management capacity** to operate and maintain renewable energy systems, especially if devices are imported without local language manuals.

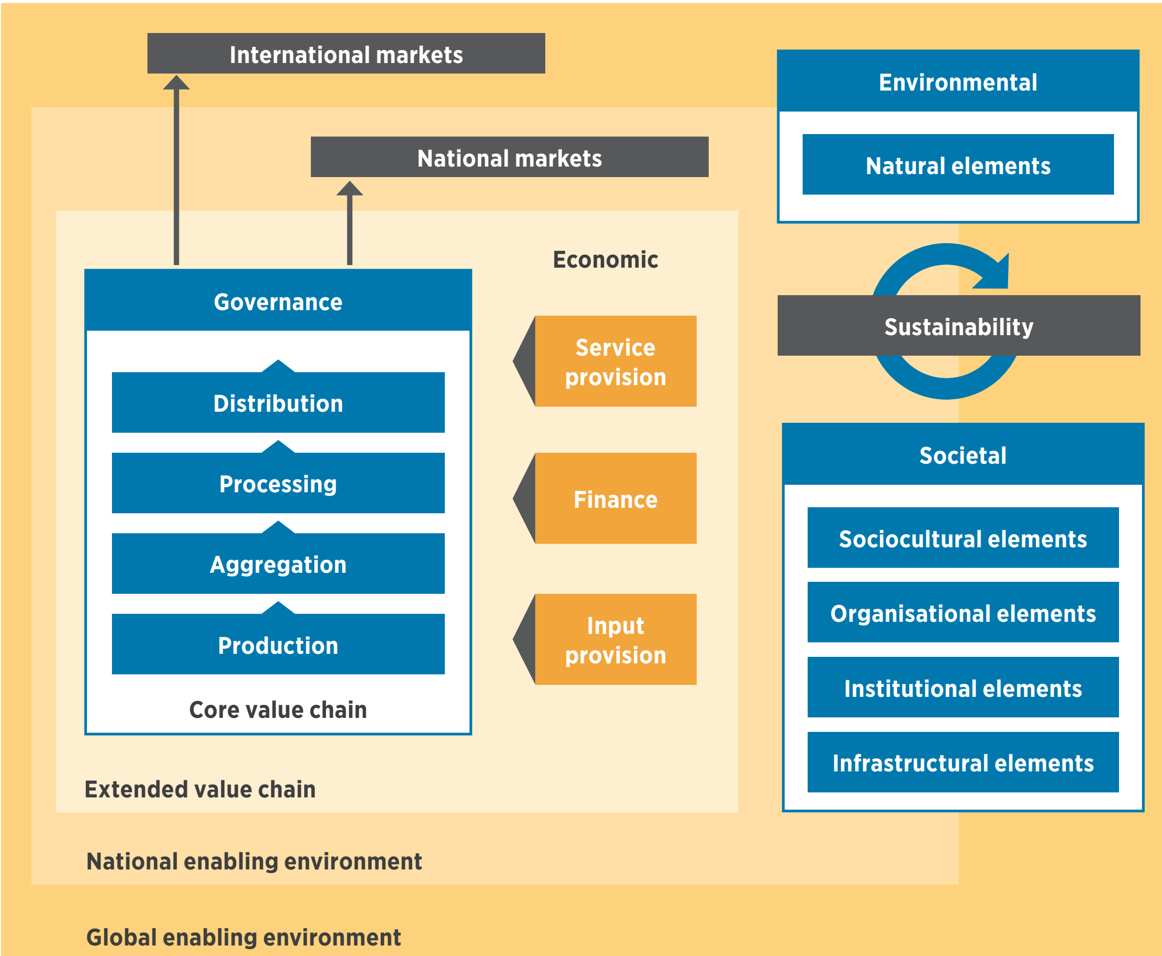
Women and women-led enterprises continue to face greater obstacles in accessing and benefitting from renewable energy in agriculture. Women produce between 60% and 80% of the food in most developing countries (IRENA, 2016b), yet they have much more difficulty gaining access to resources such as water, land, credit, and productivity-enhancing inputs and services (FAO, 2016). It is also women, predominantly, who fetch the water for food production, as well as fuelwood for cooking – both laborious and time-consuming activities (Remmington, 2015). Women, along with other disadvantaged social groups, are not equally represented in most training and consumer-awareness programmes. In the case of solar irrigation, energy for pumping affects the economic activities of men and women in different ways, especially with respect to whether water is used for "men's crops" or "women's crops". Solar energy can be particularly useful for growing the types of crops that women traditionally tend, such as fruits and vegetables, much of which goes directly back to feeding the family (IRENA, 2016b). The gender dimension should be integrated in decision making, management systems and resource allocation. The youth also represent an important target group to engage and focus capacity building efforts on with the long-term objective of creating robust local agri-enterprises, employment opportunities and contribute to reducing rural-urban migration.

4 RECOMMENDATIONS FOR DECISION MAKERS

Scaling-up the use of renewable energy in agri-food systems will require concerted efforts between government, the private sector, financing institutions, academia, and international and non-governmental organisations. A whole of a food systems approach, as illustrated in Figure 15, is necessary that looks beyond the food chains alone for solutions to be successful.

This chapter offers eight recommendations for decision makers to facilitate investments in renewable energy solutions for agri-food system transformation with attention to the water-energy-food nexus and meeting the Sustainable Development Goals and align with the Paris Agreement on Climate Change (Figure 16). The recommendations are explored in turn .

Figure 15. The sustainable agri-food system framework



4.1 Collect better data to guide renewable energy investments in food systems

The lack of data on energy flows across various value chains hinders investments in renewables-based energy systems for the agri-food sector. Better data could guide the design of technological solutions, improve understanding of the business case (*e.g.* through cost-benefit analysis), and raise awareness of potential benefits, such as higher incomes, jobs and productivity, less drudgery, improved food and energy security, and reductions in emissions.

Some data gaps are tied to specific technologies. Here, the geothermal example raised previously is illustrative. Assessing opportunities for geothermal use in agro-processing requires high-quality geological data on resource availability and fluid conditions (*e.g.* temperature, pressure).

Targeted efforts are needed nationally and regionally focusing on agri-food value chains that strongly affect food security and socio-economic outcomes. Primary data gathering can offer important insights on the structure of agri-food value chains, the nature of the enterprises involved, existing energy flows, and gaps that must be bridged to reduce losses, add value and diversify products. Granular data is needed, because although the topography of value chains may be the same, their scale and length usually varies, as do the nature of the participating enterprises and their capacities. Access to such data and information can be crucial to guide policy making, set targets, design solutions and facilitate co-ordination between ministries and other stakeholders in pursuit of common objectives.

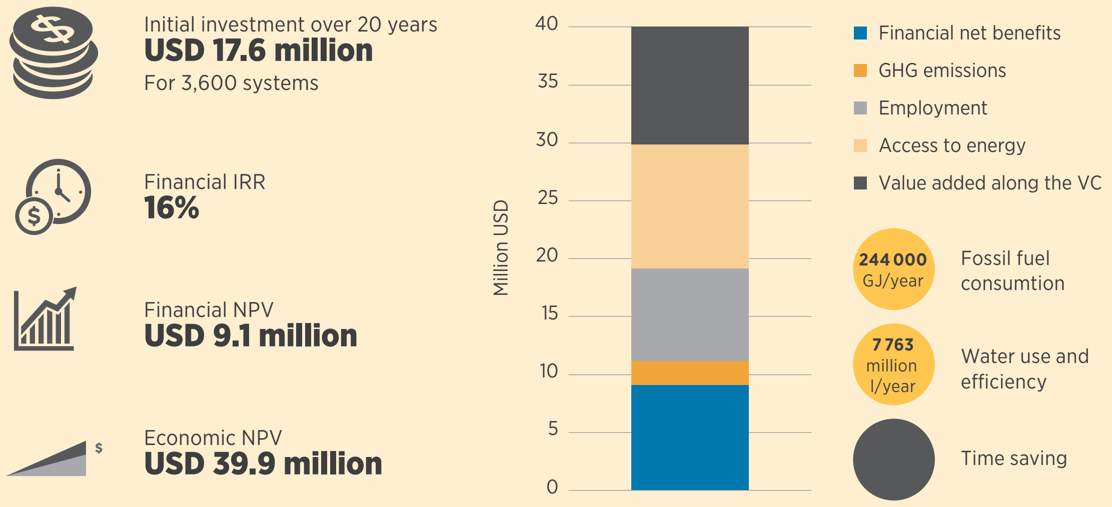
In 2019, IRENA and the International Centre for Integrated Mountain Development partnered to conduct a comprehensive energy needs assessment covering yak and bamboo value chains in the mountain areas of the Hindu-Kush Himalaya region. The primary data offered insights on energy needs and gaps, resulting in a decision to perform a cost-benefit analysis of decentralised renewable energy options. Such cost-benefit analyses strengthen the evidence base on the benefits of renewable energy investments in food systems, while also providing guidance on the financing mechanisms needed to promote adoption. FAO's INVESTA project is profiled in Box 8.

Box 8. Costs and benefits of applying renewable energy in agri-food value chains

FAO's "Investing in Sustainable Energy Technologies in the Agrifood Sector" (INVESTA) project offers a methodology for a comprehensive cost-benefit analysis of renewable energy solution in the agri-food sector.[a]

Renewable energy technologies with the potential to replace fossil fuels-based solutions and reduce energy demand in the milk value chain were considered in Kenya, Tanzania and Tunisia; in the vegetable value chain for Kenya; and in the rice value chain for the Philippines. Figure 17 illustrates the results of the analysis for a solar-powered rice processing system in the Philippines. The methodology emphasises the need to capture all economic costs and benefits arising from such interventions, including time saving and employment. The work resulted in recommendations on how policy makers and investors can facilitate renewable energy solutions through tailored financial incentives and other support measures.

Figure 16. Financial and economic performance of solar-powered rice processing in the Philippines



Source: FAO and GIZ (2019).
Note: The economic NPV (net present value) is the sum of the financial NPV and economic co-benefits. IRR = Internal Rate of Return.
a. http://www.fao.org/energy/agrifood-chains/energy-sustainable-technologies/en/.

4.2 Leverage mapping tools to assess opportunities and inform policy making

Geospatial mapping tools are increasingly used to identify areas with a high potential for renewable energy adoption in agri-food systems' applications, while maintaining environmental sustainability. Better intelligence is needed to determine where wider access to renewable energy will have the greatest positive effect on food chains. The strong synergies between food chain actors and energy suppliers are often overlooked. Food chain actors gain from energy access in the form of reduced food losses, better quality and higher yields; they also represent important anchor loads for energy suppliers. (Historically, electrification efforts in countries such as the United States were centred on powering farms.) Mapping tools can be helpful in identifying high-impact opportunities to link energy access effectively with food chain activities. Suitability maps can often integrate several layers of decision making, including economic viability and the availability of energy, water, land and infrastructure.

Determining the most suitable and promising investment opportunities may involve multiple dimensions of economic, social and environmental sustainability. Assessing the suitability of solar irrigation solutions, for example, requires careful consideration of water needs, groundwater resources, and existing irrigation practices, as discussed in the previous section. Similarly, assessing the application of renewable power to a particular form of agro-processing depends on mapping areas under cultivation; the capacity and location of existing processing centres; and the costs of accessing markets and critical infrastructure (*e.g.* power supply, roads). Boxes 9 and 10 present examples of the use of geospatial mapping tools in connection with maize milling in Uganda and solar irrigation systems in Ethiopia.

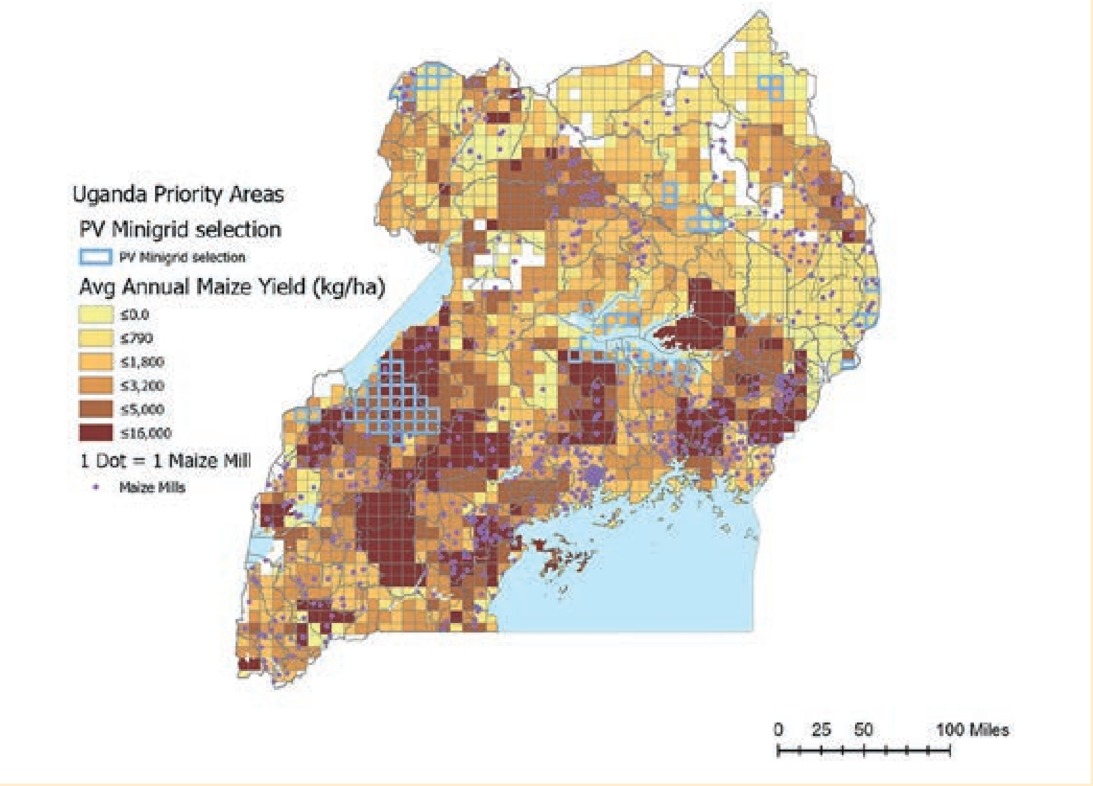
IRENA and FAO aim to advance the use of various mapping tools to improve information access on investment opportunities for renewable energy applications in agri-food systems. FAO's geospatial data platform under the Hand-in-Hand initiative and IRENA's resource assessment and country-level work provide a robust base for such analysis.

Box 9. Using mapping tools to site solar-powered maize mills in Uganda

Uganda is an agrarian economy where most farming is small-scale, low-input and non-irrigated. Maize is the primary cereal crop, grown throughout the country. However, most districts have limited processing capacity, with many relying on low-output diesel-powered mills. This limitation means that maize is not fully exploited for flours, oils and other value-added products that meet national and regional demand. High-capacity mills are found chiefly in urban, electrified areas, most of which must cope with unreliable and expensive energy supply.

With low electrification rates and standalone solar mills still not commercially viable, mini-grids represent an important opportunity to serve rural communities, with mills acting as anchor loads. It is estimated that 40% of low-input, high-yielding maize croplands in Uganda can be served most efficiently by mini-grids (Figure 18). More than half of those croplands are in districts that lack any known milling capacity, demonstrating the immediate potential of mini-grids to drive processing activity and calling for efforts to promote rapid, targeted deployment of mini-grids in underserved communities.

Figure 17. Areas where maize croplands intersect with areas of high mini-grid projection



Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

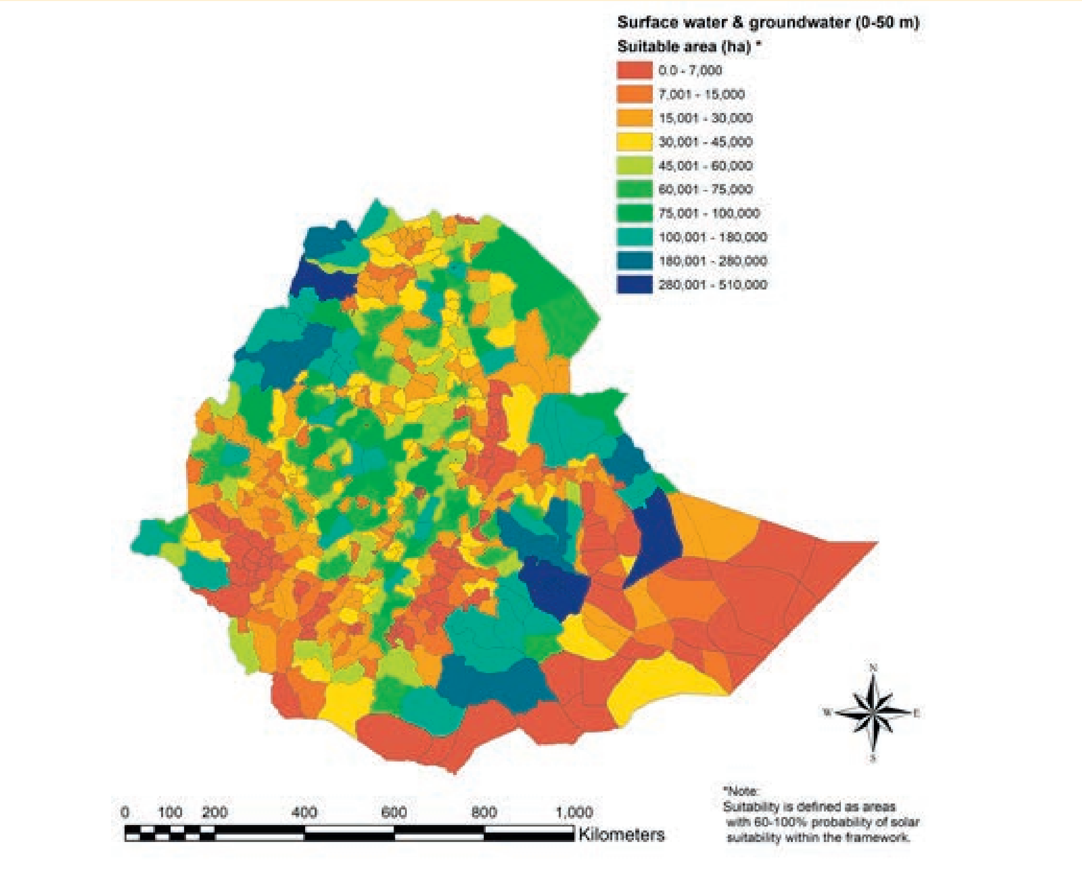
Source: Shirley (2020).

Box 10. Using mapping tools to site solar irrigation pumps in Ethiopia

In 2018, the International Water Management Institute, supported by the CGIAR Research Programme on Water, Land and Ecosystems and the USAID-funded Innovation Lab for Small-scale Irrigation, began mapping suitable sites for solar irrigation in Ethiopia. The maps pinpoint areas where smallholder farmers can introduce solar irrigation **while considering sustainability**. The resulting framework was translated with aid from the Deutsche Gesellschaft für Internationale Zusammenarbeit into an online interactive tool that maps solar irrigation suitability using surface water and groundwater at various depths over the entire area of Sub-Saharan Africa (http://sip.africa.iwmi.org/).

In developing the mapping tool, researchers paid particular attention to environmental sustainability. This took the form of specifying sustainable sources of water for irrigation (renewable groundwater) and the amount of water needed to maintain natural ecosystems. As a result, the maps considered areas that are suitable for solar irrigation while identifying those that may not be suitable and should potentially be avoided to prevent the long-term depletion of water resources (Figure 19).

Figure 18. Suitable sites for solar irrigation in Ethiopia



Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

Source: Leh (2021).

4.3 Improve access to finance for end users and enterprises

Financing needs vary greatly from context to context for both end users and enterprises. End users, whether individual farmers, co-operatives, or processors within the agri-food value chains, must be able to access affordable, long-term financing to acquire renewables-based systems. The capital intensity of such systems, relative to those based on fossil fuels, call for a mix of financial instruments sensitive to end-user cash flows (because incomes may vary depending on harvest cycles), existing energy expenditures and potential benefits. In Romania, the National Rural Development Programme approved in early 2021 offers dedicated funding support for farmers, co-operatives and producer groups to adopt renewables for own consumption (*e.g.* for processing), or supply of biomass fuels (AgroRES, 2021). In the United States, the Rural Energy for America Program offers grants and loans for farmers and enterprises for renewable energy and energy efficiency investments (NSAC, 2020). The Clean Energy Finance Corporation in Australia, directly or through commercial banks and other co-financiers, offers farmers and agri-enterprises access to tailored financing for renewable energy and energy efficiency measures (CEFC, 2021).

Financial intermediaries, including agricultural development banks and co-operatives, can play an instrumental role in making financing for renewables-based technologies accessible for local actors along the agri-food chain. In India, debt funding from the National Bank for Agriculture and Rural Development along with the Agriculture Investment Fund is being mobilised to meet targets for deployment of solar pumps under the PM-KUSUM scheme (Jai, 2020). In Brazil, biomass projects are funded mainly through banks, particularly the development bank BNDES and Banco do Brasil, who have dedicated credit lines for renewable energy sources for food producers (Climate Bonds Initiative, 2020).

Where financial intermediaries do not exist, delivery solutions (*e.g.* lease-to-own, pay-as-you-go) can help overcome the consumer affordability problem, though they depend on the financing situation of local enterprises delivering them.

Enterprise financing needs vary from high-risk capital for research and development to working capital to scale up deployment of renewable energy solutions. Targeted funding facilities for enterprises working at the intersection of energy and food can address immediate capital gaps (Box 11). The Powering Livelihoods Initiative of the Council on Energy, Environment and Water and India's Villgro, for example, offers capital support of up to USD 250 000 to bridge the gaps faced by enterprises in the commercialisation stage, along with funding of up to USD 100 000 for capacity building. The multi-donor–funded Water and Energy for Food (WE4F) programme offers mid-stage enterprises game-changing innovations at the nexus of renewable energy and agri-food systems with capacity building support and grants to scale solutions.

International development finance, including climate financing (Box 12), has an important role to play in bridging the funding gap for renewable energy in the agri-food sector, especially when the technology is less understood, awareness is limited and local ecosystems immature. Over the long-term, building a sustainable market for renewable energy requires mobilisation of local financing through domestic financial institutions. First-loss and partial-credit-risk guarantees can go far to unlock lending from local financial institutions and raise exposure and experience with the sector. Consideration should also be given to linking financial support to integrated approaches such as the water-energy-food nexus.

Box 11. Dedicated funding facility for Cambodian agri-enterprises

The Clean Energy Revolving Fund, managed by Nexus for Development, offers access to finance to small enterprises in the agri-food sector that wish to invest in clean energy technologies. The Fund offers affordable, unsecured finance in amounts suitable for small to medium-sized enterprises (USD 10 000 to 100 000). The loans are issued following an intensive due diligence process, which Cambodian banks would be unwilling to undertake for small loans. The Fund's impact therefore lies in employing a relationship-banking model to help agricultural enterprises become more energy efficient and to harness renewable energy without having to post collateral. Most loans were used to purchase solar-powered water pumps and small on- and off-grid solar installations for clients such as fruit, vegetable and pepper and pig farms. To date more than 90% of loan repayments have been made in full and on schedule.

Several lessons were learnt from the implementation of the fund. Developing pipeline of projects in frontier markets can be resource intensive and require extensive due diligence. Standardisation of due diligence can be challenging given that borrowers represented different agricultural sub-sectors (fruit, pepper, vegetables, livestock farms). Businesses with no financial track record will face challenges accessing local financing and, therefore, dedicated funding facilities should support enterprises in building a credit history for long-term sustainability. Finally, investments in renewable technologies (e.g. solar water pumps) often need to be accompanied with co-financing for allied infrastructure such as drip irrigation and storage tanks.

Source: REEEP (n.d.); REEEP (2019).

Another way to link financing to integrated approaches is by giving due consideration to the affordability of agricultural appliances powered by renewable energy. Ways to do this include:

- Selling appliances as part of a package offered by energy suppliers. Vendor financing of appliances results in an increase of more than 30% in average revenue per user (Hunt, 2020).
- Making appliances more affordable, *e.g.* through rent-to-own schemes.
- Ensuring that renewables-powered appliances perform better than those using fossil fuels. Innovations that improve the efficiency of appliances raise the income of their users and solidify the business case for renewables-powered appliances.

Larger appliances for productive use may present challenges for mini-grids related to the intermittency of use (*e.g.* a few hours per day for grain mills) and the high energy load needed to operate them. Innovations are needed to better understand and manage demand features and match them with supply. These include smart meters to measure consumption and ways to assess possible load scenarios.

Box 12. Egypt's Sustainable Agriculture Investments and Livelihoods Project (SAIL)

Egypt's water resources are increasingly stressed owing to climate variability and growing demand. The Sustainable Agriculture Investments and Livelihoods (SAIL) project was launched with funding from the Special Climate Change Fund of the Global Environment Fund and the Adaptation for Smallholder Agriculture Programme of the International Fund for Agricultural Development to contribute to climate change adaptation and mitigation, as well as to poverty reduction and food security.

A component of SAIL supports access to capital for smallholder farmers to invest in climate-smart agriculture (*e.g.* solar-powered pumps and biogas units) and diversify livelihoods (*e.g.* by investing livestock production, agro-processing or small off-farm enterprises). In rural areas, where financial services are limited and appropriate loan products for agricultural lending usually not available, SAIL provides debt financing through small and medium-sized enterprises and micro-loan facilities. The disbursement of loans started in early 2020, with most loans focused on increasing the efficiency of water use on farms. Loans for solar-powered irrigation pumps are expected to gain traction in the coming years.

Source: FAO (2021a).

4.4 Develop integrated approaches to transforming the food and energy systems

Energy and food systems should be transformed in synchrony to leverage synergies and minimise conflicts, particularly in land and water use. A holistic approach that considers climate, land, energy and water in an integrated way will address competing uses and identify ways to co-locate energy production with other land uses to increase productivity. Integrated food-energy systems also permits the optimisation of land use through mixed-cropping systems and agri-voltaic solutions, and of biomass use through cascading uses of manure and other food chain residues. Bioenergy development also offers the opportunity to improve soil conditions and thus contribute to land rehabilitation through by-products (*e.g.* biofertiliser from biogas).

Agri-voltaic systems are increasingly deployed in countries with land shortages. They have shown value in increasing land-use efficiency and improving energy system performance (through cooling effects), with limited impact on food production (as discussed in chapter 3). Pilot projects are needed to better understand the economics of such projects under local conditions and their effects on local crop production, and to align policy incentives to accelerate deployment and adoption.

4.5 Mainstream cross-sectoral perspectives into national sector strategies

The strong linkages between energy and agri-food systems require the integration of sectoral transformation strategies. Accelerating the use of renewables in agri-food systems and increasing sustainable bioenergy production will strengthen progress towards an energy transition that is aligned with the climate goals set by the Paris Agreement.

Energy and climate policies introduced to accelerate the adoption of energy transition technologies, including renewables, should account for cross-sectoral impacts on society and the economy. Beyond traditional economic and environmental metrics, the effects of technology acquisition on water use, land use, and the potential for competition for resources with agriculture and other end uses should be considered when defining transition trajectories at the national and regional levels. Policy design can further reduce negative impacts, for example, by introducing regulations governing land-use change and incentivising efficient resource use (*e.g.* agri-voltaics, floating solar, wasteland utilisation).

A stable and supportive enabling environment, one that includes dedicated policies and plans, is also needed to attract investments in renewable energy for use in agri-food systems. Cross-sectoral and multi-stakeholder co-ordination among government, the private sector and civil society, both nationally and sub-nationally, is crucial. In the Philippines, for example, the Department of Energy and Department of Agriculture in 2021 announced the Renewable Energy Program for the Agri-Fishery Sector in 2021 to promote renewable energy technologies in agri-fisheries through measures to boost research and development, standards development and enforcement, human resource development, and assistance to local manufacturers, fabricators and suppliers (Philippines Department of Agriculture, 2021) (Box 13). India has also announced a draft policy framework for developing and promoting applications of decentralised renewable energy to improve livelihoods in rural areas (MNRE, 2020). The Green Morocco Plan considers renewable energy in agriculture as a key pillar of the country's transformation strategy (Morocco Ministry of Agriculture, Fisheries, Rural Development, Water and Forests, n.d.). In Ethiopia, the Ministry of Water, Irrigation and Electricity is assessing the economic viability of 285 potential mini-grid sites, with a focus on developing Agricultural Commercialisation Clusters (Ethiopia Jobs Creation Commission, 2021).

Stimulating demand for renewable energy in food systems can be achieved in two ways: first, from the energy side, through better assessments of energy demand using digital technologies to measure energy use in food chains and remote sensing (see Box 10); and second, from the food side, by clustering demand and making renewables-fuelled appliances competitive with those using fossil fuels, as was done for solar grain mills in Tanzania (Next Billion, 2020). Demand can be clustered by means of bulk procurements and farmers' groups, such as milk co-operatives in India, farm blocks in Zambia (Middelberg, van der Zwan and Oberholster, 2020), and integrated agro-industrial parks in Ethiopia (UNIDO, n.d.).

In the near-term, it will be important to prioritise low-risk, high-impact actions particularly in the context of Covid-19 recovery – for example, reducing food losses, strengthening the circular economy, and reinforcing links between energy for food and energy for health. As an example, the European Union's Green Deal centres on the Farm-to-Fork Strategy, which aims to make food systems healthier, more fair and more environmentally friendly (Box 14). By including the food-energy nexus in national climate commitments, countries can reduce their GHG emissions and achieve their NDCs.

Box 13. Integration of Productive Uses of Renewable Energy (I-PURE) for Inclusive and Sustainable Energisation in Mindanao, Philippines

Mindanao is the food basket of the Philippines, accounting for 36% of the country's farm area and 43% of total food production. Nine of the ten poorest provinces in the Philippines are in Mindanao; most of the poor work in farming and fishing.

The region is a major source of high-value crops such as cocoa, coconut, rubber, coffee, banana, oil palm, pineapple and seaweed. These crops are also major export commodities that enhance economic resilience to shocks such as the Covid-19 pandemic. The growth of the agricultural sector is also closely linked to socio-economic development in the region.

The agricultural sector in Mindanao still lacks the enabling conditions, such as access to access to energy, to add value and foster growth. Most rural electrification projects have focused on applications such as residential lighting, electricity for health clinics and schools, and other community needs. The Mindanao Development Authority, in co-operation with the National Electrification Administration and with funding from the European Union's Access to Sustainable Energy Programme has launched a project known as I-PURE Mindanao, which stands for Integration of Productive Uses of Renewable Energy for Inclusive and Sustainable Energisation.

A key component of the I-PURE project is to support a portfolio of renewable energy investments to foster development in rural areas, particularly in agriculture. This includes deploying renewable energy in 10 post-harvest agro-fishery processing facilities to produce high-value goods that will command higher prices in the market, thereby raising the revenues of the target facilities. Further, 22 fish centres in off-grid areas will be equipped with solar-powered facilities and biomass-based processing equipment. In the municipalities of Sitangkai and Sibutu, in Tawi-Tawi Province, a total of 1.6 MW of hybrid solar projects are expected to be installed, which will improve electricity access for 5 000 households and raise the value of seaweed production by 10%. In the municipality of Taraka, in Lanao del Sur Province, solar-powered irrigation and community water systems have also been launched.

Box 14. The European Union's "Farm to Fork" strategy as part of the Green Deal

Farm-to-Fork aims to accelerate Europe's transition to a sustainable food system that has a neutral or positive environmental impact, mitigates climate change and facilitates adaptations to its impacts (Figure 20). The system is designed reverse the loss of biodiversity and ensure food security, so that everyone has access to sufficient, safe, nutritious and sustainable food. It should keep food affordable while generating fairer economic returns, fostering the competitiveness of European agricultural producers and promoting fair trade.

Farm to Fork sets out both regulatory and non-regulatory initiatives, with the common agricultural and fisheries policies as key tools to support a just transition. The strategy encourages farmers to reduce emissions using anaerobic digesters to produce biogas from waste and residues, including livestock manure and municipal waste. It also emphasises energy efficiency and the outfitting of farmhouses and barns for solar production through investments prioritised in the Union's Common Agricultural Policy.

Figure 19. Components of European Union's "Farm to Fork" strategy

Source: EU (2020).

4.6 Strengthen innovation for technology and energy efficient appliances

Appliances (including processing equipment) available for use in the agri-food sector are designed for grid-based, unlimited energy supply with a limited emphasis on efficiency. Linking renewable energy supply with appliances will require investments in innovation that test and deploy technological solutions adapted to the needs of various agri-value chains. Emphasising energy efficiency of appliances positively affects the overall cost of the technological solution, thereby improving affordability for end-users. This requires dedicated high-risk innovation funds and partnerships between local technology suppliers, R&D institutes and end-users to develop or repurpose existing technologies, pilot them to test operational viability, and establish supply chains to deliver solutions as well as long-term operational and maintenance services (Box 15).

Box 15. Africa Centre of Excellence for Sustainable Cooling and Cold Chain (ACES)

The Africa Centre of Excellence for Sustainable Cooling and Cold-Chain (ACES) was established in 2020 by the Governments of Rwanda and the United Kingdom, the United Nations Environment Programme's United for Efficiency initiative, the Centre for Sustainable Cooling, and a range of academic institutions. ACES aims to tackle the challenge of high post-harvest losses resulting from a lack of cold chain infrastructure. Key areas of focus include technology demonstration and capacity building, data acquisition and use, a business incubator with full-service training, business model and support, skills development and research on future-proof, localised solutions for food loss reduction and increased farmer income.

Source: UNEP United for Efficiency, 2020.

4.7 Focus on raising awareness and building capacity

End users' widespread lack of awareness of available renewables-based solutions and their long-term benefits have impeded the adoption of those solutions. The initial hesitancy associated with new technologies can be addressed through demonstration projects, end-user engagement in solution design, and dedicated information campaigns on the benefits offered by various solutions.

Capacity building goes well beyond the skills needed for installation, operation and maintenance of systems. Integrating renewable energy into existing agricultural practices, particularly manual ones, requires additional capacity building (e.g. to handle drip irrigation systems) and skills to market and access markets for new products and higher yields for existing products, among other skills. The Tanzania Renewable Energy Business Incubator operated by the IMED Foundation in collaboration with the SELCO Foundation supports micro, small and medium renewable energy enterprises to catalyse the adoption of renewable energy, mainly targeting Southern Agricultural Growth Corridor of Tanzania (SAGCOT) areas and Dodoma (IMED Foundation, n.d.).

Efforts are ongoing to provide technology practitioners and service providers the tools they need to assess the feasibility and design of solar pumping systems. The FAO and GIZ, for example, have developed a toolbox on solar-powered irrigation systems for advisors (FAO and GIZ, 2018). Sunfarming's

Food and Energy Training Centre in South Africa is a public-private partnership funded by KfW/DEG on behalf of the German Federal Ministry for Economic Cooperation and Development. The Centre provides knowledge transfer in greenhouse-based food production for master trainers and students in resource-poor and crisis-affected settings. This unique combination ensures effective food production and, at the same time, a sustainable energy supply through photovoltaics.

4.8 Place inclusivity at the heart of transforming the food and energy systems

The transformation of energy and food systems must be inclusive in all respects. To widen opportunities for improved livelihoods in rural areas, solutions and their benefits must be equitably accessible for all – and "all" includes women, youth and other marginalised communities. Women play a crucial role in food chains and yet, they may have different access to resources, services, information and job opportunities compared to men. These limitations make women farmers also more exposed to climate change risks (FAO and CARE, 2019).

While climate change could exacerbate existing gender inequalities in agriculture, it also offers new opportunities to maximise women's potential to deliver sustainable solutions, including renewable energy technologies. Across Africa, for example, women spend an estimated 40 billion hours each year in unpaid time for processing. Energising this process through renewables-based solutions would free up significant time for other productive or educational activities (Musinguzi, 2021). Support policies, financing and training for renewable energy in agriculture must also be equitably accessible for women and youth. It is crucial that women have access to information and training on the working of new technologies (MSSRF and CRT Nepal, 2019). Integrating energy perspectives into gender-oriented sectoral education and training programmes should be undertaken. The Agricultural Technical Vocational Education and Training for Women project in Africa focuses on delivering gender-sensitive training programmes targeted at women smallholder farmers, women-led small businesses and those already in formal vocational training. The project also focuses on improving awareness on issues of equality, access to financing and land rights. Ghana, for instance, has developed its first training programme (Women in the Driving Seat) for operation and maintenance of tractors, specifically for women (GIZ, 2019).

Involving women and youth in energy-food action is illustrated by the Regional Initiative for Promoting Small-Scale Renewable Energy Applications in Rural Areas of the Arab Region (REGEND). Operating in rural areas of Jordan, Lebanon, and Tunisia, REGEND aims to improve the livelihoods, economic benefits, social inclusiveness and gender equality of rural communities (particularly marginalised groups) by addressing issues of energy access, climate change, and water scarcity and vulnerability, among other natural resource concerns.

REGEND is taking an integrated approach to the water-energy-food nexus that concentrates on renewable energy, energy efficiency, the use of modern productive equipment, and capacity building. Recent assessments have shown particularly positive results for women and youth. One important lesson is the need to build sufficient capacity on the technical and management aspects of projects, so that local recipients can benefit fully from the productive equipment they receive (ESCWA, n.d.).

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Vegetable farmer who uses solar pumps for irrigation in the Kamalpur, Surunga Municipality 2, Saptari District of Nepal. ©Nabin Baral / IWMI

5 WAY FORWARD

The interconnected nature of energy and food systems makes a joint approach necessary to achieve the Sustainable Development Goals and the Paris Agreement on Climate Change. The transition towards a renewables-based energy system will be incomplete without considering energy use in the agri-food sector and the provision of sustainable bioenergy. Each step of the agri-food system requires diverse energy services that vary significantly depending on value chains' structure, nature, and depth. The decentralised nature of renewable energy solutions makes them apt for meeting the energy needs in an environmentally-sustainable, affordable and secure manner. As seen from the analysis presented in this report, the socio-economic dividends can be significant particularly for the hundreds of millions of people deriving subsistence and livelihoods from agriculture and facing increased uncertainty from climate impacts.

Despite the stark differences in energy use between regions and the level of development of agri-food systems, renewable energy applications find relevance in most contexts requiring tailored policy, technology, financing and delivery model solutions. Through cross-sector partnerships, action and investments can be mobilised at scale to effectively address the renewable energy opportunity in the agri-food sector, while maintaining a key focus on sustainability aspects. Governments and local stakeholder engagement will be crucial to bridge the gaps in understanding the needs, creating market linkages and delivering capacity and financing within a broader food systems transformation strategy that includes renewables as a key pillar.

IRENA and the FAO remain committed to work with partners to advance renewables adoption in agri-food, fisheries and forestry chains. The Collaboration Agreement signed in 2021 between the two organisations lays out an array of co-operation areas that can catalyse investments and mainstream the nexus thinking across both organisations' activities. IRENA and FAO are also leading an Energy Compact *Energizing Agri-food Systems with Renewable Energy* within the framework of the UN High-Level Dialogue on Energy to bridge data and information gaps for specific value-chains, forge country-level partnerships to facilitate investments in pilot projects, and strengthen the ecosystem (*e.g.* policy and regulations, project facilitation) for scale-up.

REFERENCES

AEPC (2016), "Renewable Energy Subsidy Policy, 2073 BS", https://aepc.gov.np/uploads/docs/2018-06-19_RE%20Subsidy%20Policy,%202073%20(English).pdf.

AgroRES (2021), "Romania: new financing for renewables in agriculture", https://www.interregeurope.eu/agrores/news/news-article/11786/romania-new-financing-for-renewables-in-agriculture/.

Bajan, B., A. Mrówczy´nska-Kami´nska and W. Poczta (2020), "Economic energy efficiency of food production systems", www.mdpi.com/1996-1073/13/21/5826/pdf.

Barron-Gafford, G.A., *et al.* (2019), "Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands", *Nature Sustainability,* Vol. 2, pp.848-855, https://doi.org/10.1038/s41893-019-0364-5

Bengal Solar (2021), "Solar irrigation pumps: Transforming to smart irrigation and improving agriculture in Bangladesh", www.pv-magazine.com/press-releases/solar-irrigation-pumps-transforming-to-smart-irrigation-and-improving-agriculture-in-bangladesh/.

Bhaskar, U. (2019), "ISA's tender for solar water pumps pulls down prices by half", www.livemint.com/news/india/isa-s-tender-for-solar-water-pumps-pulls-down-prices-by-half-11574879259311.html.

Borgstein, E., Wade, K., and Mekonnen, D. (2020), "Capturing the productive use dividend: Valuing the synergies between rural electrification and smallholder agriculture in Ethiopia, Rocky Mountain Institute, www.rmi.org/insight/ethiopia-productive-use/.

CEEW (2018), "Solar for irrigation: A comparative assessment of deployment strategies", www.ceew.in/sites/default/files/CEEW-Solar-for-Irrigation-Deployment-Report-17Jan18_0.pdf.

CEFC (2021), Year of firsts for trailblazing clean energy investor, www.cefc.com.au/media/r0flqsvn/cefc_2020-21_investmentupdate.pdf.

Climate Bonds Initiative (2020), *Unlocking Brazil's Green Investment Potential for Agriculture*, www.climatebonds.net/files/reports/brazil_agri_roadmap_english.pdf.

Cooper, D. (2018), "Energising agriculture value chains for sustainable business in remote areas", http://minisites.ieep.eu/assets/2367/En-Ag_nexus_-_COP24_DCooper.pdf.

Crippa, M., *et al.* (2021), "Food systems are responsible for a third of global anthropogenic GHG emissions", *Nature Food* 2: 198-209, https://doi.org/10.1038/s43016-021-00225-9.

EEP Africa (2021), "Solar irrigation for smallholder farmers scaled-up with debt financing", https://eepafrica.org/sunculture-catalyst-loan/.

EEP Africa (2018), "Opportunities and challenges in the mini-grids sector in Africa", https://eepafrica.org/wp-content/uploads/2019/11/EEP_MiniGrids_Study_DigitalVersion.pdf.

Efficiency for Access and IWMI (2021), *Sustainable Expansion of Groundwater-based Solar Water Pumping for Smallholder Farmers in Sub-Saharan Africa*, https://storage.googleapis.com/e4a-website-assets/Sustainable-expansion-of-groundwater-based-solar-water-pumping-for-smallholder-farmers-in-Sub-Saharan-Africa.pdf.

Efficiency for Access (2020), "Solar milling: Exploring market requirements to close the commercial viability gap", https://storage.googleapis.com/e4a-website-assets/SolarMilling_Market-Requirements.pdf.

Efficiency for Access (2019), *Solar water pump outlook 2019: Global trends and market opportunities*, https://storage.googleapis.com/e4a-website-assets/Solar-Water-Pump-Outlook-2019.pdf.

Elico Foundation (2020), "Solar-powered irrigation systems transforming smallholders farming practices in rural Tanzania", https://elicofoundation.org/solar-powered-irrigation-systems-transforming-smallholders-farming-practices-in-rural-tanzania/.

Energy4Impact (2021a), "Solar irrigation Rwanda: Developing a new market for smallholder farmers", https://energy4impact.org/news/solar-irrigation-rwanda-%E2%80%93-developing-new-market-smallholder-farmers.

Energy4Impact (2021b), "How solar technologies could lead Senegal towards self-sufficiency in rice production", https://energy4impact.org/news/how-solar-technologies-could-lead-senegal-towards-self-sufficiency-rice-production.

Energy4Impact (2020), "Solar milling: Exploring market requirements to close the commercial viability gap", https://storage.googleapis.com/e4a-website-assets/SolarMilling_Market-Requirements.pdf.

ESMAP (Energy Sector Management Assistance Program) (2020), *The state of access to modern energy cooking services*, World Bank, Washington, DC, http://hdl.handle.net/10986/34565.

ESCWA (n.d.), Regional initiative to promote small–scale renewable energy applications in rural areas of the Arab region", www.unescwa.org/sub-site/renewable-energy-rural-arab-region-regend.

Ethiopia Job Creation Commission (2021), *Ethiopia Job Creation Through Off-grid Energy Access*, www.ace-taf.org/wp-content/uploads/2021/08/Jobs-and-Energy-Report_Ethiopia-_August_2021.pdf.

Middelberg, S., P. van der Zwan and C. Oberholster (2020), "Zambian farm blocks: A vehicle for increased private sector investments", *De Gruyter Open Agriculture* 5: 817-825, www.degruyter.com/document/doi/10.1515/opag-2020-0079/html.

FAO (2021a), "Three sustainable energy solutions for food production and places where they are used", Food and Agriculture Organization, Rome, www.fao.org/fao-stories/article/en/c/1412108/.

FAO (2021b), "Biogas systems in Rwanda: A critical review", Food and Agriculture Organization, Rome, www.fao.org/3/cb3409en/cb3409en.pdf.

FAO (2020a), "Food loss and waste must be reduced for greater food security and environmental sustainability", Food and Agriculture Organization, Rome, www.fao.org/news/story/en/item/1310271/icode/.

FAO (2020b), *The state of food and agriculture 2020. Overcoming water challenges in agriculture*, Food and Agriculture Organization, Rome, https://doi.org/10.4060/cb1447en.

FAO and CARE (2019), Good Practices for Integrating Gender Equality and Women's Empowerment in Climate-Smart Agriculture Programmes. Atlanta. 108 pp. Licence: CC BY-NC-SA 3.0 IGO.

FAO (2019a), "Priorities related to food value chains and the agri-food sector in Nationally Determined Contributions", Food and Agriculture Organization, Rome, www.fao.org/3/ca5740en/ca5740en.pdf.

FAO (2019b), *The state of food and agriculture. moving forward on food loss and waste reduction*, Food and Agriculture Organization, Rome, www.fao.org/3/ca6030en/ca6030en.pdf.

FAO (2019c), *Measuring impacts and enabling investments in energy-smart agrifood systems*, Food and Agriculture Organization, Rome, www.fao.org/3/ca4064en/ca4064en.pdf

FAO (2018a), *The future of food and agriculture: Alternative pathways to 2050*, Summary version, Food and Agriculture Organization, Rome, www.fao.org/3/CA1553EN/ca1553en.pdf.

FAO (2018b), "Sustainable food systems: Concept and framework", Food and Agriculture Organization, Rome, www.fao.org/3/ca2079en/CA2079EN.pdf.

FAO (2018c), *Costs and benefits of clean energy technologies in the milk, vegetable and rice value chains*, Food and Agriculture Organization, Rome, www.fao.org/3/I8017EN/i8017en.pdf.

FAO (2018d), Climate Smart Agriculture Source Book, Module B5 on Integrated Production Systems, Food and Agriculture Organization, Rome, www.fao.org/climate-smart-agriculture-sourcebook/production-resources/module-b5-integrated-production-systems/b5-overview/en/.

FAO (2016), "How can women control water? Increase agriculture productivity and strengthen resource management", Food and Agriculture Organization, Rome, www.fao.org/3/i6405e/i6405e.pdf.

FAO (2015a), "The economic lives of smallholder farmers", Food and Agriculture Organization, Rome, www.fao.org/3/i5251e/i5251e.pdf.

FAO (2015b), *Opportunities for agri-food chains to become energy-smart*, Food and Agriculture Organization, Rome, www.fao.org/3/i5125e/i5125e.pdf.

FAO (2014), *Developing sustainable food value chains: Guiding principles*, Food and Agriculture Organization, Rome, www.fao.org/3/i3953e/i3953e.pdf.

FAO (2012), "Energy-smart food at FAO: An overview", Environment and Natural Resources Management Working Paper 53, Food and Agriculture Organization, Rome, www.fao.org/3/an913e/an913e.pdf.

FAO (2011), "Energy-smart food for people and climate", Issue Paper, Food and Agriculture Organization, Rome, www.fao.org/3/i2454e/i2454e.pdf.

FAO, n.d., "Food loss and food waste", Food and Agriculture Organization, Rome, www.fao.org/food-loss-and-food-waste/flw-data.

FAO and Ministry of Energy of Zambia (2020), "Sustainable bioenergy potential in Zambia: An integrated bioenergy and food security assessment", Environment and Natural Resources Management Working Paper 84, Food and Agriculture Organization, Rome, www.fao.org/3/cb1528en/CB1528EN.pdf.

FAO and GIZ (2019). *Measuring impacts and enabling investments in energy-smart agrifood chains: Findings from four country studies*, Food and Agriculture Organization, Rome, www.fao.org/3/ca4064en/ca4064en.pdf.

FAO and GIZ (2018), "The benefits and risks of solar-powered irrigation: A global overview", Food and Agriculture Organization, Rome, www.fao.org/3/I9047EN/i9047en.pdf.

Fraunhofer ISE (n.d.-a), "Agrivoltaics: Opportunities for agriculture and energy transition", https://agri-pv.org/en/.

Fraunhofer ISE (n.d.-b), "Agrivoltaics for Mali and Gambia: Sustainable electricity production by integrated food, energy and water systems", www.ise.fraunhofer.de/en/research-projects/apv-maga.html.

Fritsche, U., *et al.* (2017), "Energy and land use", Global Land Outlook Working Paper, United Nations Convention to Combat Desertification and International Renewable Energy Agency, www.globalbioenergy.org/uploads/media/1709__UNCCD_IRENA__Energ__and_Land_Use..pdf.

GCCA (2018), "2018 Global cold storage capacity report", International Association of Refrigerated Warehouses, Global Cold Chain Alliance, www.gcca.org/sites/default/files/2018%20GCCA%20Cold%20Storage%20Capacity%20Report%20final.pdf.

GBEP (2011), The Global Bioenergy Partnership Sustainability Indicators for Bioenergy, First edition, December 2011, www.globalbioenergy.org/fileadmin/user_upload/gbep/docs/Indicators/Report_HYPERLINK_updated_CM_25-05-2017.pdf

GIZ (2021), "Ice from solar energy for sustainable fishing", Gesellschaft für Internationale Zusammenarbeit (GIZ), Eschborn, www.giz.de/en/mediacenter/97240.html.

GIZ (2020), "Productive use of energy: Moving to scalable business cases", Gesellschaft für Internationale Zusammenarbeit (GIZ), Eschborn, https://endev.info/wp-content/uploads/2021/03/EnDev_Learning_Innovation_PUE.pdf.

GIZ (2019), *Gender-Transformative Change in ATVET*, www.giz.de/en/downloads/giz2020_en_Gender-Transformative_Change.pdf.

GIZ (2018), "The White gold of Félane", *Akzente: The GIZ Magazine*, https://akzente.giz.de/en/artikel/white-gold-felane.

GIZ (2016a), "Solar powered irrigation systems: Technology, economy, impacts", Gesellschaft für Internationale Zusammenarbeit, Eschborn, https://energypedia.info/wiki/Solar_Powered_Irrigation_Systems_-_Technology,_Economy,_Impacts.

GIZ (2016b), "Promoting food security and safety via cold chains", Gesellschaft für Internationale Zusammenarbeit, Eschborn, www.giz.de/de/downloads/giz_2016_Food_Security_Cold_Chains.pdf.

GOGLA (2021), *Global off-grid solar market report: Semi-annual sales and impact data, July-December 2020*, Amsterdam, www.gogla.org/sites/default/files/resource_docs/global_off-grid_solar_market_report_h2_2020.pdf.

GOGLA (2020), "Productive use of off-grid solar, appliances and solar water pumps as drivers of growth", Utrecht, Netherlands, www.gogla.org/sites/default/files/resource_docs/gogla_pb_use-of-off-grid-solar_def.pdf.

GOGLA (2019), "How solar water pumps are pushing sustainable irrigation", Utrecht, Netherlands, www.gogla.org/about-us/blogs/how-solar-water-pumps-are-pushing-sustainable-irrigation.

Government of India (n.d.), "PM-KUSUM (Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan) Scheme", www.india.gov.in/spotlight/pm-kusum-pradhan-mantri-kisan-urja-suraksha-evam-utthaan-mahabhiyan-scheme

Guilpart, J. (2018), "Refrigeration in food production and processing", IIR–UN Environment Cold Chain Technology Brief, Paris, https://wedocs.unep.org/bitstream/handle/20.500.11822/32570/8141Food_Proc_EN.pdf?sequence=1&isAllowed=y.

Hunt, S. (2020), "Five years on from the launch of Green Mini-Grids Africa: What has been achieved, and what have we learned?" *MGP Newsletter*, May 12, Mini-Grids Partnership. https://minigrids.org/5-years-on-from-the-launch-of-green-mini-grids-africa-whats-been-achieved-and-what-have-we-learned/.

IDCOL (2020), "IDCOL solar irrigation program: driving sustainable agricultural development in rural Bangladesh", Presentation, Infrastructure Development Company Ltd., https://prize.equatorinitiative.org/wp-content/uploads/formidable/6/Presentation-IDCOL-Solar-Irrigation-Program.pdf.

IDCOL (n.d.), "Solar irrigation program", https://idcol.org/home/solar_ir.

IEA (2019), *World Energy Balances and Statistics, 2019 edition*, International Energy Agency, Paris, www.iea.org/reports/world-energy-balances-2019.

IEA, IRENA, UNSD, World Bank and WHO (2021), *Tracking SDG 7: The Energy Progress Report*, World Bank, Washington, DC, http://hdl.handle.net/10986/33822.

IEA and FAO (2017), "How to guide for bioenergy: Roadmap, development and implementation", International Energy Agency, Paris, www.fao.org/3/i6683e/i6683e.pdf.

IEEFA (2021), "Powering up solar irrigation effort will support India's renewable energy targets", Institute for Energy Economics and Financial Analysis, Lakewood, Ohio, USA, https://ieefa.org/ieefa-powering-up-solar-irrigation-effort-will-support-indias-renewable-energy-targets/.

IFAD (2020), "Renewable energy for smallholder agriculture", International Fund for Agricultural Development, Rome, www.ifad.org/documents/38714170/41937394/resa.pdf/715e1a75-35df-bafc-f491-7effde867517.

IFC (2020), *Off-grid solar market trends report 2020*, International Finance Corporation, Washington, DC, www.lightingglobal.org/wp-content/uploads/2020/03/VIVID%20OCA_2020_Off_Grid_Solar_Market_Trends_Report_Full_High.pdf.

IMED Foundation (n.d.), "Tanzania Renewable Energy Business Incubator (TAREBI II)", https://imedfoundation.or.tz/portfolio/tanzania-renewable-energy-business-incubator-ii/.

IRENA (International Renewable Energy Agency) (2021a), *World energy transitions outlook: 1.5°C pathway*, International Renewable Energy Agency, Abu Dhabi, https://irena.org/publications/2021/Jun/World-Energy-Transitions-Outlook.

IRENA (2021b), "Renewable energy capacity statistics 2021", International Renewable Energy Agency, Abu Dhabi, www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Apr/IRENA_RE_Capacity_Statistics_2021.pdf.

IRENA (forthcoming 2021), "Renewables for heating/cooling in agriculture sector: Case studies from Southeast Asia", International Renewable Energy Agency, Abu Dhabi.

IRENA (2019a), "Accelerating geothermal heat adoption in the agri-food sector: Key lessons and recommendations", International Renewable Energy Agency, Abu Dhabi, https://irena.org/publications/2019/Jan/Accelerating-geothermal-heat-adoption-in-the-agri-food-sector.

IRENA (2019b), *Sugarcane bioenergy in southern Africa: Economic potential for sustainable scale-up*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Apr/IRENA_Sugarcane_bioenergy_2019.pdf.

IRENA (2017), *Renewable Energy Outlook: Thailand*, International Renewable Energy Agency, Abu Dhabi, www.irena.org/-/media/files/irena/agency/publication/2017/nov/irena_outlook_thailand_2017.pdf.

IRENA (2016a), "Renewable Energy Benefits: Decentralised solutions in the agri-food chain", International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2016/Sep/Renewable-Energy-Benefits-Decentralised-solutions-in-agri-food-chain.

IRENA (2016b), "Solar pumping for irrigation: Improving livelihoods and sustainability", International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2016/Jun/Solar-Pumping-for-Irrigation-Improving-livelihoods-and-sustainability.

IRENA (2015), "Renewable Energy in the Water, Energy & Food Nexus", International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2015/Jan/Renewable-Energy-in-the-Water-Energy--Food-Nexus.

IRENA (2014), "Global bioenergy: Supply and demand projections: A working paper for REmap 2030", International Renewable Energy Agency, Abu Dhabi, www.irena.org/-/media/Files/IRENA/Agency/Publication/2014/IRENA_REmap_2030_Biomass_paper_2014.pdf.

IRENA, IEA Bioenergy and FAO (2017), "Bioenergy for sustainable development", International Renewable Energy Agency, Abu Dhabi, www.ieabioenergy.com/wp-content/uploads/2017/01/BIOENERGY-AND-SUSTAINABLE-DEVELOPMENT-final-20170215.pdf.

IWMI (International Water Management Institute) (2021), "Capitalizing on crowdfunding to scale up solar irrigation", International Water Management Institute, Colombo, www.agrilinks.org/post/capitalizing-crowdfunding-scale-solar-irrigation.

IWMI (2020), "Solar Irrigation for Agricultural Resilience (SoLAR)", International Water Management Institute, Colombo, https://solar.iwmi.org/wp-content/uploads/sites/43/2020/02/About-SoLAR.pdf.

IWMI (2010), "Managing water for rainfed agriculture", International Water Management Institute, Colombo, www.iwmi.cgiar.org/Publications/Water_Issue_Briefs/PDF/Water_Issue_Brief_10.pdf.

IWMI (n.d.), "Rain-fed agriculture: Summary", International Water Management Institute, Colombo, www.iwmi.cgiar.org/issues/rainfed-agriculture/summary/.

Jai, S. (2020), "NABARD, Agri Infra Fund Loans to be made available for PM-KUSUM scheme", www.business-standard.com/article/economy-policy/nabard-agri-infra-fund-loans-to-be-made-available-for-pm-kusum-scheme-120112700965_1.html.

Khoza, T., *et al.* (2018). "Factors affecting smallholder farmers' participation in agro-processing industry", Agricultural Economics Association of South Africa, 2018 Annual Conference, September 25-27, Cape Town, South Africa.

Kitinoja, L. (2013), "Use of cold chains for reducing food losses in developing countries", Postharvest Education Foundation, La Pine, Oregon, USA, www.postharvest.org/Cold_chains_PEF_White_Paper_13_03.pdf.

Lange, B., *et al.* (2016), "Promoting food security and safety via cold chains: Technology options, cooling needs and energy requirements", Deutsche Gesellschaft für Internationale Zusammenarbeit, Eschborn, https://energypedia.info/wiki/File:GIZ_ (2016)_-_Promoting_Food_Security_and_Safety_via_Cold_Chains.pdf.

Leh, M. (2021), "Mapping tool helps private sector identify high-potential locations for solar irrigation pumps", https://wle.cgiar.org/thrive/2021/06/23/mapping-tool-helps-private-sector-identify-high-potential-locations-solar.

Lorentz (2012), Solar-powered Vineyard Irrigation System, https://partnernet.lorentz.de/files/lorentz_casestudy_vineyardlurton_chile_en.pdf.

Lukhanyu, M. (2021), "Brookside partners with Sun-Culture to provide farmers with Solar-powered irrigation system", https://techmoran.com/2021/05/26/brookside-partners-with-sun-culture-to-provide-farmers-with-solar-powered-irrigation-system/.

McDonald, R., *et al.* (2009), "Energy sprawl or energy efficiency: Climate policy impacts on natural habitat for the United States of America", PLOS One, https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0006802

MEFCC (Ministry of Environment, Forest and Climate Change) (2021), "Nationally Determined Contributions 2020", Ministry of Environment, Forest and Climate Change, People's Republic of Bangladesh, https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Bangladesh%20First/Updated_NDC_of_Bangladesh.pdf

Mercy Corps (2020), "Policy brief: Achieving food security in Kenya through smart solar irrigation", Mercy Corps, Portland, Oregon, USA, www.mercycorpsagrifin.org/wp-content/uploads/2020/06/AgriFin-Solar-Irrigation-Report-Full-Length.pdf.

Minas Mae, A., *et al.*, (2020), "Bridging agricultural livelihoods and energy access: Barriers and opportunities for rice and rice husk value chains in Labutta, Myanmar", https://themimu.info/sites/themimu.info/files/documents/Report_Bridging_Agricultural_Livelihoods_Energy_Access_in_Laputta_MercyCorps_Sep2020.pdf.

Mitra, S., Sugam, R. and Ghosh, A. (2014), "Collective action for water security and sustainability: Preliminary investigations", Council on Energy, Environment and Water, Delhi, India, www.ceew.in/publications/collective-action-water-security-and-sustainability.

MNRE (Ministry of New and Renewable Energy) (2021a), *Annual Report 2020-21*, Ministry of New and Renewable Energy, Government of India, https://mnre.gov.in/img/documents/uploads/file_f-1618564141288.pdf.

MNRE (2021b), "Invitation for expression of interest for installation of innovative solar pump", Ministry of New and Renewable Energy, Government of India, https://mnre.gov.in/img/documents/uploads/file_f-1617858634315.pdf.

MNRE (2021c), "Physical progress", Ministry of New and Renewable Energy, Government of India, https://mnre.gov.in/the-ministry/physical-progress.

MNRE (2020), "Draft policy framework for developing and promoting decentralized renewable energy (DRE) livelihood applications in rural areas: For comments of stakeholders", Ministry of New and Renewable Energy, Government of India, https://mnre.gov.in/img/documents/uploads/file_f-1603098738291.pdf.

Morocco Ministry of Agriculture, Fisheries, Rural Development, Water and Forests (n.d.), "The Green Morocco Plan", www.ada.gov.ma/en/foundations.

MSSRF and CRT Nepal (2019), The Gender Factor in Political Economy of Energy Sector Dynamics. Research report RA3, ENERGIA, www.energia.org/assets/2019/02/RA3-Gender-factor-in-political-economy.pdf.

Musinguzi, B. (2021), "Will solar milling technology take root in Africa?", www.monitor.co.ug/uganda/special-reports/will-solar-milling-technology-take-root-in-africa--3338902?utm_content=buffer7a11a&utm_medium=social&utm_source=twitter.com&utm_campaign=buffer.

Next Billion (2020), "Milling on mini-grids: How Africa's largest crop could go diesel-free", https://nextbillion.net/milling-on-mini-grids-africa-maize/.

NREL (2019), "Benefits of agrivoltaics across the food-energy-water nexus", National Renewable Energy Laboratory, Golden, Colorado, USA, www.nrel.gov/news/program/2019/benefits-of-agrivoltaics-across-the-food-energy-water-nexus.html.

NSAC (2020), "$50 million now available for rural renewable energy projects", https://sustainableagriculture.net/blog/50-million-now-available-for-rural-renewable-energy-projects/.

NSEFI (National Solar Energy Federation of India) (2020), "Agrivoltaics in India: Overview of operational projects and relevant policies", National Solar Energy Federation of India, New Delhi, www.energyforum.in/fileadmin/user_upload/india/media_elements/Photos_And_Gallery/20201210_SmarterE_AgroPV/20201212_NSEFI_on_AgriPV_in_India__1_.pdf.

Nyika, J., *et al.* (2020). "The potential of biomass in Africa and the debate on its carbon neutrality", IntechOpen, www.researchgate.net/publication/344638846_The_Potential_of_Biomass_in_Africa_and_the_Debate_on_its_Carbon_Neutrality/link/5f8664a9458515b7cf7f653a/download.

Philippines Department of Agriculture (2021), "Formulation and implementation of renewable energy program for the agri-fishery sector (REPAFS)", Department of Agriculture/Department of Energy, Republic of the Philippines, www.da.gov.ph/wp-content/uploads/2021/03/jmc01_s2021.pdf.

PIB (Press Information Bureau) (2021), "Agriculture voltage technology", Press Release, Ministry of Agriculture and Farmers' Welfare, Government of India, https://pib.gov.in/PressReleasePage.aspx?PRID=1703539

Power for All (2020), "Mini-grids productive use of energy (PUE) in agriculture", Fact Sheet, www.powerforall.org/application/files/9615/9302/4971/FS_Mini-grids_productive_use_of_energy_PUE_in_agriculture3.pdf.

Powering Agriculture (2020), "Navigating policy and regulation in the clean energy-agriculture nexus: A guide for companies to engage policymakers", https://sun-connect-news.org/fileadmin/DATEIEN/Dateien/New/powering-agriculture_nov2020_navigating-policy-and-regulation-in-the-clean-energy-agriculture-nexus-a-guide-for-companies-to-engage-policymakers.pdf.

REEEP (Renewable Energy and Energy Efficiency Partnership) (2019), "Clean Energy Revolving Fund Handbook", Renewable Energy and Energy Efficiency Partnership, Vienna, Austria, www.reeep.org/sites/default/files/CERF-HANDBOOK-REEEP_1.pdf

REEEP (2018), "Clean energy solutions in dairy value chains: Analysing and sharing challenges and opportunities in India and Kenya", Renewable Energy and Energy Efficiency Partnership, Vienna, Austria, www.reeep.org/sites/default/files/Clean%20Energy%20Solutions%20-%20Dairy%20Value%20Chains.pdf

REEEP (n.d.), "Affordable loans for clean energy in agriculture: The clean energy revolving fund", Renewable Energy and Energy Efficiency Partnership, Vienna, Austria, www.reeep.org/sites/default/files/REEEP%20-%20Clean%20Energy%20Revolving%20Fund%20Brochure.pdf.

Remmington, G. (2015), "Gender and water security: The rest of the puzzle", International Water Association, London, https://iwa-network.org/gender-and-water-security-the-rest-of-the-puzzle/.

REN21 (2021), *Global status report 2021*, Renewables 2021, Paris, www.ren21.net/wp-content/uploads/2019/05/GSR2021_Full_Report.pdf.

Ringler, C., *et al.*, (2021), "Water for food systems and nutrition", Food Systems Summit Brief, https://reliefweb.int/sites/reliefweb.int/files/resources/FSS_Brief_water_food_system.pdf.

SEforAll (2021), *Chilling prospects: Tracking sustainable cooling for all 2021*, Sustainable Energy for All, Vienna, www.seforall.org/system/files?file=2021-05/Chilling-Prospects-21-SEforALL.pdf.

SELCO Foundation (2018), *Sustainable energy and livelihoods: A collection of 50 livelihood applications*, www.selcofoundation.org/wp-content/uploads/2019/01/SF_SELivelihoods-compressed.pdf.

Shakya, B. (2015), "In rural Nepal, tying micro hydropower plants to the main grid brings electricity for all", World Bank, Washington, DC, https://blogs.worldbank.org/endpovertyinsouthasia/rural-nepal-tying-micro-hydropower-plants-main-grid-brings-electricity-all.

Shirley, R. (2020), "Powering agriculture: Unlocking Africa's next green revolution", Policy Briefing, South African Institute of International Affairs, Johannesburg, https://media.africaportal.org/documents/Policy_Briefing_207_shirley.pdf.

Springer-Heinze, A. (2018), *ValueLinks 2.0: Manual on sustainable value chain analysis, Volume 1: Value Chain Analysis, Strategy and Implementation*, ValueLinks, Eschborn, Germany, https://valuelinks.org/material/manual/ValueLinks-Manual-2.0-Vol-1-January-2018.pdf.

SNV (SNV Netherlands Development Organisation) (2014), “Renewable energy for smallholder irrigation: A desk study on the current state and future potential of using renewable energy sources”, SNV, Burkina Faso, www.practica.org/wp-content/uploads/2014/10/Renewable_Energy_for_Smallholder_Irrigation.pdf.

Taghizadeh-Hesary, F., E. Rasoulinezhad and N. Yoshino (2019), “Energy and food security: Linkages through price volatility, *Energy Policy* 128: 796-806, https://doi.org/10.1016/j.enpol.2018.12.043.

Tiwary, R. (2012.), “An experiment in solar power based community tube-wells for irrigation in Nalanda District, Bihar: An assessment”, Water Policy Research Highlight, IWMI-Tata Water Policy Program, www.iwmi.cgiar.org/iwmi-tata/PDFs/2012_Highlight-27.pdf.

Tubiello, F., et al. (2021), “Greenhouse gas emissions from food systems: Building the evidence base”, Environmental Research Letters 16(6): 065007, https://iopscience.iop.org/article/10.1088/1748-9326/ac018e.

UNEP United for Efficiency (2020), “Africa Centre of Excellence for Sustainable Cooling and Cold-chain: Food saved is as important as food produced”, https://united4efficiency.org/wp-content/uploads/2020/10/Africa-Centre-of-Excellence-20210219.pdf

UNIDO (United Nations Industrial Development Organization) (n.d.). “Ethiopia: Integrated agro-industrial parks”, United Nations Industrial Development Organization, Vienna, Austria. www.unido.org/news/ethiopia-integrated-agro-industrial-parks.

USAID (U.S. Agency for International Development) (2020), “Clean energy cold storage”, Technology Case Study, U.S. Agency for International Development, Washington, DC, https://pdf.usaid.gov/pdf_docs/PA00WHC6.pdf.

USAID (2018), “Clean energy for productive use in post- harvest value chains: An integrated literature review with field work for the Kenya and Senegal dairy sectors”, U.S. Agency for International Development, Washington, DC, www.climatelinks.org/sites/default/files/asset/document/2018_USAID_E4AS-Integrated-Lit-Review-and-Case-Study-Report_final-%20Sept-2018.pdf.

Vaghela, D. (2019), “Community enterprise hydro mini grids: A closer look at decentralized renewable energy in South and Southeast Asia”, Presentation, Hydro Empowerment Network, www.irena.org/-/media/Files/IRENA/Agency/Events/2019/Jul/DiptiVaghela_HPNET_IRENA_RRA-Bhutan.pdf?la=en&hash=5D141ADDAD4C92F473A6EFB5B7949741EEF6DB3E.

Van Nguyen, M., et al. (2015), Uses of geothermal energy in food and agriculture – Opportunities for developing countries. Rome, FAO, www.fao.org/3/i4233e/i4233e.pdf

Verploegen, V., R. Ekka and G. Gill (2019), “Evaporative cooling for improved fruit and vegetable storage in Rwanda and Burkina Faso”, Feed the Future, https://horticulture.ucdavis.edu/sites/g/files/dgvnsk1816/files/extension_material_files/Evaporative-Cooling-Improved-Fruit-Vegetable-Storage-in-Rwanda-Burkina-Faso-190531.pdf.

Weselek, A., *et al*. (2019), Agrophotovoltaic systems: applications, challenges, and opportunities. A review. Agron. Sustain. Dev. 39, 35, https://doi.org/10.1007/s13593-019-0581-3.

Wilson, D., *et al.* (2018), “Effects of USB port access on advanced cookstove adoption”, *Development Engineering* 3:, 2018, Pages 209-217, available at: www.sciencedirect.com/science/article/pii/S235272851730057X

Wisions (2014), Powering Milk Chilling Units With Biogas in Pakistan, https://wisions.net/files/uploads/SEPS_Summary_SG016_Pakistan_Biogas_manure_milk_chilling.pdf.

World Bank (2021), “COVID-19’s impact on the transition to clean cooking fuels: Initial findings from a case study in rural Kenya, *Live Wire 2021/115*, World Bank, Washington, DC, http://hdl.handle.net/10986/35258.

World Bank (2020), “Accelerating irrigation expansion in Sub-Saharan Africa: Policy lessons from the global revolution in farmer-led smallholder irrigation”, World Bank, Washington, DC, www.fsnnetwork.org/sites/default/files/2021-01/accelerating-irrigation-expansion-in-sub-saharan-africa.pdf.

World Bank (2019), *The market opportunity for productive use leveraging solar energy (PULSE) in Sub-Saharan Africa*, World Bank, Washington, DC, www.lightingglobal.org/wp-content/uploads/2019/09/IFC-PULSE-Final-Report-30092019_compressed-1.pdf

World Bank (2018), *Agriculture in Africa: Telling myths from facts*, World Bank, Washington, DC, https://openknowledge.worldbank.org/handle/10986/28543.

World Bank and FAO (2014), "Business and livelihoods in African livestock: Investments to overcome information gaps", World Bank, Washington, DC, www.fao.org/3/i3724e/i3724e.pdf.

Zafar, S. (2020), "Cogeneration of bagasse", Bioenergy Consult, www.bioenergyconsult.com/cogeneration-of-bagasse/.

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