Off-grid and decentralized energy solutions for smart energy and water use in the agrifood chain

Technical paper by the secretariat

United Nations
Framework Convention on
Climate Change

Summary

This paper focuses on the opportunities for meeting energy and water demands in the agrifood sector with off-grid and decentralized energy systems and on the co-benefits of these systems for stakeholders across the sector. It has been prepared in response to a request of the Conference of the Parties and on the basis of a review of the literature and discussions that took place during the technical expert meetings held in 2019 under the technical examination process on mitigation.

Renewable energy and energy-efficient technologies suitable for application in the agrifood sector are mature and the cost of their installation are declining. Many examples exist, from small-scale solar power systems for off-grid family farms to large-scale combined heat and power plants for supplying mini grids. Technically viable and socially beneficial low-carbon technologies include wind- and solar-powered water pumps, solar water heaters, straw-fired crop drying heaters, biomass-fired heat and power plants, mini hydropower turbines, insulated cool stores, efficient greenhouse lighting systems, precision irrigation systems, biogas for heat or transport fuel, and solar photovoltaic milk coolers.

The transition by the agrifood sector to taking a circular economy approach to water and energy management and the careful management of ecosystem services under the water–energy–food nexus approach can help avoid environmental impacts, which are of growing concern. Government policies, measures and incentives should be developed to improve freshwater conservation and encourage the circular economy. Policies relating to nature-based solutions and ecosystem services that reduce the demand for energy and water inputs to the agrifood chain should be holistic, given that they involve many stakeholders who often have conflicting interests. Coherent policy development requires dialogue and close collaboration among ministries as well as between national and local authorities.

While there are many examples of the successful deployment of cost-effective energy-smart and climate-smart agrifood systems, these systems have not been widely promoted or deployed in many countries, and off-grid and decentralized energy is yet to become mainstream. The potential for replication and scaling up implementation is good, but will require education, capacity-building and national standards, as well as support for innovative business models that overcome the challenge of high upfront capital costs, where these are a constraint to uptake. A conducive policy environment, developed in consultation with the private sector, can help improve energy access and enable the agrifood sector to reduce its dependence on inputs of fossil fuels and fresh water.

Contents

Abbreviations and acronyms

AC	alternating current
CH4	methane
COP	Conference of the Parties
CO2	carbon dioxide
CO2 eq	carbon dioxide equivalent
DC	direct current
EBRD	European Bank for Reconstruction and Development
FAO	Food and Agriculture Organization of the United Nations
GDP	gross domestic product
GEF	Global Environment Facility
GHG	greenhouse gas
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
LED	light-emitting diode
NDC	nationally determined contribution
N2O	nitrous oxide
OECD	Organisation for Economic Co-operation and Development
PV	photovoltaic
R&D	research and development
SDG	Sustainable Development Goal
SIWI	Stockholm International Water Institute
TEM	technical expert meeting
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNIDO	United Nations Industrial Development Organization

Chapter 1

Introduction

A. Mandate

1. COP 21 resolved to strengthen the existing technical examination process on mitigation[1] and requested the secretariat to organize the process and disseminate its results, including by:[2]

   a. Organizing, in consultation with the Technology Executive Committee and relevant expert organizations, regular TEMs focusing on specific policies, practices and actions representing best practices and with the potential to be scalable and replicable;

   b. Updating, on an annual basis, following the TEMs and in time to serve as input to the summary for policymakers,[3] a technical paper on the mitigation benefits and co-benefits of policies, practices and actions for enhancing mitigation ambition, as well as on options for supporting their implementation.

2. COP 23 concluded the assessment of the technical examination process, and suggested that the key ways of improving its effectiveness are to:[4]

   a. Better integrate the technical examination process with the Marrakech Partnership for Global Climate Action;

   b. Focus on specific policy options and opportunities that are actionable in the short term, including those with sustainable development co-benefits;

   c. Engage expert organizations in organizing TEMs;

   d. Engage Parties and non-Party stakeholders in organizing regional TEMs, building on existing regional climate action events;

   e. Make the TEMs more interactive; provide an agenda and guiding questions well in advance of each TEM; and conclude the TEMs with a session on proposing ways forward and necessary actions;

   f. Provide input to the summary for policymakers, the high-level events and the Talanoa Dialogue.

3. The high-level champions of global climate action, in consultation with the Technology Executive Committee and the Climate Technology Centre and Network, identified the following topic for the technical examination process on mitigation for 2019 in response to a request by the COP:[5] off-grid and decentralized energy solutions for smart energy and water use in the agrifood chain.

1 Decision 1/CP.21, para. 109.
2 Decision 1/CP.21, para. 111.
3 Decision 1/CP/21, para. 111(c).
4 Decision 13/CP.23, paras. 1, 2 and 6–8.
5 Decision 13/CP.23, para. 3.

4. This latest technical paper in the series referred to in paragraph 1(b) above has been prepared in response to the request by the COP. The paper covers the benefits and co-benefits of implementing mitigation policies, practices, actions and technologies that support smart energy and efficient water use in the global food supply chain. The focus of the paper is on identifying solutions that would make the agrifood sector more sustainable; reduce GHG emissions through changing the present reliance of the agrifood sector on fossil fuels; provide renewable energy to rural communities without grid access; and improve the efficiency of energy inputs and water use throughout the food supply chain. The paper also explores options for supporting implementation and the scaling up of implementation of solutions that would enhance mitigation ambition.

B. Objective of the paper

5. The objective of this paper is to compile and share information on the mitigation potential, benefits and co-benefits of policy options, technological innovations and best practices that enable low-carbon energy access and efficient freshwater use throughout the agrifood chain. Actions that could be taken by Parties and non-Party stakeholders to replicate and scale up such innovative solutions are explored. Conservation tillage, land degradation, soil carbon, CH_4 emissions from enteric ruminants and rice paddies, N_2O emissions from nitrogenous fertilizers and animal waste, forest carbon sinks, food retailing, transport, cooking and consumer behaviour are not discussed to a major extent.

6. Energy-smart solutions, such as improved energy efficiency, energy storage technologies, efficient water use, and off-grid, mini grid and decentralized renewable electricity and heating and cooling systems, can provide access to affordable and reliable energy and water by rural communities where food is produced, processed and transported to markets. If widely implemented, these solutions could lead to more sustainable food production and processing methods that would provide a range of benefits to rural communities. The opportunities are linked with the necessary transition to circular economy activities that could enhance the mitigation ambition of pre-2020 action and beyond and support the achievement of the SDGs.

7. This paper is based on information presented at the global TEM on mitigation that took place during the fiftieth session of the subsidiary bodies (held from 17 to 27 June 2019 in Bonn, Germany) as well as at the regional TEMs during Latin America and Caribbean Climate Week 2019 (held from 19 to 23 August 2019 in Salvador, Brazil) and Asia-Pacific Climate Week 2019 (held from 2 to 6 September 2019 in Bangkok, Thailand).[6]

6 Detailed information on the global and regional TEMs on mitigation is available at https://unfccc.int/topics/mitigation/workstreams/technical-examination-process-on-mitigation

8. The information presented in this paper does not imply consensus among Parties on any of the issues or subjects discussed within the context of the TEMs. The paper serves as a summary of the discussions that took place in the context of the TEMs supplemented by the latest knowledge as published in the literature and by leading international organizations and partners working in this field.

C. Structure and scope of the paper

9. Following the introductory chapter, chapter II outlines the issues around the present agrifood chain model in relation to GHG emissions, population growth, energy demand, freshwater supply, the water–energy–food nexus and rural communities. It presents information on the potential, progress, benefits, costs and barriers to enabling emission reduction actions along the agrifood chain and provides a discussion of the status quo of the sector to help explain the global scale of the issues.

10. Chapter III provides an overview of off-grid and decentralized energy solutions and then outlines the opportunities and benefits that exist when:

    a. Decarbonizing the primary production, post-harvest and food processing phases of the agrifood chain;

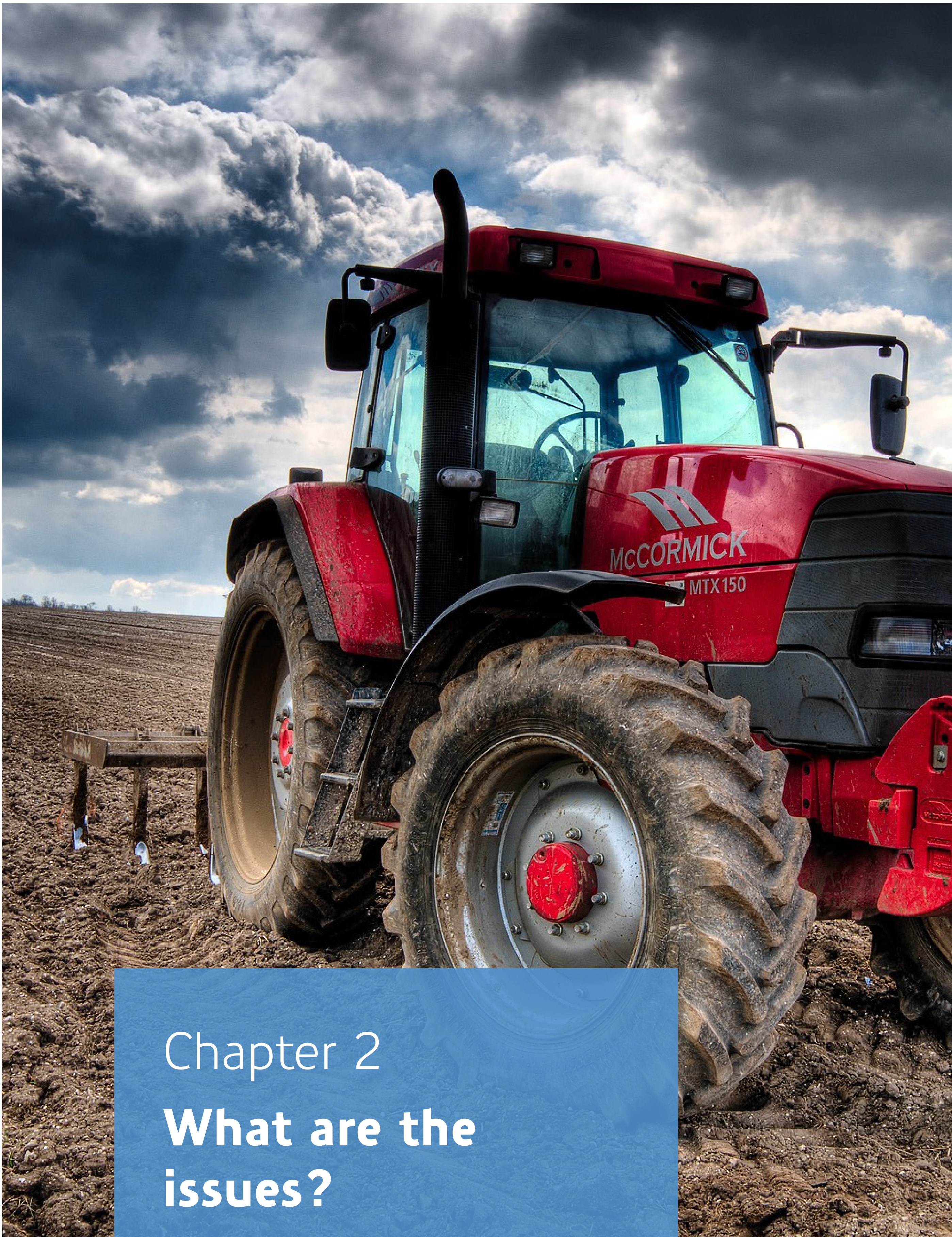
    b. Moving away from a linear 'take, make, waste' approach towards a circular economy;

    c. Using nature-based solutions and ecosystem services to support the water–energy–food nexus approach and improve revenue and livelihoods for rural communities;

    d. The SDGs are supported by the agrifood sector transition.

11. A range of technology solutions that could increase the mitigation potential of food production and processing in the coming decade if supported by strong policies are discussed. Case studies throughout the chapter highlight real-world experience and illustrate the potential of solutions. Recommendations for stakeholders are included at the ends of the subchapters.

12. Chapter IV considers the next steps that could accelerate action to reduce GHG emissions throughout the agrifood sector as a result of deploying off-grid and decentralized energy solutions and efficient water use. It considers government policies and the short-term actions needed to be taken by various stakeholders in order to encourage greater implementation of climate actions by 2020 and beyond. Innovative business models are examined, possible technological solutions for the longer term discussed and knowledge gaps identified.



Chapter 2
What are the issues?

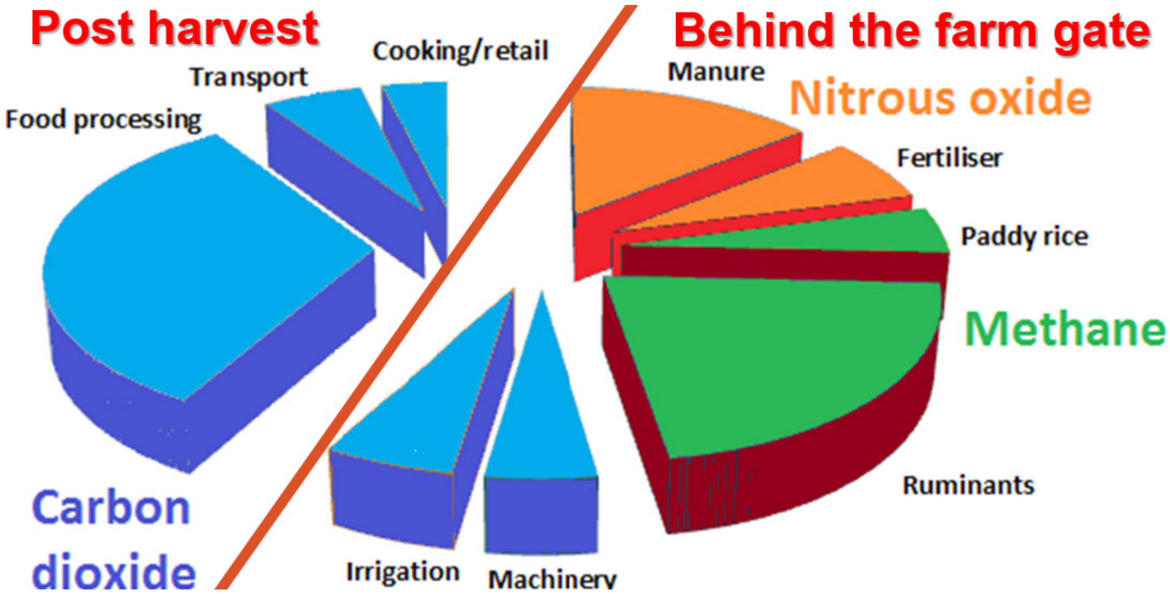
13. The overarching problem inherent in securing the food supply, ensuring the sustainability of the agrifood chain and reducing GHG emissions (linked mainly to energy and water inputs) in agriculture was described well by Barack Obama in May 2017 when he stated, "As well as energy, climate change discussions should focus more on food production and cutting food waste, but a lack of knowledge is fuelling public resistance. All these things can help us ensure that, in producing the food that we need to feed the billions of people on this planet, we're not destroying the planet in the process"(Pujol-Mazzini, 2017).

A. Greenhouse gas emissions

14. The global agrifood sector uses more than 30 per cent of global end-use energy demand, which is mostly met by fossil fuel sources, and emits around 22 per cent of total anthropogenic GHGs (FAO, 2011a). As well as CO_2 from the combustion of fossil fuels used for field machinery, water pumping, drying, heating, cooling and transport throughout the food value chain, other GHGs, including CH4 (mainly from ruminant livestock and paddy rice) and N2O (mainly from nitrogenous fertilizers and animal waste) are emitted (see figure 1). Land-use change – converting forests and peatlands to areas of agricultural production – also releases carbon stored in the biomass and soil, which contributes a further 10 to 15 per cent of total emissions as CO_2. These emissions are not discussed in this paper as it focuses on behind-the-farm-gate and post-harvest CO_2 emissions.

Figure 1

Shares of total annual greenhouse gas emissions from the global agrifood sector arising from behind-the-farm-gate and post-harvest activities

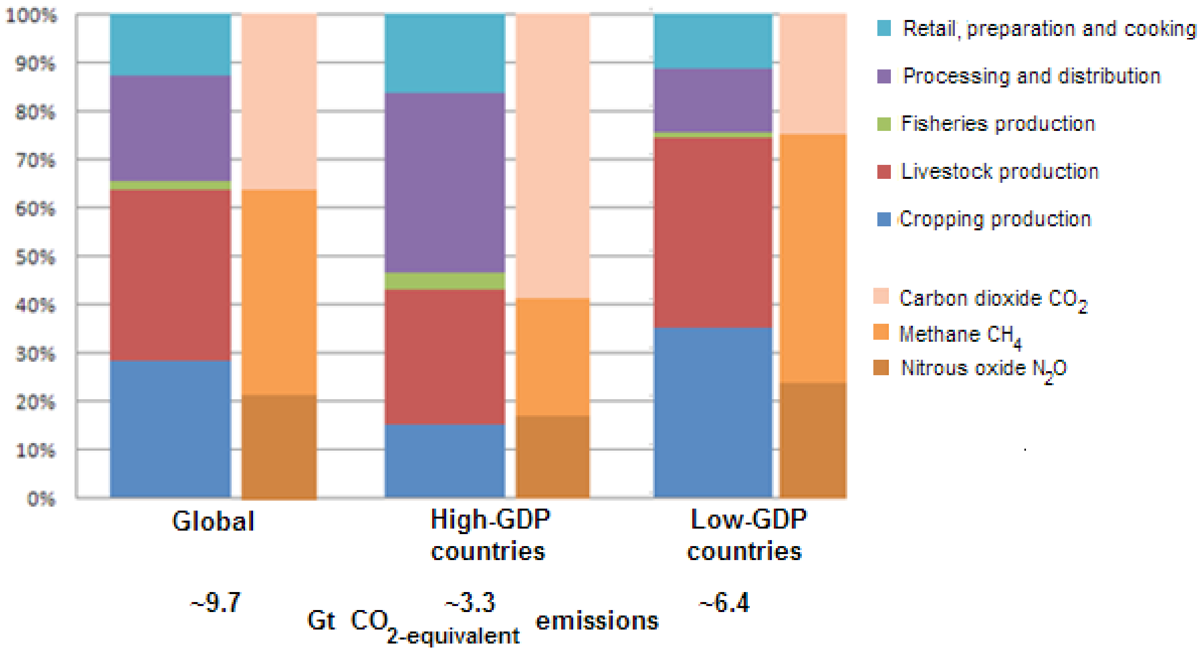


Source: Adapted from FAO, 2011a, annex 1.

15. Around 9.7 Gt CO_2 eq GHGs are emitted annually by the agrifood sector. The top 50 high-GDP countries are responsible for one third (2.2 t CO_2 eq/capita/year) and the remaining countries are responsible for two thirds (1.16 t CO_2 eq/capita/year) of global emissions from the food value chain (see figure 2). The top 50 high-GDP countries have more intensive food production systems than the low-GDP countries, which have a greater portion of small subsistence and family farm systems and hence lower food processing activities. The higher amount of fossil fuel combustion for machinery, transport, heat and electricity generation in the high-GDP countries results in a higher share of CO_2 emissions. The high level of CH_4 emissions in low-GDP countries is attributable, in part, to emissions from paddy rice fields.

Figure 2

Shares of total greenhouse gas emissions and the three main greenhouse gases for the global food value chain and for countries with high and low gross domestic product



Source: FAO, 2011a, fig 7.

B. Climate change impacts on agrifood

16. It is well understood that the 1.5 °C target, or even the 2 °C target, of the Paris Agreement cannot be met without significant GHG emission reductions in the agrifood sector. Agricultural production systems are highly vulnerable to the impacts of climate change. Ocean warming, floods, droughts, cyclones and sea level rise will affect the future health and productivity of pastures and crops, livestock production, fish stocks and forests. These impacts will also

threaten the livelihoods of rural communities dependent on these resources. For some countries with developing economies, the impacts could exacerbate the food security challenges already being experienced (FAO, 2018a).

17. In lower latitude regions, where most developing and least developed countries are located, agriculture is already being adversely affected by a higher frequency and extremity of droughts and floods. Rising average temperatures will stress crops and livestock as well as have an impact on water sources and thereby reduce productivity and food quality. Elsewhere, the increased incidence of droughts and floods and the spread of pests and diseases will cause crop failures and food losses. Protected cropping (in greenhouses), hydroponics, urban agriculture, bio-culture, algae production and aquaculture all offer more climate-resilient means of producing food; however, they usually require higher energy inputs per unit of food produced.

C. Population growth

18. The world population, currently 7.6 billion, is expected to reach 9.8 billion in 2050 (UNDESA, 2017), resulting in increased food demand. Protein demand per capita is also increasing. It has been projected that food production will need to increase by 50 per cent to meet the projected food demand in 2050. This production increase must be achieved without placing additional pressure on natural resources, particularly freshwater resources, and without creating higher demand for fossil fuels.

19. Sufficient nutritious food for everyone has to be produced sustainably while minimizing the negative impacts food production currently imposes on the planet's resource base and climate and without compromising the natural capital or ecosystem services that presently support food production. Growth in food supply could be achieved to a limited extent by increasing the productivity of crops and animals (e.g. tonnes per hectare, milk solids per cow) through improved management and breeding; developing innovative technologies; changing consumption patterns; reducing food losses; and minimizing negative externalities in the food supply value chain. However, a major transition will be needed to avoid hunger and freshwater scarcities.

D. Energy demand

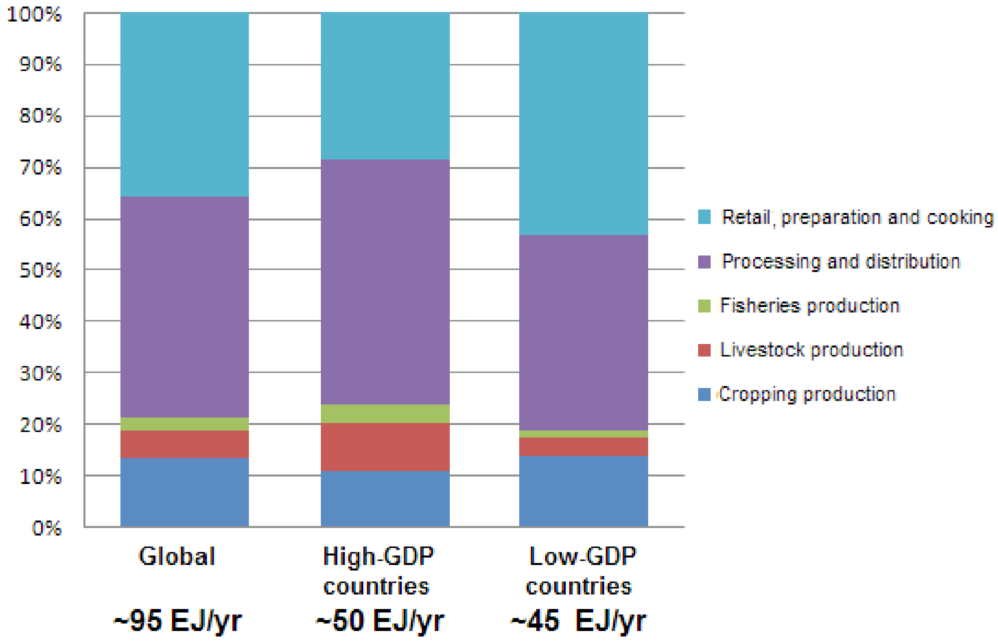
20. Around 95 EJ of energy from coal, oil and gas (one third of global end-use energy demand) is consumed annually to produce, process and bring to the table the world's food. Direct energy inputs essential for the primary production[7] of food are also needed for harvesting, irrigation, storage,

7 The term 'primary production' as used in this paper includes cropping, pastoral livestock, intensive livestock, aquaculture and fishing, but largely excludes forest production, which is less relevant to the topic.

processing, transport, retailing and cooking. Indirect energy inputs are needed for the cool chain as well as for fertilizer and machinery manufacture (see figure 3 for shares of energy inputs throughout the agrifood chain). The total of 95 EJ/year in 2011 was around 32 per cent of the global end-use energy demand (more than 300 EJ/year). The more intensive farm and food processing systems in the top 50 high-GDP countries consumed around 35 GJ/capita/year, whereas for the low-GDP countries, where subsistence farming is common and a greater share of total energy is used for cooking, the agrifood sector consumed only around 8 GJ/capita/year (FAO, 2011a).

Figure 3

Shares of energy inputs throughout the agrifood chain



Source: FAO, 2011a, fig. 6.

21. With the exceptions of human labour, animal power, the combustion of traditional biomass to provide heat (fuelwood and dung comprise around 12 per cent of total global primary energy demand), and renewable heat and electricity (small shares at present), most of the agrifood sector's energy demand is met by combusting fossil fuels (Sims et al., 2015). However, the high financial cost and volatile prices of oil, coal and natural gas raise concerns about future energy security, production costs, competitiveness and affordable food prices for consumers (OECD, 2017). Emissions of black carbon (a short-lived climate forcer produced from diesel engines, brick making, charcoal production and fuelwood combustion in cookstoves (Sims, Gorsevski and Anenberg, 2017)) that arise from the agrifood chain are also of growing concern.

22. The total energy required to bring food to the table can be a significant share of a nation's total consumer energy supply; for example, about 15 per cent in the United States of America, about 20 per cent in the United Kingdom

of Great Britain and Northern Ireland, and as much as 30 per cent in New Zealand, where the economy depends on food production and the export of a wide range of processed food products. In low-GDP countries, the share of national energy demand used for the agrifood chain can be even higher – as much as 55 per cent – of which around 10 per cent is for primary production and transport over short distances, 15 per cent is for processing and 75 per cent is for cooking using traditional biomass.

23. It is expected that energy and water inputs in the agrifood chain will need to increase over the coming decades to avert climate-related challenges while simultaneously attempting to increase agricultural productivity. Increasing fossil fuel dependence has to be avoided. The needs to decarbonize energy sources throughout the agrifood chain, improve water use efficiency and transition to a more sustainable food supply system through a combined water–energy–food nexus approach are urgent (IRENA, 2016). Decentralized energy systems that depend on renewable energy will have a key role to play, as will the improvement of energy efficiency on farms and in water pumping, transport and food processing (see chap. III.B–C below).

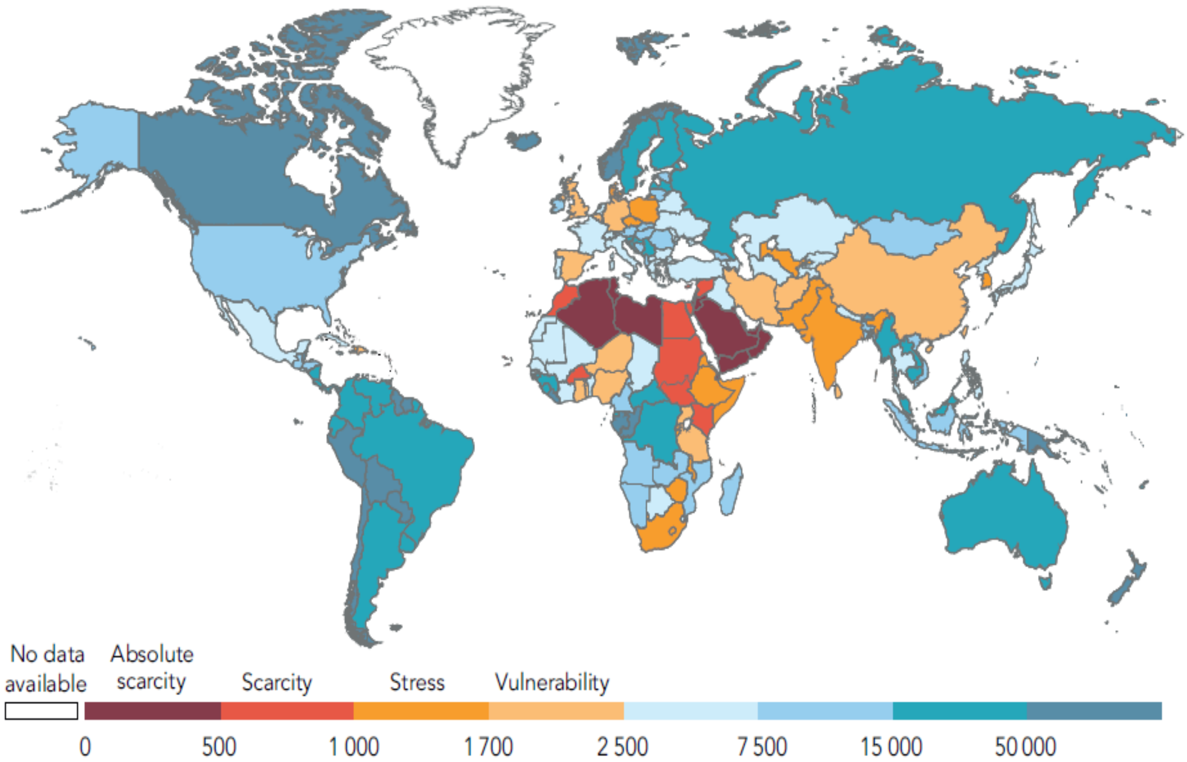
E. Freshwater supply

24. Globally, the demand for fresh water is projected to increase by more than 50 per cent by 2050, with agricultural demand for water increasing by 20 per cent or more (Smedly, 2017). Withdrawal of fresh water from lakes, rivers, wetlands and aquifers is already around 4,500 billion m^3/year. Agriculture consumes nearly three quarters of that withdrawal (excluding natural rainfall), with irrigated land producing around 45 per cent of the world's food supply.

25. The extraction of surface water affects lake, stream and river ecology and flow rates. Freshwater shortages are already occurring owing to the depletion of aquifers and rivers, the lowering of water tables (where extraction has been greater than the recharge rate) and the adverse impacts of climate change such as glacial retreat (e.g. in East Africa and the Andean countries of Latin America). Many countries have shifted their designation from 'water-abundant' to 'water-scarce'[8] because of their increasing demand for water as a result of climate change and population growth (see figure 4). To exacerbate the situation, agrichemical use, fertilizer infiltration, soil sediment run-off, waste from livestock, food processing effluents and nitrate infiltration often adversely affect local waterways, aquifers, and estuaries. Such pollution can also have impacts on biodiversity.

8 For example, Jordan, which now has a freshwater supply of only around 140 m^3/capita/year. See chapter III.B.5 below for details about Jordan's irrigation policy.

Figure 4
Total freshwater resource availability per capita by country in 2013



Source: UNESCO, 2015.
Note: The horizontal scale of m^3/capita/year is non-linear.

26. Where energy supply is available and affordable, contaminated watersheds can be restored to acceptable ecological quantity and quality by improving the management of local farms, fisheries, food processing factories and wastewater treatment plants. Monitoring water availability, managing water extraction rates and employing efficient irrigation technologies can also contribute to watershed restoration.

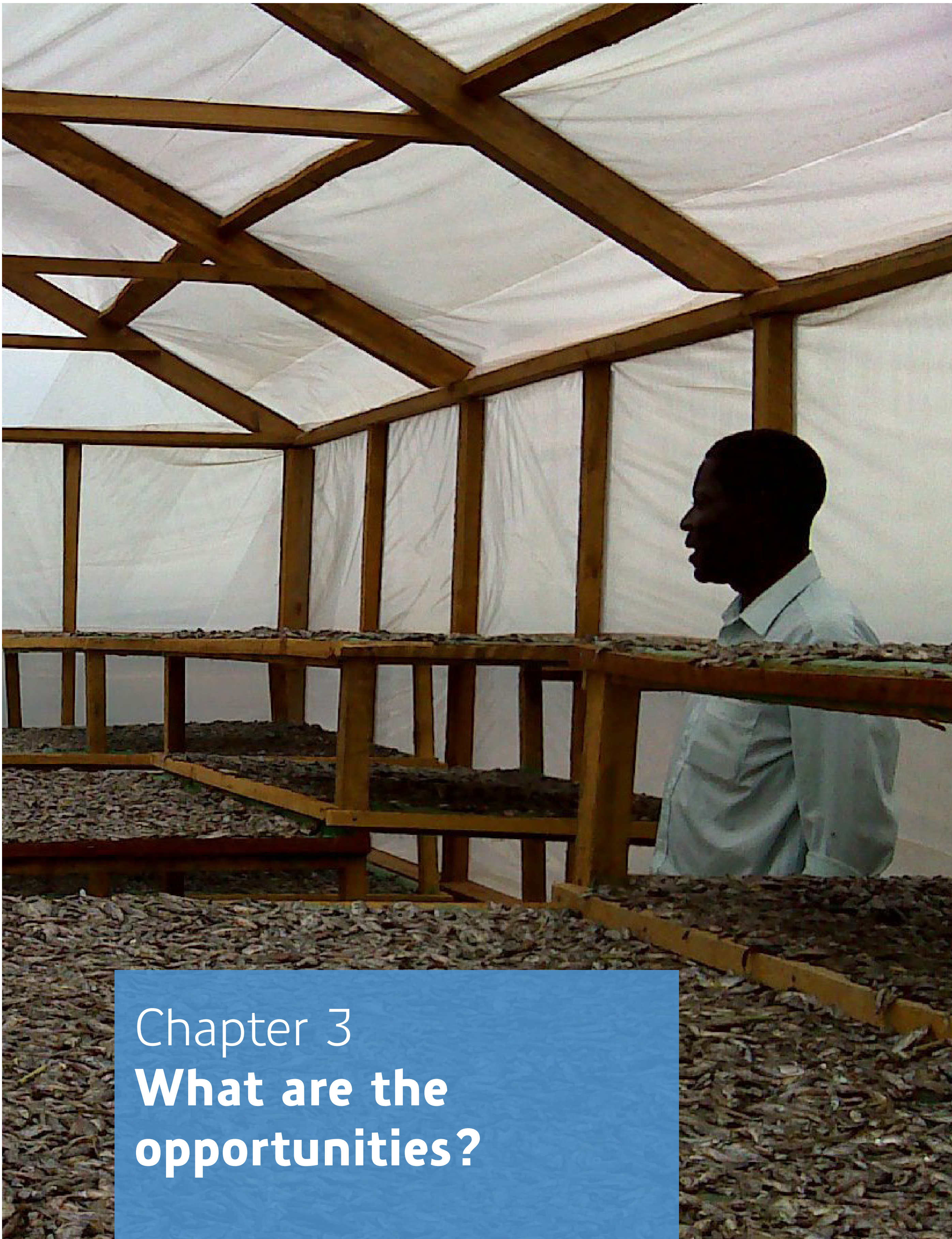
F. Water–energy–food nexus

27. The current global agrifood supply chain is highly dependent on large inputs of fossil fuels and fresh water, together with inputs of nutrients such as phosphate (from mining and extraction) and nitrogen (from the manufacture of ammonia or urea). The current linear 'take, make, waste' approach relies on depleting finite resources, so is not sustainable. There is a necessity for the agrifood sector to transition to adopting a circular economy approach that replaces fossil fuels with renewable energy and bioenergy, recycles water and nutrients, avoids food losses and reduces waste (see chap. III.D below).

28. Despite all the sustainability problems of the present model of the agrifood chain, including its high share of GHG emissions, there is potential for it to evolve, adapt and implement innovative technologies and systems so that it becomes part of the solution to climate change. The environmental and economic impacts of the global food system can be reduced, food security enhanced and access to energy increased by the rapid and wide deployment of decentralized energy systems based on renewable energy options, as well as by the improvement of energy efficiency and water use efficiency throughout the agrifood chain.

G. Rural communities

29. Approximately 1 billion people are without access to electricity and around three times that number rely on unsustainable fuelwood and animal dung for cooking and heating. The majority of people lacking access to modern energy live in rural areas where more than 70 per cent of the world's poor people live. The basic rural economies in these areas depend on agriculture and small-scale manual agrifood processing activities. Many rural and island communities that do have access to grid electricity often have expensive diesel motors driving generators, with distribution using local mini grids. Even rural communities connected to a national grid tend to have inadequate and insecure supply, with frequent outages. Rural communities are therefore often limited to producing low-quality food products and other goods of little diversity destined for local markets. The provision of affordable, reliable and environmentally sustainable decentralized energy systems using renewable energy sources and local mini grids could drive community development, strengthen livelihoods and improve the quality of life (IRENA, 2016). In addition, by retaining revenue within local communities, the economic benefits of selling electricity from community-owned decentralized energy networks provide additional sources of income and can help alleviate poverty.



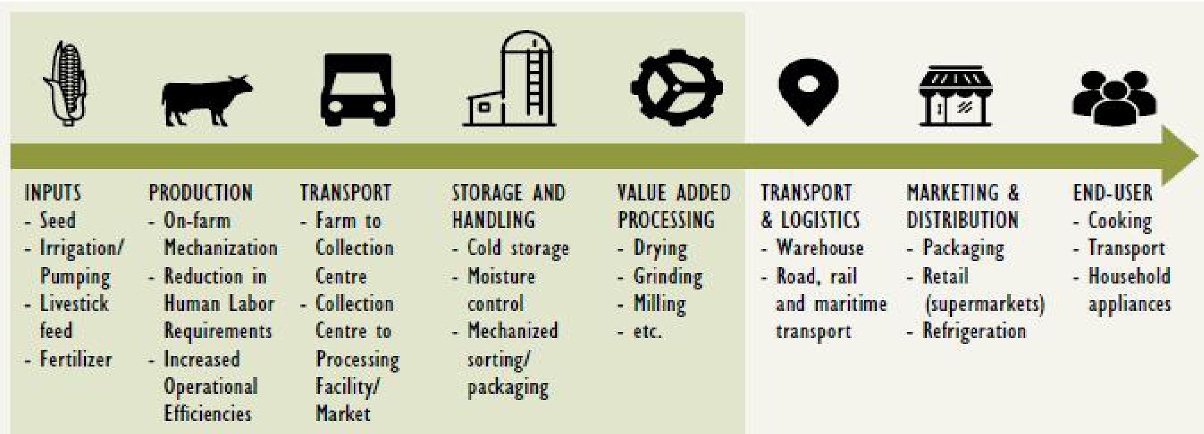
Solar fish drying at Kachulu Beach, Malawi by Matthews Tsirizeni is licensed under CC BY-NC-ND 2.0

Chapter 3
What are the opportunities?

30. Technological advances along the agrifood chain can unlock mitigation potential and generate sustainable development benefits (see figure 5). This paper focuses on the production, storage, handling and value-added processing components of the chain, providing limited discussion of the transport, marketing and end-user consumption components. For small farmers supplying local markets with fresh produce, only production and transport are relevant. Emphasis is on the potential for GHG emission reduction actions linked to energy and water inputs. The progress of developments and the benefits, costs and barriers to deployment are assessed on the basis of real-world experience. Related policies are covered in chapter IV below.

Figure 5

Energy inputs required at links throughout the 'plough to plate' agrifood chain



Source: Flammini et al., 2019.

31. Many opportunities exist at all levels along the agrifood chain. Farmers and local community members can benefit from secure and affordable energy supply, improvements in energy efficiency, reduction in water demand, and the avoidance of food losses through better post-harvest storage. These actions all lead to cost savings, higher revenue and more sustainable practices.

32. Businesses can benefit from deploying innovative technologies and systems as they become mainstream. Examples of these technologies are solar- and wind-powered water pumps, heating and drying systems using biomass, solar-powered ice-making equipment, small-scale milk cooling systems and energy-efficient cool storage designs. New business models are under development that will help overcome the high capital cost barrier for small farms and operators. The real-world case studies presented throughout this paper illustrate a few of the many demonstration projects that have been established to assess new systems under development and others near to, or having reached, full commercialization.

33. Local, regional and national governments are ideally placed, given the present concerns over meeting future food demand, to support their rural constituents and businesses in moving towards a more sustainable food supply system. Developing appropriate policies and measures, including R&D investment and capacity-building, can improve livelihoods by:

    a. Decarbonizing the primary production and post-harvest phases of the agrifood chain, such as by encouraging decentralized renewable energy systems that can also offer energy access to all;

    b. Adapting to climate change impacts that can affect the food supply chain while increasing food productivity and access to markets;

    c. Securing non-contaminated freshwater supplies and water-efficient irrigation systems;

    d. Moving towards a circular economy;

    e. Accelerating the uptake of nature-based solutions.

34. A range of adverse environmental impacts are frequently observed to result from the practices of both small subsistence farms, family farms and fisheries that supply local markets, and large intensive farming systems linked with vertically integrated corporations producing high volumes of food products for supermarket chains or export. This paper focuses on smaller-scale farms and food processing systems in low-GDP countries for which energy and water are key demands and inputs along the entire agrifood chain. Many of the principles do, however, also apply to large-scale farms and agrifood businesses in high-GDP countries.

35. To assist the reader in understanding the concepts being discussed and their relationship with production enterprises at various scales, 'small' and 'large' farms and food processing enterprises have been differentiated, even though there are no rigid boundaries between the two scales. Figure 6 clarifies the relationships between the concepts discussed throughout this paper and the scale of activity. The typology is based on qualitative assessments of unit scale, level of production intensity, labour demand, direct and indirect fossil fuel dependence, investment capital availability, food markets supplied and energy intensity. Supplying food markets and retail companies is feasible at all levels other than subsistence, but to do so, small- and large-scale producers usually have to invest in modern cool chain facilities that commonly require a reliable electricity supply. It should be noted that there are many exceptions to this typology. For example, small tea plantations usually employ many pickers and small family-owned fishing boats have relatively high fossil fuel dependence and related costs.

Figure 6

Simplified typology of typical subsistence, small-scale and large-scale farms and fisheries

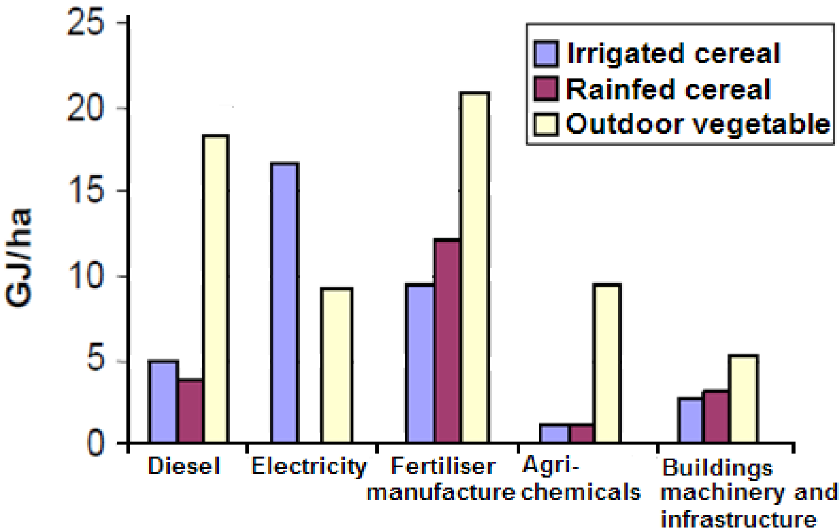
Scale of producer	Overall input intensity	Human labour units	Animal power use	Fossil fuel dependence	Capital availability	Major food markets	Energy intensity
Subsistence level	Low	1-2	Common	Zero	Micro-finance	Own use	Low
Small family unit	Low	2-3	Possible	Low/medium	Limited	Local fresh/process/ own use	Low to high?
	High	2-3	Rarely	Medium/high	Limited	Local fresh/regional process/own use	Low to high?
Small business	Low	3-10	Rarely	Medium/high	Medium	Local/regional/export	Low to high?
	High	3-10	Never	High	Medium	Local/regional/export	Low to high?
Large corporate	High	10-50	Never	High	Good	Regional process/export	Low to high?

Source: FAO, 2011a.

36. Major variations in energy demand per hectare are observed depending on the type and scale of primary production enterprise, as illustrated for three agricultural enterprises in New Zealand (see figure 7). The direct energy inputs of an extensive unsubsidized grazing enterprise in Australia (2–3 GJ/ha) are far lower than those for an intensive subsidized dairy farming system in the Netherlands (70–80 GJ/ha) (Smil, 2008). However, the energy intensity per kilogram of food product depends on the relative productivity of the enterprise.

Figure 7

Shares of direct and indirect energy inputs for primary production systems in New Zealand



Source: Barber, 2004.

A. Overview of off-grid and decentralized energy solutions

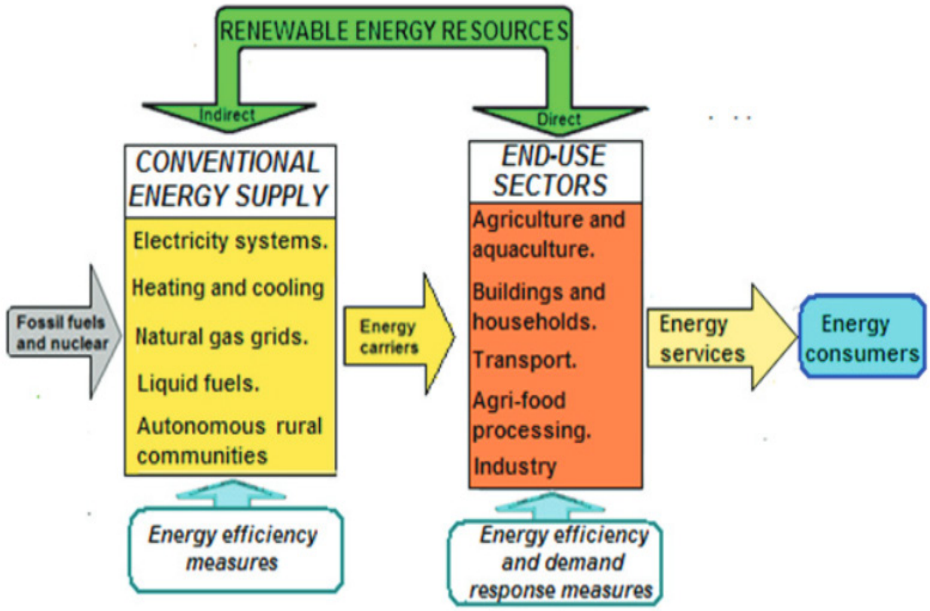
37. Renewable energy systems that generate and distribute energy independently of a centralized electricity grid to provide energy access can be stand-alone or off-grid, or use mini grids (REN21, 2018). All these systems "provide a wide range of services – including lighting, operation of appliances, cooking, heating and cooling – in both urban and rural areas of the developing world. These systems represented about 6% of new electricity connections worldwide between 2012 and 2016, mainly in rural areas" (REN21, 2018). Examples of national status are that "about 13% of the population of Bangladesh have gained access to electricity through off-grid solar systems, while 51% of the off-grid population of Kenya is served by distributed renewable energy systems" (REN21, 2018).

38. Climate-smart agriculture aims to simultaneously increase farm productivity, raise revenue, adapt to climate change impacts, improve the resilience of ecosystems and livelihoods, reduce emissions of GHGs, and where feasible, remove carbon from the atmosphere and lock it up in soils and forests.

39. Renewable energy "can enhance access to reliable, affordable and clean modern energy services, is particularly well-suited for remote rural populations, and in many instances, can provide the lowest cost option for energy access" (IPCC, 2011). Off-grid renewable energy systems depend on local wind, solar, hydro and biomass resources. Appropriate conversion technologies can provide heat, power and transport fuels for uptake by the end-user sectors of the agrifood chain directly as well as indirectly through integration with conventional energy supplies (see figure 8). In both cases, energy efficiency improvements have a key role to play in reducing GHG emissions from fossil fuel use – they can help reduce fossil fuel dependency and secure energy and water access. Energy storage technologies can help ensure the reliability of supply.

Figure 8

Renewable energy: indirect use through integration with conventional energy supply systems and direct use by end-use sectors on site



Source: IPCC, 2011, chapter 8.

40. Energy-efficient and renewable energy systems are well understood and their use is growing rapidly worldwide. Electricity generation in many remote rural communities has depended on importing diesel, gasoline or liquefied petroleum gas to fuel stationary engines that drive generators (a generator set – also known as a genset). Owing to the potential supply constraints, costs and difficulties of delivering these fuel supplies to remote locations, there is a growing trend in the use of local renewable resources, where these are available. It is often feasible to use agricultural land and food processing factories for both producing food and capturing useful energy by installing wind turbines, solar PV panels, mini hydro turbines, geothermal heat and power systems, and bioenergy plants fuelled by local biomass resources. Food processing plants often have biomass co-products available (e.g. rice husks, tallow, nut shells, vegetable peelings) that can be converted to useful heat, electricity and transport fuels via combustion, anaerobic digestion, pyrolysis and other technologies.

41. A barrier to economic and social development in many rural regions is the poor availability of efficient modern energy services that can help improve food production and distribution and hence safeguard food security (FAO, 2011a). Several business models exist for decentralized energy systems that can also provide co-benefits for landowners, businesses and rural communities. In the more remote rural areas and on islands, access to energy facilitates economic activity, improves livelihoods and alleviates energy poverty. A significant segment of the population in low-GDP

countries with a largely food-based economy lives in poverty, depending primarily on farming and fishing for their livelihoods. Improving food production and processing practices, post-harvest and storage facilities, and distribution and retail trade can contribute to poverty alleviation. Many of these functions require the local availability of modern energy services, ideally based on sustainable energy systems rather than fossil fuel combustion. Further studies are needed to fully grasp the potential benefits of sustainable energy systems. Innovative policy implementation, institutional arrangements and financing mechanisms that involve several partners and stakeholders can help support the development of these systems.

42. Energy systems introduced into remote areas can contribute to rural development through increased productivity per capita; improved communications and Internet connection; enhanced social and business services, such as education and the establishment of markets; better supply of water for drinking and irrigation; improved security due to street lighting; decreased poverty; and improved health, sanitation and environmental conditions (IPCC, 2011). Renewable electricity supply options that are easily dispatchable (e.g. small hydro or bioenergy (see table 1)) can better match varying local load profiles than those that fluctuate widely (e.g. wind and solar). Dispatchable generation technologies are therefore often an essential part of the generation mix of a central or decentralized electricity system, because an increase in the share of variable systems in the mix, even if these systems have lower costs per kWh generated, can lead to grid instability. Energy storage is an alternative solution; but while it provides reliability of supply, it tends to be more expensive, although battery costs continue to decline.

Table 1
Characteristics of renewable energy technologies suitable for electricity generation and integration into rural mini grids

Technology type	Generation plant size range[a] (MW)	Variability of generation[b] (timescale)	Degree of plant dispatchability[c]	Geographic diversity potential[d]	Predictability[e]	Capacity factor range[f] (%)
Bioenergy						
Solid biomass	0.1–200	Seasonal, depending on biomass type and when available	XXX	X	XX	50–90
Biogas	0.01–40					
Solar PV	0.003–100	Minutes to months	X	XX	X	12–27
Geothermal power	2–100	Years	XXX	Not applicable	XX	60–90
Hydropower						
Run-of-the-river	0.01–15 000	Hours to years	XX	X	XX	20–95
Reservoir	1–20 000	Days to years	XXX	X	XX	30–80
Ocean energy						
Tidal range	0.1–300	Hours to days	XX	X	XXX	22–28
Tidal current	1–200	Hours to day	X	X	XX	19–60
Wave	1–200	Minutes to years	X	XX	XX	22–30
Wind power	0.1–200	Minutes to years	X	XX	X	20–50

Source: Adapted from IPCC, 2011.
a Range of typical rated plant capacity.
b Timescales for which variability is significant for power system integration and reliability.
c Degree of plant dispatchability: X, low; XX, partial; XXX, easily.

d Degree to which siting of the technology may reduce variability and improve predictability: X, moderate potential; XX, high potential.
e Accuracy of plant power output prediction at relevant timescales to assist system operation: X, moderate; XX, high; XXX, very high.
f Varies with site location (e.g. a wind turbine located on a 10 m/s mean annual wind speed site generates three times more power than one on a 7 m/s site).

43. Off-grid systems are autonomous energy supply systems for farmers, rural communities and business enterprises not connected to an electricity grid and without easy access to liquid fuels for diesel-powered generation. They are typically small in scale and usually located in remote areas or on small islands with a low energy demand. There is growing interest in the potential to develop decentralized energy supply mini grids. These could utilize advanced control systems to integrate numerous small heat and power generation technologies using smart meters and time-of-use and price-responsive appliances. However, the overall system costs, benefits and limitations are site-specific so need careful analysis. Demonstration projects based on small, autonomous community micro grids (see box 1) have been established in Brazil, China, Denmark, India, Japan, the United States and elsewhere, but few have been built in rural communities in developing countries.

44. Planning an autonomous energy system in a remote rural area involves considering future fossil fuel supply options for the location; the local renewable energy resources available; the costs of delivering, installing and maintaining technologies; future technology innovation prospects; and the possible avoidance of construction costs (should new or expanded grid infrastructure ever become an option for the location).

45. The desire to avoid the high costs of transmission and distribution associated with extending the main grid makes decentralized energy systems the most economical solution for providing energy access to many remote rural areas in developing countries (IRENA, 2015). Local mini grids can be designed to incorporate a communications network, turning them into 'smart' mini grids.

Box 1
Micro grids

A micro grid (or slightly larger mini grid) is a small-scale local electricity distribution network that delivers power from a range of distributed energy generation sources, including renewable energy systems, combined heat and power plants, and diesel- or gas-powered gensets, to multiple users.

Stand-alone micro grids based on solar power and other renewables – but possibly with diesel genset backup and battery storage – have the potential to electrify remote areas. Establishing micro grids is usually more efficient, more technically and economically feasible, and more effective than extending a national grid to a remote location.

Micro grids provide the opportunity for social organizations to enter the energy market by establishing co-operatives that benefit members through excluding conventional electricity enterprises and therefore selling cheaper electricity.

Renewable energy can be integrated with other generation sources so that micro grids can provide markets for local generators while aiming to provide electricity at prices that are affordable for local residents and businesses. If the micro grid is initially connected to a national grid, the ability to disconnect and operate discretely may be possible.

A practical barrier to micro grids is the possible perception by rural communities that they do not provide reliable AC electricity, that is, without outages and unstable voltage fluctuations. Demonstrations of micro grids may need to be developed, monitored and widely promoted to build greater confidence in the technology.

46. Autonomous electricity systems can usually be designed to provide the full range of energy services needed to support the agrifood sector, including heating, lighting, drying, space cooling, refrigeration, desalination, water pumping and telecommunications. Compared with large electricity generation systems, smaller autonomous systems may have limited access to renewable energy supply options – this will depend on their location. In addition, forecasting wind and solar resources accurately, implementing peak demand smoothing effects of demand-side response options (e.g. shutting down cool stores or hot water heating for periods of a few hours) and utilizing geographical and technical diversity to avoid peak loads all become more difficult for smaller systems.

47. In rural communities with small electricity distribution networks, in small villages using simple low voltage DC mini grids and in individual buildings the limited deployment of a single type of renewable electricity generation technology such as micro hydro or solar PV with battery storage can be a good option (see box 2).

Box 2

Case study: Solar-powered mini grids in Ghana

A World Bank/GEF project, linked with other partner organizations and the private sector, invested around USD 230 million in five mini grids to provide electricity to health centres, small businesses and approximately 10,000 residents of fishing communities in Ghana. Mini hydro and wind power were considered but solar PV was ultimately chosen for all five locations to take advantage of the economies of scale and related simplicity in maintenance, which would make the systems affordable, resilient and able to be managed by local staff. The Government of Ghana has established a legal and regulatory framework comprising measures to support the further development of the nascent renewable energy industry in the country.

Source: World Bank, 2018.

48. Autonomous systems with high shares of variable wind and solar resources will need to focus on energy storage as well as on various types of demand response to provide the system with stability. Highly flexible generation systems enable a reliable balance between ever-fluctuating demand and supply to be maintained even when the wind is not blowing or the sun is not shining.

49. For electricity to become affordable for rural customers, small autonomous systems often have difficult trade-offs to make between wanting a reliable and continuous supply and needing to minimize overall supply costs. For people, currently without access to electricity, relatively low standards of reliability may be acceptable, at least in the short term – until battery or other storage systems (e.g. electrolysers to produce the energy carrier (hydrogen) and fuel cells to use it for electricity generation) become cheaper, recyclable and more reliable.

50. Energy storage technologies are an attractive option for autonomous systems, but currently – no matter whether they have 1 kWh or 1 MWh capacity – have relatively high investment costs. The costs of large-scale storage projects using lithium ion batteries have fallen 35 per cent in the past 12 months such that "batteries co-located with solar or wind projects are starting to compete with coal- and gas-fired generation for the provision of 'dispatchable power' that can be delivered whenever a grid needs it in many markets and without subsidies" (McCrone, 2019).

51. Battery storage with capacity sufficient to meet two to three days of electricity demand can be installed, but the cost of such a storage option should be carefully evaluated against the desired level of reliability. Small PV systems and small wind turbines coupled with battery storage packs are already in common use. Other options include hydrogen storage, pumped hydrosystems, backup diesel gensets, and fuelling of gensets with gaseous or liquid biofuels. Biofuels produced from oil crops such as sunflower, palm or Jatropha tree can be used to power diesel engines used to generate electricity and those installed in tractors, harvesters and trucks. Raw

vegetable oil can be used directly but only in the short term as resulting engine malfunctions become likely over time. Raw oils are usually chemically processed to convert them from triglycerides to esters that have properties more closely resembling diesel fuel, with which they can be blended. Biogas is cheap and easy to store at low or medium pressure in butyl containers or cylinders. Liquid biofuels such as biodiesel can be stored in steel or butyl rubber tanks.

52. Heating and cooling demands in rural locations can be met using renewable energy, particularly where good solar, geothermal or biomass resources are available. Variability may be of some concern where solar thermal is used, but it can be overcome through the addition of thermal storage solutions such as hot water (or cold water in the case of cooling systems).

53. Distributed energy systems such as solar thermal, small bioenergy combined heat and power plants, ground-source heat pumps, micro hydrosystems, building-integrated or stand-alone solar PV, and small wind turbines have all been demonstrated, and there are many successful examples of their subsequent commercialization. Domestic and commercial buildings, including buildings used by small agrifood businesses, can be designed to be energy-efficient (e.g. with air-tight structure, good heat insulation, and efficient ventilation, air conditioning, lighting and water heating). They can also use embedded renewable energy systems that generate as much energy as they consume with the option to sell surplus heat or power to local consumers.

54. Integrating renewable energy conversion technologies and balancing options and end-use technologies in an autonomous energy system depend on the site-specific availability of renewable resources and the local energy demand, which can vary with local climate and the range of farm enterprises, businesses and lifestyles involved. Prioritization of the available options for integrating large shares of wind and solar into these autonomous energy systems will depend on the type of system, geographic location and expectations of reliability.

55. In terms of demand-side measures, autonomous renewable energy systems can be integrated with selected end-use technologies that use surplus electricity only when it is available. These include solar stills, humidifiers and dehumidifiers, membrane distillers, reverse osmosis or electrodialysis water desalinators, water pumps using solar PV and an AC or DC motor, solar adsorption refrigerators, and oilseed presses for the production of biodiesel transport fuel.

56. Micro hydroschemes are popular in hilly regions and provide a resource-dependent, continuous power supply, but they have the risk of generation output being constrained in dry seasons. For run-of-the-river hydroelectricity, a cost-efficient solution for system balancing can be used for load control instead of controlling the power generation output.

57. Where suitable and sustainable biomass supplies are available, including an organic waste stream, their use can often be the cheapest option for providing basic services for cooking, water heating, lighting and small-scale power generation. Solar thermal water heating can easily and cheaply be used in isolated rural dwellings and provides environmental, social and economic co-benefits.

58. Barriers to the deployment of the wide range of renewable energy technologies available include difficulties with making their design, construction and maintenance appropriate for a specific location. These difficulties can lead to capital investment and operational cost increases, inadequate maintenance and possible failure, in turn leading to the poor public perception of a specific technology that would be hard to change even if it is not fully justified. Establishing standards, certifying products, integrating planning tools and developing a knowledge database could help in avoiding technology reliability problems. Local capacity-building, the training of installers and maintenance workers, good planning and careful market establishment could result in lower operational and maintenance costs and enhanced reputation of the technology in question, as well as in greater employment opportunities and other social benefits.

59. Deploying renewable energy systems into autonomous systems on a broad scale may require policy measures to help cover the costs and provide an enabling environment. Even where a renewable energy system is considered to be economically feasible over its lifetime, appropriate financial schemes to remove the barrier of high initial capital investment costs could be warranted.

B. Decarbonizing primary production

60. With the exception of subsistence farming, primary food production is carbon intensive because of its heavy reliance on fossil fuel energy, especially regarding field machinery and fertilizer manufacture and use. Currently a great deal of irrigated water is wasted, which, given the present reliance on diesel-powered engines to power the pumps, also adds to GHG emissions. This subchapter focuses primarily on the implementation of technological solutions to decarbonizing the primary production phase of the agrifood chain, for which the aim is to enhance the uptake of renewable energy, including through applying new business models. Capacity-building and financial barriers limit wider deployment in some countries.

1. Energy intensity

61. Many opportunities to improve energy efficiency exist throughout the food supply chain, including on the farm and during storage and transport. Present practices at each stage of the chain can be adapted to become less energy

intensive.[9] Cost-effective energy efficiency measures can be implemented while delivering food in a safe and environmentally sustainable manner.

62. For primary production systems, the aim should be to produce similar amounts of food, or more, per unit of land area or water input, but using less energy input to do so. In high-GDP countries, declining energy intensities have been observed in recent decades partly because average annual incremental crop yields continue to increase. Conversely, steadily increasing fertilizer and machinery use in low-GDP countries, such as China and India, have led to rising energy intensities. Raising the national agricultural energy efficiency level of countries that are below average in this regard could be achieved by employing a range of energy efficiency improvements (Schneider and Smith, 2009).

63. Energy demand for primary production can be lowered by either reducing energy intensity or changing the volume and mix of the food commodities produced to include more commodities with lower energy inputs (e.g. growing vegetable protein to displace animal protein). Because the annual direct energy demand of the primary production sector is only 3–5 per cent of total consumer energy in most countries, energy efficiency measures will not make a significant contribution to reducing national energy demands. However, energy saving measures can assist the profitability of individual enterprises, particularly capture fishing that uses boats with high fuel consumption. Besides containing costs and reducing emissions, energy efficiency measures can also help to make food production less vulnerable to possible interruptions in future energy supply.

64. Reducing energy intensity depends both on behavioural changes being made by farmers and managers and on new practices and technologies that improve energy efficiency at little or no cost being developed and deployed. Historically, energy costs have been a small component of the total operating costs for many agrifood businesses, hence the incentives to reduce energy demand have not been strong. As energy costs increase and more businesses set targets to reduce their carbon footprints, renewed interest in improving energy efficiency to gain win–win benefits is becoming apparent.

65. Where significant capital investment in modern equipment is required, this can become a constraint to adopting improved energy-efficient technologies (Flammini et al., 2019). Examples of technologies with high investment needs include precision farming, irrigation monitoring, boat propellers, global positioning systems for tracking truck routes, speeds and road congestion for transport logistics, LED lighting, heat exchangers and variable-speed electric motors. A balance usually needs to be sought between energy efficiency and current and projected energy costs. The improvement of energy access must consider affordability.

9 Using less energy to achieve the same result, for example the amount of energy input per unit of food produced (MJ/kg).

66. There are many opportunities for reducing the energy intensity of large-scale agrifood systems, and there are good examples of success in doing so, as measured by reductions in energy input/output ratios, energy inputs per kilogram of food processed (MJ/kg) and energy inputs per hectare of land area (MJ/ha). Energy reduction strategies across the diverse range of agrifood management options are complex and can involve trade-offs. For primary production management practices, any methods used to reduce energy inputs that also lower productivity (e.g. simply cutting back the amount of fertilizer applied rather than optimizing the frequency, time and accuracy of application) are rarely beneficial and should be avoided. Primary productions systems with high external inputs do not necessarily have high energy intensities (MJ/kg product), especially when they result in increased yields. Conversely, low-input systems can have relatively high energy intensities if lower yields result.

67. For some small-scale family farms, there may be a case for increasing both direct and indirect energy inputs over time in order to improve productivity and water use efficiency. The most efficient use of energy could possibly result from agroecological farming practices that also achieve good yields and benefit livelihoods. Energy conservation and efficiency measures can be implemented in several ways at all stages along the agrifood chain, including on the farm (see table 2). The energy and energy efficiency savings can be either direct savings owing to changes in technology or behaviour, or indirect savings arising as a co-benefit of agroecological farming practices or of social change. For both large and small farming systems, any means of avoiding food wastage should be encouraged as it usually results in considerable savings of the energy embedded in the food chain and at the same time reduces the growing competition for land and water.

Table 2

Examples of energy efficiency measures involving direct or indirect technological and social interventions in the primary production sector behind the farm gate

Direct	Indirect
Applying water precisely	Selecting lower input crop varieties and animal breeds
Applying fertilizers precisely	Practising agroecological farming
Adopting no-till practices	Reducing water demand and losses
Controlling building environments	Manufacturing more energy-efficient fertilizers and machinery
Managing heat in greenhouses	Identifying fish stock locations and markets using information technology
Improving propeller designs for fishing vessels	

Source: Adapted from FAO, 2011a, and OECD, 2017, where the measures are described in detail.

68. Any improvements in energy efficiency bear the risk of a 'rebound effect'. Such an effect occurs when reductions in energy demand result in lower energy bills, which, in turn, encourage additional energy purchases in other areas. For example, a fisher who saves fuel by more careful operation of his

or her vessel might use the money saved to purchase a larger and faster outboard motor that has higher fuel consumption – the energy intensity of the fish catch (MJ/kg fish) would actually increase although the time spent on the water would decline. While the scale of the rebound effect and its duration are the subject of much debate, there is agreement that the phenomenon is real and should therefore be taken into account when estimating potential overall energy savings.

2. Renewable energy

69. Energy-smart food production systems have been assessed at all scales of farming and fishing in both developing and developed countries (FAO, 2011a). FAO has also undertaken a broad cost–benefit analysis of deploying renewable energy technologies in the agrifood sector using milk, rice and vegetable value chains as examples (Flammini et al., 2019; Flammini, Bracco and Sims, 2018; Sims et al., 2015). Deploying renewable energy systems behind the farm gate to increase productivity and add value and quality to food products is feasible where good resources are available.

70. For any specific location, it is wise to measure mean annual wind speeds, solar radiation levels, stream flows and fluctuations, seasonal volumes of biomass and other relevant variations rather than relying on weather records and estimates. The costs and non-economic benefits of renewable energy have been evaluated in detail: the benefits include improved human health, savings of time, reduced drudgery, savings of water, increased productivity, improved soil quality and fertility, protection of biodiversity, improved livelihoods and quality of life, and reduced risk of food insecurity (Flammini, Bracco and Sims, 2018). Trade-offs need to be taken into account when developing policies to encourage the uptake of sustainable energy technologies.

3. Tractors and machinery

71. In Africa, approximately 80 per cent of cultivation is carried out using hand tools and animal-powered machinery. Increasing the level of agricultural mechanization requires access to affordable and reliable fuel supplies together with suitable financing arrangements; ownership agreements; hiring opportunities for tractors off-farm; availability of spare parts, maintenance and repair services; and skill upgrading and education of farmers (Ashburner and Keinzle, 2011). The 27 million tractors operating in the world (around one third of which are in low-GDP countries) consume around 5 EJ of diesel fuel for land development, transport and field operations (Smil, 2008). Additional fuel demand for the numerous two-wheel designs commonly used (mainly by small farmers) is not known. An approximate further 1.5 EJ/year of energy is used during the manufacture and maintenance of tractors and farm implements.

72. In Bangladesh, the deployment of small mobile demountable multi-purpose diesel engines for powering small boats, tractors and trucks, electricity generators, processing equipment and water pumps (including for irrigation) has enabled agro-mechanization and revolutionized local food production.

Public policy has been changed to allow the import of this innovative Chinese-made equipment that can easily be repaired by local mechanics and be purchased at a lower cost than more sophisticated machinery manufactured in India. The concept has been copied in Nepal and India, with the engines being sold mainly into low-cost farm machinery markets where farm services have expanded as a result of the versatility and transportability of this equipment (Biggs and Justice, 2011). The success of this technology illustrates the benefits that the availability of cheap fossil fuels has brought to food production at the small-farm scale over recent decades, often through government subsidies. Machinery manufacturers have recognized business opportunities, so reducing the dependence of rural communities on fossil fuels in order to reduce GHG emissions will be challenging without government intervention.

4. Water use efficiency

73. The agrifood sector consumes fresh water mainly for irrigation but also for food processing activities. Access to potable fresh water is limited for about 10 per cent of the global population and around one third lacks access to adequate hygiene and sanitation services. Environmental degradation, climate change, population growth, conflict and migration will exacerbate the global water crisis. The most vulnerable groups will be unable to access water and to manage safely potential contamination of drinking water supplies.

74. A part solution to water scarcity in some regions would be for bordering countries to cooperate in order to share river, lake and groundwater systems, improve water resource management, and access water supplies to provide water for all. Fulfilling human rights to safe drinking water and sanitation would contribute to achieving several goals of the 2030 Agenda for Sustainable Development (the SDGs) (UNESCO, 2019).

75. Sharing water across boundaries will require regional cooperation. Currently around two thirds of the world's surface-water resources are shared between two or more countries and that approximately 40 per cent of the world's population lives in watersheds (SIWI, 2019). Therefore, the impacts of water-related decisions cross political borders and cooperation on the use of shared resources is essential (GEF, 2019).

76. The GEF has provided grants to countries sharing river, lake and groundwater systems, having brought these countries together to discuss and realize a common development vision for policy and strategy reforms and investments at the regional, national and local level. The GEF, through its international waters knowledge management program (IW:LEARN),[10] shares lessons learned from International Waters projects in sub-Saharan Africa, Southern Africa, Europe and Central Asia, and South-East Asia with international organizations and other partners.

10 https://iwlearn.net/

5. Irrigation

77. Irrigated land produces around 40 per cent of the global cereal supply. Irrigation produces higher yields than rain-fed systems and provides the option for instigating yearly double and triple cropping. The mechanical pumping of water on approximately 10 per cent of the world's arable land (approximately 300 Mha) consumes around 0.3 EJ/year in powering the pumps plus 0.05 EJ/year in indirect energy for manufacturing and delivery of irrigation equipment (Smil, 2008). In Africa, only 4 per cent of cropland is irrigated, mainly owing to a lack of financial investment in irrigation plants. In India, irrigation practices have increased yields but are powered mainly by diesel engines that are responsible for around 3.7 per cent of the country's total GHG emissions. Energy-intensive electric pumping in deep wells accounts for two thirds of these emissions, and the emissions are projected to rise significantly as shallow water reserves are depleted and the pumping of deeper sources is required.

78. Around two thirds of the global water used for irrigation is drawn from underground aquifers for which extraction rates exceed the recharge rates. This fact, together with the high cost of and energy inputs required for seawater desalination, is the reason some countries, for example Saudi Arabia and Morocco, have reduced irrigated crop production and now rely more heavily on imported grain.

79. Given the pressure on water resources and the increasing demand for food, it is necessary to improve irrigation efficiency. Jordan is a prime example of how taking a water–energy–food nexus view can help a water-scarce country ensure that measures taken to meet different needs do not compromise one another (Tran and VandenBroek, 2014). Solar-powered pumps and drip irrigation cover over 80 per cent of Jordan's cropland as a result of government policies to promote them.[11] Typically, a small solar PV system powers a submersible pump located in a well or a water storage tank, which supplies water through polyethylene distribution lines with internal drippers that enable water to be supplied precisely to the growing crop plants. Taking the nexus view could help other water-scarce countries better manage their limited resources. The link between the high-energy input required for irrigation pumping, especially when the water is extracted from deep underground sources, and the need to restrict water use throughout the agrifood chain, indicates that policies in the future will need to address both water and energy use.

80. Drip irrigation is used widely in some countries, particularly for fruit and vegetable production. Water is applied as and where needed to the soil at lower rates and pressures than in flood and overhead sprinkler irrigation systems, thereby reducing energy demand for pumping. Instead of wetting the whole soil profile, as is done in flood and overhead sprinkler irrigation systems, in drip irrigation water is applied only near the roots of the plants. Drip irrigation can save water, increase crop productivity, and if solar-powered pumps are

11 See AQUASTAT, the FAO Global Information System on Water and Agriculture, at http://www.fao.org/aquastat/en/

used to displace diesel engines or fossil-fuelled main-grid electricity, reduce GHG emissions (see box 3). A solar PV generator or small wind-turbine-powered electric pump can raise the water from a well to an elevated storage tank, from where water can be supplied to the field using gravity pressure. To maintain a higher pressure, the wind turbine and/or PV generator can continuously power the irrigation system either as a stand-alone weather-dependent system or one that is combined with a battery, grid or diesel engine for backup.

Box 3
Case study: Solar-powered water pumps in Rajasthan, India

The State of Rajasthan has the largest solar-powered water pump programme in the world. The programme promotes sustainable livelihoods for farmers in this arid region and increases resilience to acute water shortages. From the initial target of installing 50 solar pumps in 2010–2011, the programme was scaled up and has now installed approximately 30,000 solar pumps, far exceeding its target.

Various State Government agencies combined funding schemes and provided a subsidy of 86 per cent for the capital costs during the initial roll-out of the programme, but the subsidy has been scaled down to 60 per cent.

Farmers now have a better profit margin for their produce. However, along with the benefits – improved water security, climate change resilience and cost savings – is the potential for water wastage owing to overirrigation given that there is no longer a diesel fuel cost associated with water pumping. Drip irrigation is being promoted to counteract this issue and minimize water wastage.

Sources: Ahuja, 2017, and Goyal, 2013.

6. Fertilizers

81. Application of the macronutrients nitrogen, phosphorus and potassium as inorganic fertilizers has contributed significantly to crop yield increases in recent decades and demand for these fertilizers will continue to increase. In 2000, the amount of energy consumed for inorganic fertilizer production was around 7 EJ globally (Smil, 2008). Nitrogen fertilizer production alone accounted for about half of the fossil fuel used in primary production, and significant amounts of N2O are emitted after its application. Average annual inorganic fertilizer applications range from low to zero in sub-Saharan Africa to 50–500 kg/ha in double-cropped Chinese rice fields (Smil, 2008). Nitrogen uptake by plants tends to be as low as around 26–28 per cent of the total applied for cereals and 20 per cent for vegetables. More precise and frequent fertilizer application can improve the uptake efficiency.

7. Livestock

82. Intensive livestock enterprises usually rely on bought-in feed. Extensive pastoral systems for sheep, goats, deer and cattle tend to have lower energy inputs than more intensive livestock systems housed on feedlots or indoors that rely on forage crop production, hay and silage conserved on the farm and purchased feed delivered to the farm, which can account for a significant component of total energy input. Regional differences are evident: small

family farms in low-GDP countries consume about 1 MJ energy per MJ animal-based food energy, whereas more intensive farm systems in high-GDP countries consume about 4 MJ/MJ. Beef grown on feedlots consumes around 80–100 MJ energy input/kg meat, pork 25–70 MJ/kg, chicken 25–35 MJ/kg and fish from trawler capture 5–50 MJ/kg (mainly for the vessel fuel) (Smil, 2008). Beef cattle also produce enteric CH4 and individually consume around 20,000 litres of fresh water per year.

8. Protected cropping

83. Fruit, vegetable and flower production in peri-urban areas using intensive greenhouse designs with closed cycle system, hydroponic or aeroponic cultures (delivering water and nutrients without soil) rely on relatively large direct energy inputs, particularly for LED lighting and seasonal heating. These inputs can amount to as much as 40 MJ/kg fresh product such as tomatoes or peppers (FAO, 2011b). The area covered by simple shade houses is increasing in some countries, for example China and the Republic of Korea – these shade houses have lower energy inputs than energy-intensive heated greenhouses. In general, crops grown in greenhouses can have an energy intensity that is 10 to 20 times higher than that for the same crops grown in open fields.

84. The GHG emission reduction potential of innovative technologies for greenhouses lies in the increased productivity per unit of water, fertilizer and energy used. These technologies combine innovations in greenhouse construction materials, climate control (ventilation, heating, cooling, humidity), lighting and low-carbon energy sources with careful management of soil, water, crops and pests (FAO, 2013). The use of alternative renewable energy sources is also considered an innovative technology for greenhouses, but any such technology and improved practices proposed to reduce emissions will be site-specific.

85. Adoption of the sustainable intensification approach is based on 'Save and Grow' principles to produce more with less (FAO, 2011b). The majority of greenhouses have passive climate control systems based on simple ventilation and shading facilities, and do not need energy-intensive heating or cooling systems. The principles for improving energy efficiency in greenhouse crop production include the continuous application of integrated preventive environmental strategies to processes, products and services in order to increase overall productivity. In warmer countries, energy consumption for the heating of greenhouse crops is significantly lower per kilogram of product than it is in colder countries.

9. Fishing

86. Capture fishing is an energy-intensive method of food production. The global fishing fleet captures around 80–90 Mt fish and invertebrates each year, consuming around 620 litres fuel per tonne of catch (about 25 MJ/kg catch). Indirect energy inputs for boat building and maintenance account for around 10 per cent of the fuel energy consumed (Smil, 2008). Boats are

relatively high fuel consumers and most owners aim to reduce fuel use; fuel costs are typically 15 per cent of their total costs, and can be up to 50 per cent of catch revenue.

87. Small-scale enterprises produce around half of the total fish catch with a fleet of about 4.6 million small vessels. Two thirds of these are powered by internal combustion engines that rely on fossil fuels; the rest, powered by sails and oars, are mainly used in Asia and Africa (FAO, 2016). Small boats typically have inefficient engines that consume large amounts of fuel and that cannot be easily improved, but there is little data on their use.

88. Aquacultural enterprises (fish farming and mariculture) produce a further 55 Mt/year marine products and they are expanding. Some, such as shrimp farming, rely on direct energy for pumping and aerating water as well as on indirect energy for producing and delivering feed.

10. Summary

89. Farms and fisheries have good potential to reduce energy demand through improving efficiency (OECD, 2017) and utilizing local sources of renewable energy (Sims et al., 2015). Doing so would enable the sector to become both a consumer and a producer of energy sources (Vourdoubas and Dubois, 2016). Local renewable heating, cooling and electricity systems can enable improved productivity at all stages along the agrifood chain, including for water pumping, greenhouse production and waste management. Increasing the availability and utilization of decentralized renewable energy systems requires effective policies and regulations, appropriate business models and integrated resource management. Box 4 summarizes solutions for decarbonizing primary production and provides recommendations for stakeholders.

Box 4
Decarbonizing primary production

Technological developments in water and energy use in irrigation are rapidly accelerating, and solar-, wind- and hydro-powered pumps present an opportunity to decarbonize 200 to 300 million smallholder farms before they move to diesel-powered irrigation systems.

Precision farming, aided by tools for providing accurate data on rainfall, hours of solar illumination and soil moisture levels, can enable more efficient and effective farming practices that curb emissions.

Mitigation solutions in agriculture that empower subsistence farmers and smallholders, including women, can lead to major social and economic co-benefits ranging from the empowerment of women to the production of more – and more nutritious and better-quality – foods with increased revenue.

Providing information to farmers and other stakeholders and maintaining good communication with end users is critical when deploying new low-carbon energy technologies and systems. For example, stakeholders need to understand the life-cycle price differences between conventional energy and renewable energy systems and any trade-offs, such as water demand for agriculture competing with water demand for hygiene and sanitation.

Governments should provide R&D funding to universities and research organizations for developing innovative low-carbon agrifood systems.

Recommendations for stakeholders
The quality of renewable energy technologies needs to be assured through testing and the establishment of international standards, because any failures will erode the confidence of potential users.
Technological advancement, partnerships, investment and capacity- building are all needed for smart water and smart energy use in agriculture.

Hybrid public and private finance is an effective approach to financing smart water and smart energy tools; therefore, the creation of environments that enable public–private partnerships is crucial. Farmers, public sector actors and financing institutions need to see first-hand the business case for smart agriculture to fully appreciate the benefits it can bring; therefore, awareness-raising through demonstration projects and education is imperative.

Fossil fuel subsidies by governments are major barriers to the uptake of renewable energy and low-carbon technologies so should be urgently reduced or removed.

C. Decarbonizing post-harvest and during food processing

90. This subchapter focuses on the implementation of technological solutions to enhance energy efficiency and the uptake of renewable energy in the post-harvest phases of the agrifood chain, including food processing. Suitable business models to overcome financial barriers and the development of a conducive policy environment are discussed. Food waste should be minimized but can be used for bioenergy or animal feed. If post-harvest losses can be reduced, GHG emissions from storage, transport and processing will consequently also be reduced.

91. Crop drying and curing is one of the more energy-intensive post-harvest operations. Cereal grains are normally dried artificially after harvest prior to storage and transport in order to maintain their quality. Electricity, natural gas, liquefied petroleum or modern biomass combustion is used to provide heat at around 0.5–0.75 GJ/t in order to dry wet grain harvested at 20–30 per cent wet basis down to a more acceptable moisture content for long-term storage of 12–14 per cent wet basis. Solar heat can also be used directly for drying grain, fruit and fish, either naturally in the open air or in solar-heated facilities.

1. Cool chain

92. Cold storage refers to any temperature-controlled infrastructure for post-harvest storage and handling of food products. Preventing the rapid deterioration and prolonging the peak quality of fresh milk, fruit and vegetables after harvest depends largely on rapidly lowering their temperature (sometimes down to –25 °C). For plant products, maintaining air humidity at more than

85 per cent is also usually required to avoid accelerated transpiration, which can be a major issue in arid climates. With the technology, currently available, cold-storage facilities require external energy inputs to maintain desired temperatures and humidity levels. In developed countries, more than 50 per cent of food goes through a reliable cold chain from harvest to table – a chain that has been developed over the past 130 years. In developing countries, only a minor share of food products is refrigerated.

93. Drying and cooling after harvest are not always practised in low-GDP countries where post-harvest losses, including from pests, can therefore be high. For fresh milk products, fruit, vegetables, fish and meat, cooling is one of the most important steps in the post-harvest handling chain to reduce respiration rates, extend shelf life and increase transport range (thus contributing to the minimization of food losses). Cooling also offers the opportunity for actors in the food supply chain to increase their income by extending the period for selling and marketing their products to a time when better prices might be achieved. Further, cooling protects food and lowers safety and health risks by slowing down microbial growth and toxin production.

94. The cold chain is responsible for around 15 per cent of all electricity consumed worldwide, including domestic refrigeration (Coulomb, 2006). However, only a small part of this percentage relates to immediate post-harvest cold storage. For food products that depend on the cold chain to reach markets, refrigerated storage, including during transport, can account for up to 10 per cent of the total carbon footprint of these refrigerated products if coal- or gas-fired electricity is consumed and when electricity inputs, the manufacture of cooling equipment and GHG emissions from leaked refrigerants are included (FAO, 2012). The refrigeration component of the carbon footprint for the food supply chain of the United Kingdom, for example, is currently around 24 per cent for transport, 31 per cent for retail refrigeration and 40 per cent for domestic refrigeration, with the remaining 5 per cent coming from embedded energy in the manufacturing of the equipment. Food storage requires 1–3 MJ/kg retail food product (Smil, 2008). Because global milk, meat and fish consumption is rapidly increasing, installed cold-storage capacity is expected to expand. New installations should incorporate the most advanced energy efficiency measures, such as good insulation, into their designs.

95. In rural areas without reliable electricity generation and lacking distribution networks, the provision of cold chain and cold-storage facilities for cooling large quantities of fresh produce such as milk is challenging. Developing a local supply of renewable electricity that is reliable would overcome this problem.

96. Cooling and ice making can be achieved at the small to medium scale using electricity generated by solar PV systems (see box 5) or by direct solar inputs. Distributed energy systems have good potential to provide solar-assisted cooling for air conditioning and refrigeration, whereas the direct solar option is

more complex, being based on a thermo-chemical sorption process (OECD and IEA, 2007). Closed systems, including both adsorption and absorption chillers,[12] are close to being commercialized and can be used for central or decentralized cooling. One advantage of solar-assisted cooling technologies is that peak cooling demands often correlate with peak solar radiation levels and hence with peak electricity loads for conventional refrigeration and air conditioning. The cost, however, is relatively high at present.

Box 5
Case study: Solar milk cooling system in Kenya

Chilled milk deteriorates more slowly so can be transported further to markets where its better quality can result in better price premiums. In 2015, Nestlé collaborated with FullWood Packo to produce a small-scale milk cooling system using solar PV electricity. The self-contained MilkPod has the capacity to process 600 litres milk per day and was designed to be used by dairy farmers in off-grid remote villages. The MilkPods have reduced energy consumption, GHG emissions and operating costs in comparison with using electricity from diesel-powered generators that consume approximately 8.5 litres fuel daily to cool the same volume of milk. The fuel costs of approximately USD 2,500 annually can be avoided by harnessing solar energy for operating the MilkPods. The milk is cooled immediately after it is collected, reducing the rate of spoilage by minimizing the time between milking and cooling. This results in less milk being wasted and minimizes the associated economic losses for the dairy farmers.

Owing to the relatively high capital costs, subsidies and grants are often required to increase the uptake of solar cooling systems by smallholders who would otherwise find them unaffordable. Larger mobile systems are also available using ice banks. Insulated milk cans holding 30 litres of milk with a central cylinder for keeping ice have also been developed (Flammini et al., 2019).

For more information on solar milk cooling with insulated milk cans, see https://energypedia.info/wiki/Solar_Milk_Cooling_with_Insulated_Milk_Cans

Source: (Flammini, Bracco and Sims, 2018).

2. Food processing

97. The total amount of energy needed for processing and packaging has been calculated to lie between 50 and 100 MJ/kg retail food product (Smil, 2008). The food processing industry requires energy for heating, cooling and electricity, with the total demand being around three times the amount of direct energy consumed behind the farm gate. Energy is also embedded in packaging, which can be relatively energy intensive owing to the use of plastics and aluminium foil. In the United Kingdom, packaging accounts for around 5 per cent of the total weight of supermarket food purchases, and only about 60–70 per cent of the packaging is recyclable (OECD, 2017). For processing fish, the direct energy demand for ice making, canning, freezing, drying or curing, and producing fish meal and fish oil by-products is about 0.5 PJ/year. Many means of improving energy efficiency exist (see table 3) and renewable energy can displace fossil fuels (see box 6).

12 A liquid or gas can be either attached to a solid porous material (adsorption) or absorbed by another liquid or solid material (absorption).

Table 3

Examples of energy efficiency measures involving direct or indirect technological and social interventions in the food processing and transport sectors beyond the farm gate

Direct	Indirect
Improving truck design and operation	Improving road infrastructure
Developing variable-speed electric motors	Reducing food losses at all stages
Improving lighting and heating	Matching food supply with demand
Insulating cool stores	Changing diets away from animal products
Minimizing packaging of food	Lowering obesity levels
Promoting technology transfer and education	Labelling food products
Improving the efficiency of cooking devices	

Source: Adapted from FAO, 2011a, and OECD and IEA, 2007, where the measures are described in detail.

Box 6

Case study: Renewable process heat generation in a milk processing plant in New Zealand

Synlait has for many years used coal-fired boilers to provide process heat – mainly used for milk pasteurization and water heating – at its two milk processing plants. Concerned about its relatively high CO_2 emissions, the company installed an innovative, 6 MW electrode boiler in its Dunsandel plant. The local electricity distribution company upgraded its lines and transformers to meet the extra demand. The electrodes are submerged into water that, when electricity flows, is vaporized into steam, a form of process heat that is used to pasteurize milk, sterilize milk, clean production lines and product packaging. Given that New Zealand's electricity grid comprises around 85 per cent renewable electricity, the 99.5 per cent efficient boiler provides near zero-carbon process heat and avoids 13.7 kt CO_2 emissions per year. Synlait also has looked at using biomass for meeting some of its other heat demands, has plans to reduce its water demand and aims to assist its farmer suppliers in reducing their GHG emissions on the farm.

Source: https://www.synlait.com/sustainability/

98. Process heat is usually provided by the combustion of fossil fuels, although many examples exist of providing it with modern bioenergy systems that use crop residues (e.g. rice husks) and forest residues as fully sustainable fuels. Solar water heating is also commonplace for providing low temperature heat for both domestic users and small businesses. Other solar thermal systems to meet higher temperatures are being demonstrated (see box 7).

Box 7

Case study: Concentrated solar thermal system for process heat in Surat, India

In 2006, Tapi Food Products invested in a concentrated solar thermal system to generate heat and steam in order to meet the demand of its food processing facility in Surat, India. Ten automatic solar tracking parabolic mirrors of 9.3 m^2 surface area were installed on the factory roof, each generating approximately 350 kg steam per day. The State Government subsidized around 75 per cent of the capital costs and the company covered the remainder. The technology saves approximately 45,000 kg fuelwood consumption annually.

Source: http://www.cshindia.in/images/ProcessHeat/Tapi%20Foods.pdf

3. Transport

99. Fresh food needs to be transported from the farm to local markets or to processing plants from where the food products are transported to larger markets or to storage facilities, possibly before being exported. Transport and distribution are vulnerable links in the agrifood chain given that oil prices fluctuate. In 2000, more than 800 Mt global food shipments were made (Smil, 2008), equating to more than 130 kg per person. Journeys by householders to purchase food can account for an additional 1–4 MJ vehicle energy input per kilogram of food purchased. Transport can account for 50 to 70 per cent of the total carbon footprint of some products, but in low-GDP countries, where poor roads restrict long distance travel to markets, this percentage can be much lower.

100. Locating facilities for the production and handling of food closer to areas of high population density can help to reduce transport energy inputs. However, because long distance transport by ship or rail has a relatively low MJ/tonne-kilometre, it can be argued that producing specific crops and animal products in locations where productivity is naturally the highest and then transporting them over long distances can outweigh any transport savings from local production.[13] The growing trend in high-GDP countries of buying food at farmers' markets that sell only local produce may therefore save relatively little energy from transport, but purchasing food at these markets can save energy on processing and packaging (as compared with supermarket goods) because it is usually sold fresh or minimally processed (Bomford, 2011).

101. When fresh food is transported by air, the transportation energy input can be more than half of the total energy input required to produce the food.[14] Air transport is costly in terms of energy intensity and economic cost so should be rarely used. Consumer expectations regarding the purchase of out-of-season fresh food products have, however, increased the demand for air freight. Globalization in the past two decades has increased the average movement of food products. Nevertheless, the total global GHG emissions from the transportation of food remains far smaller than that from primary production.

4. Energy costs

102. The total energy-related cost as a share of the consumer purchase price varies widely by food product, but the share is usually relatively high, particularly for agrifood systems in high-GDP countries. The total energy-related cost as a share of the production cost varies widely for agrifood products. For example, in the United States, the energy-related cost as a proportion of total crop production cost ranged from 10 per cent for soybean to 31 per cent for maize (FAO, 2011a).

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13 A simple comparison of 'food miles' is therefore not valid in terms of total energy input (MJ) per unit of food product (kg).

14 A total of 7.67 MJ energy was consumed per kilogram of apples produced in New Zealand and delivered to Europe: 1.45 MJ in the orchard, 0.51 MJ during the post-harvest phase, 1.46 from packaging and 4.24 MJ for shipping in air-conditioned containers (Frater, 2011).

103. In low-GDP countries, agricultural development can be constrained by fossil fuel prices, particularly where imported fossil fuels are a heavy burden on total GDP. The correlation between energy prices and food prices is therefore of concern. Farming costs are dependent on fossil fuel inputs, and poorer people – whether as small-scale producers or as staple food consumers – are the most vulnerable to price fluctuations and spikes. Future high and volatile fossil fuel prices, global energy scarcities and increasing GHG emissions are the key reasons the global agrifood sector needs to become more energy-smart (see box 8).

Box 8
Case study: Energy-smart agrifood sector in Ukraine

The GEF and UNIDO in 2011 invested in establishing demonstration projects, strengthening policy and regulatory frameworks, and creating a project pipeline for the agrifood sector in Ukraine. One demonstration project involved replacing the compressor system and two evaporative condensers at a modern State-owned refrigeration plant. This replacement saved 930 MWh electricity, avoided 1,140 t CO_2 emissions during the operation of the cold-store plant and reduced the risk of ammonia emissions.

Source: GEF and UNIDO, 2018.

5. Summary

104. Box 9 summarizes solutions for decarbonizing after harvest and during food processing and provides recommendations for stakeholders.

Box 9
Decarbonizing post-harvest and during food processing

Technological solutions such as solar cooling, natural refrigerants and energy efficiency improvements are currently available but need innovative business models to overcome barriers to uptake.

The deployment of sustainable post-harvest technologies with low-carbon footprints can avoid food waste and improve water use efficiency.

Energy efficiency interventions can provide benefits in the short term, with potential energy input savings of up to 20 per cent.

Solutions relating to food processing activities, energy servicing and training that have been successfully demonstrated may need adapting to suit the local context.

The implementation of decentralized renewable energy systems for cooling, storage and local transport of food can minimize losses and their associated costs. These systems can improve profits for farmers and processors while also contributing to food security.

Renewable energy interventions by businesses can be accelerated if a conducive policy framework exists and the private sector engages.

Recommendations for stakeholders

To improve the business case for developing renewable energy systems for use by food processors, feasibility analyses should move beyond the energy access benefit to that of gaining productive use of energy in rural areas. As a result, energy would become more affordable and the business case for energy supply companies could be improved.

The education of technicians, auditors and decision makers will improve their understanding of the benefits of decentralized energy systems. Training facilities should be established in local institutions with government assistance provided to train the trainers.

Favourable policies and regulations are necessary to improve energy efficiency and promote the use of renewable energy and natural refrigerants with low climate impact. Two examples are obligations for food processing plants to undergo regular energy and water use audits and reduced import duties on energy-efficient equipment.

Where high capital costs of decentralized energy systems are a barrier, access to finance and appropriate payment schemes (e.g. pay as you go) would encourage investments by smaller food processing enterprise end users at the factory level, as well as farmers.

Viable business models and financing opportunities for technology providers exist. For example, decentralized renewable electricity systems can be very competitive with diesel-powered generation, but this depends on system utilization (capacity factors) and energy storage and battery management systems (where these are needed).

Cross-sectoral cooperation, such as among the private sector, the finance sector, sectoral ministries, non-governmental organizations and other development partners, is recommended.

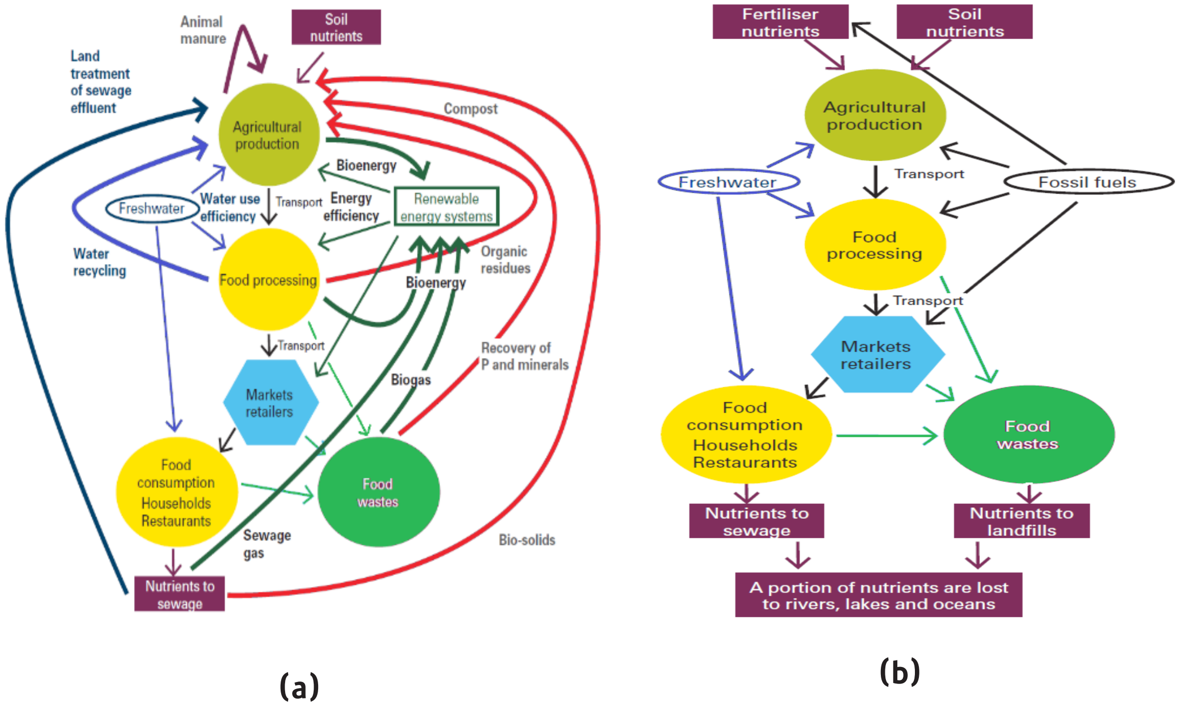
D. Circular economy solutions

105. Circular economy innovations in water and energy management, renewable energy and nutrient cycling within the agrifood chain can help reduce food waste, promote the wise use of energy and reduce water scarcity by metering and recycling. Agricultural co-products, such as dry crop residues and animal and green waste converted to biogas, can be used for heat and electricity as well as for fuel for tractors and trucks. Water is required for food production, urban settlements and conventional energy processes, so scarcity can constrain economic and social development. Agriculture is the main consumer of fresh water but can also be a solution to water scarcity through the reclamation and reuse of domestic and industrial wastewater for agricultural uses. Suitable business models and conducive policy environments are required for implementing circular economy innovations.

106. The modern food supply system is linear with respect to inputs of nutrients, energy, water and transport to markets (see figure 9(a)). It relies on the extraction and addition of nutrients (e.g. from rock phosphate) and inputs of fossil fuels, both of which lead to adverse environmental impacts, including emissions and the pollution of waterways. A few circular economy elements are already in common practice, such as applying animal manure onto land and using rice husks for heat and power generation, but others are in limited use.

The transition to a circular economy would improve resource use efficiency and substitute renewable or recyclable resources for finite ones (Wood, Sebastian and Scheer, 2000). Alongside their improved energy efficiency, in renewable energy systems nutrients can be recovered and recycled to farmland (red arrows in figure 9(b)); food losses can be reduced and food waste can be used for animal feed, compost and bioenergy (green arrows); and water can be reclaimed and recycled and the efficiency of its use can be increased (blue arrows) to reduce the demand for irrigation and cleaning and to avoid the pollution of waterways. Co-products (termed 'waste' in conventional systems) from food processing activities, such as grains left over after malt has been extracted during beer making, can be used for animal feed, in bioenergy applications or for manufacturing bioplastics. The Ellen MacArthur Foundation has helped to promote the circular economy concept internationally, but with less emphasis on sustainable energy than on other aspects such as nutrient recovery and urban food supply (Ellen MacArthur Foundation, 2019). The concept is also being evaluated by the European Union Horizon 2020 programme.[15]

Figure 9
Food supply through (a) a conventional system and (b) a circular economy



Source: Sims et al., 2018a.

107. The anaerobic digestion of organic products is a mature technology for the circular economy. The gas is used both at the domestic scale (see box 10) and at the large scale – biogas plants are located at landfill sites, sewage treatment plants and in rural communities to generate heat and electricity for local use.

15 https://cordis.europa.eu/project/rcn/216082/de

Box 10

Case study: Domestic biogas production for cooling milk in the United Republic of Tanzania

The Dutch company Simgas manufactures modular domestic-scale biogas plants and sells them to small livestock farmers in East African countries and elsewhere. With partners, it has also developed a biogas-powered milk cooler for use on small dairy farms where no electricity is available for refrigeration.

Presently, most of the raw milk produced in sub-Saharan Africa is not processed, and between 30 and 50 per cent goes to waste before reaching the market. With a capacity of up to 10 litres, the coolers can reduce the temperature of milk from 35 °C down to an acceptable 7 °C within four hours, which is faster than a refrigerator. Payments for the milk coolers are spread over time and their price is based on the premium price that can be obtained for the improved quality milk.

Source: http://simgas.org/projects/biogas-milk-chilling/

108. Reclaiming water from wastewater treatment systems is a growing activity for the circular economy, especially in dry countries, for example Spain, where water shortages are common. However, to date, in Spain, the application of reclaimed water reaches only around 1.5 per cent of the total agricultural land area and farmers are reticent about purchasing the water. Policies and incentives may be required to increase uptake. When reclaimed water is used for irrigation, its nutrient content has value as it can increase the productivity of crops and pastures (see box 11).

Box 11

Case study: Treated wastewater for irrigation and nutrient recycling in Morocco

SUEZ has built water treatment plants in many cities, urban areas and rural towns around the world and has assisted local authorities with their resource management policies. One solution for wastewater treatment offered by the company, especially for regions affected by water shortages and droughts, is to reuse purified wastewater for irrigation and hence also recycle the phosphate content given that mining rock phosphate for use in mineral fertilizers is costly. In general, an economic case needs to be made for connecting urban wastewater treatment plants to local agricultural production. The concentration of heavy metals varies in every waste stream, so before effluent is applied to cropland or pastures, potential heavy metal contamination of soil has to be accounted for and regulated under a code of conduct.

In the Casablanca suburb of Mediouna, where raw sewage was released into the Hassar stream, SUEZ built a membrane bioreactor treatment plant in 2013. Metal trace elements in the treated water were lower than in the raw sewage and mostly below acceptable limits, except for copper (Nahli et al., 2017). However, this should not be a constraint when using the stream water for irrigation.

Source: https://www.suez-africa.com/fr/notre-action/nos-realisations-pour-les-municipalites/du-stockage-a-la-valorisation-des-dechets-l-exemple-de-meknes

109. Box 12 summarizes circular economy solutions and provides recommendations for stakeholders.

Box 12
Circular economy solutions

Biogas production from both small-scale and large-scale (e.g. sewage plants, livestock farms, vegetable processing plants) wastewater treatment streams can provide energy for heat, electricity and transport fuels and thereby reduce fossil fuel demand and stimulate the local economy. The circular economy should help to accelerate the delivery and diffusion of proven technologies for recovering phosphates and nitrates after wastewater treatment and reapplying them to cropland and pastures. This will require regulatory support from local and regional governments and the removal of present subsidies for fertilizers.

Education and awareness can help identify where circular economy actions can be implemented. Such actions can result in cost savings and provide economic benefits to businesses.

The circular economy can help promote sustainability throughout the agrifood sector and also increase the value chain through reducing energy and water inputs.

Circular economy interventions are in line with the 2030 Agenda for Sustainable Development (notably SDGs 1, 2, 6, 12, 13 and 15).

Recommendations for stakeholders
Water reclamation from food processing and wastewater treatment plants is challenging and not always cost-effective unless environmental externalities and development co-benefits are also taken into account.

Governance can play an important role in non-market public monopolies (e.g. reticulated water supply) by placing a value on water resources and facilitating the infrastructure required for a circular economy (e.g. infrastructure for transporting treated wastewater and/or sludge to farms for application to the land).

Government policies and grants and other incentives can help scale up the circular economy benefits for water and energy supply in the agrifood chain, but coherent policies among ministries and between national and local authorities are required.

Investment opportunities exist in developing circular economy solutions, including through crowd-financing schemes, with proven outcomes able to be scaled up in the future.

The range of co-benefits from implementing a circular economy can help meet the objectives of the NDCs under the Paris Agreement for some countries.

E. Nature-based solutions

110. Nature-based solutions integrate energy and water aspects into the agrifood chain and result in energy savings because food and water crises are intertwined with the environment and pose significant threats to sustainable development. Environmental challenges are complex and interlinked among themselves as well as with social and economic challenges. The achievement of better human well-being through poverty reduction, improved health and energy access is linked

to ecological factors (Bierbaum et al., 2018b). Ecosystem services can enhance the quality of land and water used for food production while preserving the integrity of those resources. Agroecosystems can contribute to environmental health, watershed functions, disaster risk mitigation and healthy human habitats. Through nature-based solutions, biodiversity could be better sustained and landscapes in production regions returned to wilderness; food losses and wastage could be minimized, consumption patterns changed and acceptable human nutrition achieved universally (UNEP, 2012). Application of the water–energy–food nexus approach can improve water availability and quality and the intrinsic interdependence and interactions between them (FAO, 2018b). The integrity of ecosystems needs to be preserved. Challenges include the complexity of the interrelated issues and the time required for benefits from nature-based solutions to be realized.

111. Under many conditions, agroecological practices can compete with conventional farming practices to maintain crop yields. In addition, they can deliver ecosystem benefits such as soil health, rainfall retention, aquifer recharge, contaminant removal, reduced run-off, natural habitat management and increased productivity (Garbach et al., 2014).

112. Improving crop productivity and reducing GHG emissions without substantial investment being required may be possible by using an agroecological approach. This approach would encourage low-input organic production of crops and animals, conservation tillage, crop rotation and integrated crop and livestock systems. Where crop residues and animal waste can be recycled to the land, soil losses from wind and water erosion are reduced (but not always eliminated) and the soil carbon content is preserved (Sims et al., 2018).

113. As well as safeguarding agroecological systems, the carbon content of soils should be increased where feasible, particularly on degraded land. Soil carbon sequestration at scale is feasible using a variety of measures, including the application of biochar[16] produced from sustainable sources and incorporated into the soil to lock up the carbon as well as enhance productivity in some poorer soils.

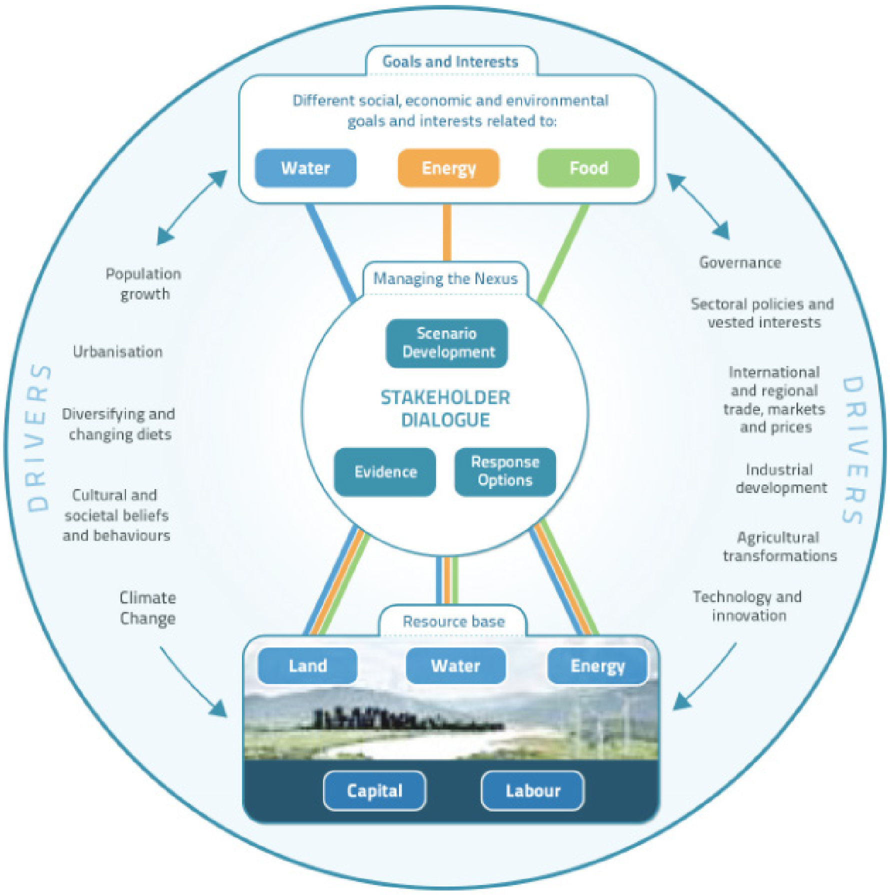
114. Implementing smart irrigation schemes, conserving water, improving water catchment systems, recharging aquifers and avoiding pollution of waterways will benefit many farmers and food processors. In countries where water supply and use are subsidized, efforts to conserve water are less likely to succeed. Conversely, the market pricing of water has resulted in its more efficient use in some countries (e.g. Australia). The Australian market pricing model can be followed by other countries. Alternative sources of fresh water such as desalination plants, crop fogging systems and recycled grey water (e.g. from buildings, food processing plants, wastewater treatment plants and urban storm

16 Biochar produced from the pyrolysis of biomass can also provide useful energy co-benefits. The process of biochar production is similar to that of charcoal production but the latter is very inefficient because gases with an energy value are released into the atmosphere rather than being captured and used, for example in a pyrolysis plant.

water drains) could all be used for intensive horticultural irrigation, livestock drinking water and urban agriculture, where economically viable.

115. The water–energy–food nexus approach (see figure 10) explicitly addresses complex interactions and feedback between anthropogenic and natural systems. Managing this complexity involves better understanding the resource base through closer stakeholder dialogue. The resource base includes both natural and socioeconomic resources on which humans depend in order to achieve social, environmental and economic goals pertaining to water, energy and food.

Figure 10
Drivers and goals of the water–energy–food nexus



Source: Flammini et al., 2014.

116. In order to make the nexus concept operational, three non-sequential sets of activities should be undertaken through stakeholder involvement:

a. **Evidence:** data should be collected and analysed to enable stakeholders to discuss and identify the interlinkages of water, energy and food systems and the impacts that any change, such as in the climate, can have on the systems;

b. **Scenario development:** the possible impacts of specific interventions or policies on the natural environment and society should be identified, assessed and discussed by stakeholders;

c. **Response options:** stakeholders should engage in an open and participatory dialogue to build consensus on specific policy issues and decide how best to intervene.

117. The FAO nexus assessment addressed the first two sets of activities (evidence and scenario development) through both qualitative and quantitative assessment (Flammini et al., 2014). Nexus challenges can possibly be resolved through multi-stakeholder institutional arrangements addressing a variety of issues. These arrangements include technical support services and the division of labour that is determined by different types of outgrower schemes wherein farmers take responsibility for what they do best, which is growing crops and animals, while other people manage the specialized needs of heat and power generation. Preliminary experience shows that no institutional scheme provides significantly better success rates than others (Utz, 2012). More complex arrangements, or schemes with many partners involved, are especially prone to politically or commercially motivated actions that question the rules in an environment that is still developing in legal terms as well as still developing financial schemes and business models (see chap. IV.B below).

118. The water–energy–food nexus, and nature-based solutions in general, are not particularly well understood. To help educate the general public and inform policymakers about the benefits of these approaches, which include bringing nature back into cities, a knowledge platform has been established by Think Nature.[17]

119. Box 13 summarizes nature-based solutions and provides recommendations for stakeholders.

Box 13
Nature-based solutions

Nature-based solutions support the agricultural transformation of food production systems and can save energy inputs by utilizing renewable natural resources in an integrated land and water management framework while maintaining landscape diversity and ecological integrity.

Nature-based solutions preserve the integrity of ecosystems in terms of soil moisture, forest carbon sinks and soil carbon sequestration. They can conserve groundwater and have minimal impact on biodiversity. Their many co-benefits include the preservation of genetic diversity of plant species for resilient food systems.

Ecosystems can provide low-energy-intensive solutions that avoid energy inputs by facilitating natural processes that capture surface water, increase soil moisture and filter pollutants that otherwise could end up in the receiving water bodies.

17 https://platform.think-nature.eu/

Nature-based solutions can provide sustainable development co-benefits for local communities. Urban food production systems are rapidly evolving and have good potential for supplying a significant share of a city's total food supply. Innovative solutions require the integration of small-scale farming practices into the urban context, along with innovative food production technologies that draw on nature-based solutions for sustainable water use.

Recommendations for stakeholders
Policies relating to the management of nature-based solutions and ecosystem services must be holistic, acknowledging that ecosystems involve a range of stakeholders, often with conflicting interests.

Assisted natural regeneration is sometimes required to restore ecosystem services in degraded landscapes, which can then contribute to mitigation actions.

To preserve nature-based solutions over the long term, open access policies and shared ownership are required, with all stakeholders jointly producing common property resource management regulations.

Policies are most effective when they incorporate traditional knowledge because this knowledge considers regional issues and lessons learned over many generations regarding optimized primary agricultural production and fishing.

Policies and land-use regulations need to accommodate urban food production practices.

The implementation of nature-based solutions related to the water–energy–food nexus requires government action and funding. There are also feasible opportunities for private sector investment where the provision of ecosystem services can be shown to provide a return on investment.

Sufficient time must be made available to fully assess the benefits of nature-based solutions because they often take time to materialize. This also means that subsidies and incentives are needed for practitioners at an early stage of implementation.

Regeneration of ecosystems requires sufficient space and time, and often the involvement of many stakeholders. Therefore, a joint approach early in the planning phase is necessary for nature-based solutions.

F. The agrifood chain and the Sustainable Development Goals

120. The United Nations Millennium Development Goals established in 2000 made no reference to specific objectives or targets for energy access, and they did not take into consideration renewable energy. To address this situation, and ensure energy had a higher priority in international and national policy debates, the United Nations General Assembly designated 2012 as the International Year of Sustainable Energy for All. In 2015, the United Nations introduced the SDGs, to be reached by 2030 by delivering sustainable development benefits. Several of the goals have served as a platform to raise awareness about the importance of energy access for sustainable development and improved livelihoods and well-being in rural areas.

121. The agrifood sector has wide-ranging impacts on several of the SDGs because it encompasses many disciplines. Reducing GHG emissions throughout the agrifood chain by deploying off-grid and decentralized energy systems, as well as by efficiently using water, will make a valuable contribution to:

a. SDG 2 (zero hunger);

b. SDG 6 (clean water and sanitation, including efficient extraction and use of fresh water);

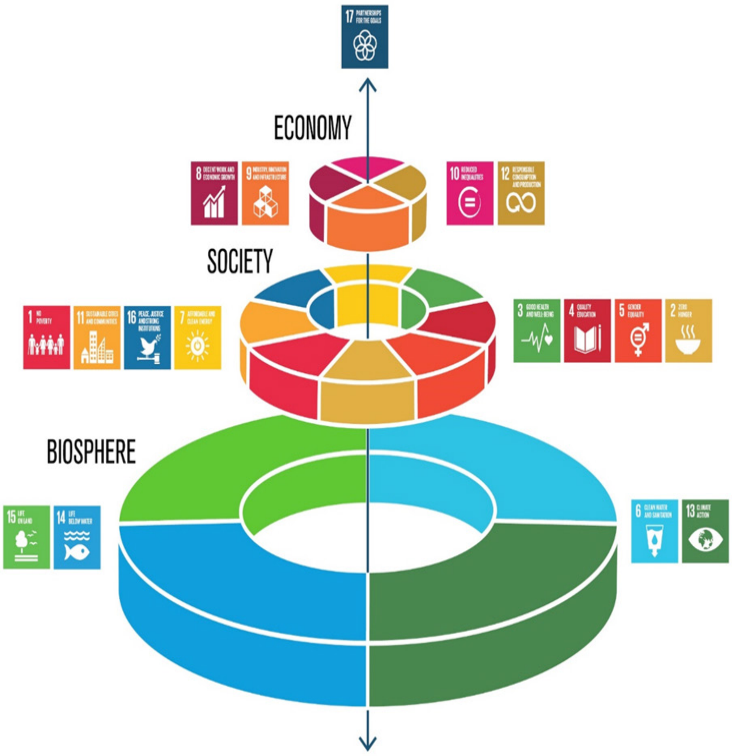
c. SDG 7 (affordable and clean energy, including energy-smart food);

d. SDG 12 (responsible consumption and production);

e. SDG 13 (climate action, including climate-smart food).

122. Of lesser relevance are SDG 9 (industry, innovation and infrastructure), SDG 14 (life below water) and SDG 15 (life on land). Several of the society SDGs also have linkages with the agrifood sector including SDG 4 (quality education), SDG 10 (reduced inequalities), SDG 11 (sustainable cities and communities), SDG 16 (peace, justice and strong institutions) and SDG 17 (partnerships for the goals). In essence, the four economy and eight society SDGs can be considered to be embedded within the four biosphere SDGs, with virtually all of the goals linked directly or indirectly with the global agrifood sector and connected to producing sustainable and healthy food (see figure 11).

Figure 11
Hierarchy of the Sustainable Development Goals



Source: Rockstrom and Sukhdev, 2016.

123. Achieving the SDGs will not be possible without urgent climate action, including by the agrifood sector, as outlined in this paper:

a. Energy- and water-wise solutions for decarbonizing primary production contribute mainly to SDGs 6, 7, 12, 14 and 15 (chap. III.B above);

b. Decarbonizing the post-harvest and food processing phases of the agrifood chain using financially viable renewable energy, energy efficiency and water-saving measures can help to meet SDG 7 as well as SDGs 2, 6, 8, 9, 12 and 13 (chap. III.C above);

c. Encouraging the circular economy can help achieve SDGs 2, 6, 7, 12 and 13 (chap. III.D above);

d. The water–energy–food nexus approach, in the context of nature-based solutions, to improving energy access, water availability and quality, and sustainability of food production is in line with SDGs 1, 2, 6, 13 and 15 (chap. III.E above);

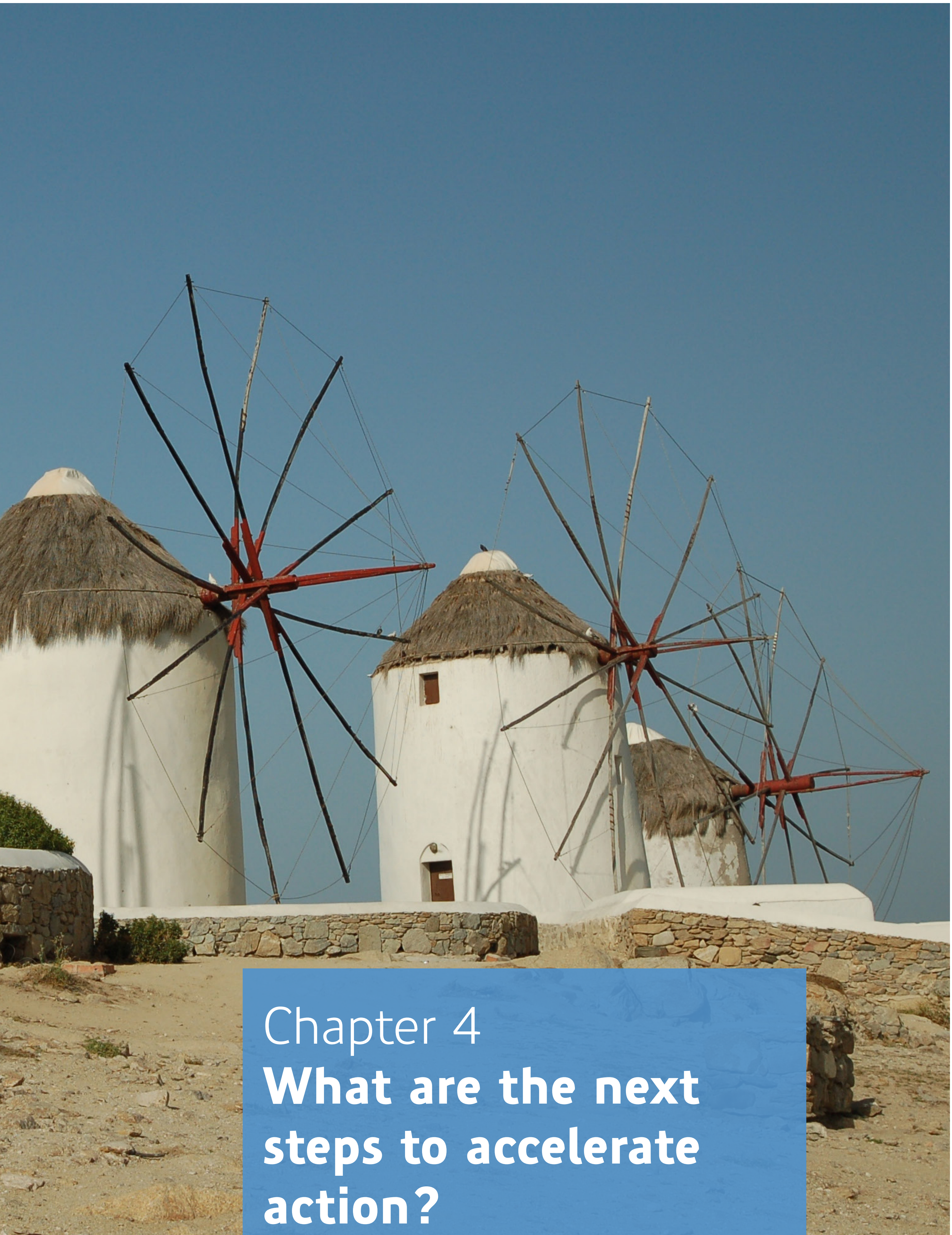
e. Government development of conducive policy frameworks and enabling environments to support the agrifood sector can produce socioeconomic benefits and help realize SDGs 2, 5, 6, 7, 8 and 9 (chap. IV.A above).

124. Agriculture consumes nearly three quarters of the 4,500 billion m^3 freshwater withdrawals per year. Clean water is linked to healthy communities (SDGs 3 and 11). In sustainable food production, soils need protecting, mineral fertilizers need to be manufactured without fossil fuel inputs,[18] and animal, crop and food nutrients need to be recycled (SDGs 2, 9 and 15). Failing to consume around one third of all food produced owing to post-harvest losses (especially in developing economies) and retail and consumer wastage (mainly in OECD countries) requires education and responsible consumption (SDGs 4 and 12).

125. To avoid hunger in the ever-growing global population, improve human health, avoid animal welfare concerns and reach climate goals, societies will need to transition away from producing and consuming animal protein and replace it with protein from, for example, vegetable crops, pulses and insects, or synthetic protein (SDGs 3, 4, 10, 12 and 13). There is a growing trend of producing synthetic protein biochemically under factory conditions by fermenting vegetable proteins or multiplying stem cells. Several commercial companies (e.g. California-based Impossible Foods, established in 2011) are already developing and retailing such products. The energy input required per kilogram of protein produced is not known, but if it can be met from renewable sources, the carbon footprint is likely to be much lower than protein produced from the farming of animals. There is also the potential to reduce input volumes of water and amounts of nutrients and lessen the impacts on biodiversity and on ecosystem services.

18 Novel methods with lower GHG emissions are under evaluation, such as using renewable electricity to produce hydrogen that is then used to produce ammonia (e.g. see Licht et al. (2014)).

126. Peri-urban agriculture will continue to expand (SDG 11) and could eventually provide 20–30 per cent of local food demand with the rest coming from nearby farms and fisheries (Ellen MacArthur Foundation, 2019). Rooftop gardens, community vegetable plots and living building facades are becoming more common in cities around the world. Together with the development of multi-storey vertical farms, these could provide a significant amount of food for the local population.



Chapter 4 **What are the next steps to accelerate action?**

127. Improving the knowledge of farmers, fishers and food processing enterprises about the benefits of using low-carbon technologies and systems and providing them with access to these technologies and systems through innovative business models and capacity-building can help accelerate the deployment and installation of decentralized energy projects in the agrifood chain by 2020 and beyond. Developing integrated policies to support innovative concepts encompassed by the water–energy–food nexus would help increase uptake and provide food security while also reducing GHG emissions.

128. There are three basic means for food systems to become more energy-smart in the short to medium term:

   a. Increase the efficiency of direct and indirect energy use at all stages along the food supply chain so that the energy intensity (MJ/kg food produced) is decreased;
   b. Develop renewable energy systems as a substitute for fossil-fuel-based heat, power and transport fuels, without reducing food productivity;
   c. Improve access to modern energy services with a focus on off-grid rural communities to improve food product quality and reduce food losses.

129. In the short term, fossil fuels may be required to address energy poverty in rural areas. However, where feasible, it would be preferable to leapfrog to renewable energy systems and avoid investments in technologies that will lock users into fossil fuel dependence for the foreseeable future. The potential co-benefits of decentralized energy investment should be considered by investors and policymakers.

130. Economic, social and environmental co-benefits can result from policies that support the deployment of renewable energy technologies. These include stronger local development, increased employment opportunities, improved livelihoods, greater social cohesion, enhanced skills of local tradespeople, better health due to reduced air pollution, reduced drudgery from manual labour, and a more equitable gender balance in the division of labour (IPCC, 2011). For smallholders, better access to energy can also help increase the labour supply needed for producing food of adequate quality and increasing revenue. Furthermore, improving access to modern energy systems can free up a substantial amount of the time spent by householders (usually women) collecting fuelwood or dung that can be used for more productive tasks such as improving food quality or assisting children's education. Such potential co-benefits should be acknowledged during the policy development process.

A. Developing integrated policies

131. This subchapter covers novel approaches and considerations for policy implementation and governance that can facilitate decentralized energy systems and a more sustainable water–energy–food nexus within the agrifood chain. It draws upon case studies and real-world experience to explore which policies, regulations and institutional frameworks work and why some do not.

132. Providing energy access to impoverished communities is usually the responsibility of national and regional governments. The free market approach followed by several high-GDP countries is not generally considered suitable for providing access to energy services in rural areas of low-GDP countries (IPCC, 2011). Several initiatives are being carried out to provide a baseline and a practical means for measuring energy access in the most impoverished areas (Practical Action, 2018). Multilateral and bilateral agencies, governments, academia and civil society all acknowledge that access to a secure supply of energy is critical for sustainable development (IPCC, 2011). The potential of sustainable energy to reduce GHG emissions and deliver co-benefits provides an incentive for local, regional, state and national governments to formulate policies that are conducive to encouraging energy efficiency, the development of renewable energy projects and the deployment of decentralized energy systems.

133. At times, depending on local conditions, governments can help improve access to energy by instigating balanced economic policies. This can be accomplished by one of two means:

    a. Developing policies to improve the efficient use of existing fossil fuel energy systems by subsidizing the retail price paid for imported fossil fuels, including diesel, for fuelling electricity generation plants;

    b. Introducing measures that support the deployment of renewable energy technologies that can then supply heat, electricity and mechanical power directly to the local rural community and agrifood enterprises.

134. A range of policies has been utilized by various countries to promote the increased deployment of renewable energy resources including for heating, cooling, water pumping, electricity and transport across the agrifood sector (OECD and IEA, 2009). The policy types are described below.

1. Governing by leadership

135. Targets can be set for a specified level of renewable energy deployment (e.g. area (m2) covered by solar collectors installed by 2020) or more broadly (e.g. percentage reduction in GHGs by 2020 to which renewable energy deployment would make a contribution). Targets are typically not legally binding; rather, they act as a signal for farmers and local food processing businesses to consider how they might better utilize sustainable energy

systems. Setting a target at the right level can be difficult: too high and a loss of enthusiasm and momentum can occur when it becomes clear it cannot be met; too low and complacency may set in once it has been met with little effort or changes. Ideally, the target is achievable but at a stretch. Target-setting will require initial analysis of the local renewable energy resources available and a comparison of the levelized costs of the energy technology options.

2. Governing by authority

136. 'Sticks' are schemes generally implemented by means of governance through regulatory authority, depending on the legal powers devolved. Local (or central) governments can intervene in the market by placing requirements on specified sectors; for example, issuing rules that limit GHG emissions per tonne of product or from transport modes. This type of instrument can force renewable energy deployment by directly requiring the development of specified technologies. The legal and administrative costs of political incentives are often kept to a minimum, although monitoring and enforcement may be required at the local or regional level. Where an environmental tax or a carbon charge is in place, it can affect the cost-competitiveness of renewable energy technologies. For example, a disincentive can be set for heating and cooling technologies using fossil-fuel-based electricity, coal or natural gas and a more appropriate rate applied to incentivize investment in renewable energy heating and cooling technologies (OECD and IEA, 2007). Under such circumstances, government regulations for tax reductions need to be specifically adjusted to include low-carbon technologies.

3. Governing by provision

137. 'Carrots' are typically financial incentive schemes that encourage and facilitate farmers and businesses to take actions additional to those legally required of them. Incentives can entice the utilization of renewable energy technologies to meet local energy services by addressing the cost gap between them and conventional technologies. In order to be effective, these incentive schemes need to be designed so that sufficient levels of funding are allocated to bridge any conceivable gap between the market price of energy and the costs for equivalent renewable energy supply. The incentives should also be predictable and consistent over the period during which the policy is in effect in order to build investment confidence. Local governments could add additional incentives to incentives offered by central governments, where legislation allows. Tax incentives, including tax credits, tax reductions and accelerated depreciation, may be based on investment costs or energy production. A wide array of tax incentives exist and these can increase the competitiveness of renewable energy. Fiscal incentives typically present a lower financial burden in terms of covering administration and transaction costs and are thus an attractive option for governments, but the overall level of incentives needs to be carefully established if a successful outcome is to be achieved.

4. Governing through enabling

138. Guidance measures include implementing education schemes, promoting technologies, demonstrating new technologies (with industry to help provide 'market push'), improving market awareness by stakeholders, and supporting further R&D and deployment.

5. Self-governing

139. Voluntary actions (other than setting voluntary targets) are often led by business and have been widely employed. They include:

a. Local government operations wherein, in order to help meet its voluntary targets and/or reduce its operational costs, 'green energy' can be purchased from a local power generation utility to meet its own demands;

b. Voluntary, informal agreements between local governments and private sector companies leading to investment in renewable energy for mutual benefit.

140. Policymakers should consider reviewing existing policies (both successful and unsuccessful) in other jurisdictions before implementing policies and measures. Policy implementation could involve:

a. Investing in technology transfer and adaptation;

b. Applying R&D outputs;

c. Accessing energy-smart technologies;

d. Providing fiscal support mechanisms;

e. Encouraging capacity-building;

f. Instigating extension services;

g. Supporting education and training;

h. Filling the more important knowledge gaps.

141. Initiatives targeting food consumers can help reduce the agrifood sector's demand for energy and reduce GHG emissions. These initiatives include mandating labels on retail food packaging that display the energy used in the production, processing, packaging and distribution of the product; mounting campaigns to promote healthier diets comprising significantly less animal products; and raising awareness about how to avoid food losses. A supporting policy environment without the appropriate allocation of financial and human resources is unlikely to succeed in establishing energy-smart food systems.

142. National and local governments will need to consider policies and measures that combine food security with energy security; support rural development, technology transfer, climate change adaptation and resilience strategies; and help meet GHG emission reduction targets. Recommendations are to:

a. Establish public–private partnerships that promote energy-smart approaches to food production and trade and reduce the agrifood sector's dependency on fossil fuels;

b. Encourage international cooperation on climate-smart initiatives and GHG mitigation measures for the agrifood sector;

c. Coordinate the formulation of energy-smart food policies among the ministries responsible for food, agriculture, energy, health, transport, economic development and the environment, among others;

d. Promote a multi-stakeholder dialogue on practical options for energy production and energy-efficient demand choices, and the policies and institutional arrangements needed to achieve the desired results.

143. Box 14 summarizes integrated policymaking and provides recommendations for stakeholders.

Box 14
Developing integrated policies

Supporting rural areas in gaining access to affordable, secure and low-carbon energy along all stages of the agrifood chain can support the economic and social development of communities through diesel fuel savings, job creation, poverty reduction, improved health, enhanced access to water and food, better livelihoods and gender equality.

Investments to improve energy efficiency and establish renewable energy projects are increasing throughout the agrifood sector. However, awareness raising, capacity-building and technical field support are essential if such projects are to be successfully established, operated and maintained to avoid premature closure.

Integrated policies for water, energy and food can help realize the targets of a country's NDC and the SDGs.

Co-benefits from policy solutions, if well designed, include improved livelihoods, increased social welfare and reduced spending on centralized infrastructure.

Energy service companies can be encouraged and supported by governments and international agencies in providing advice and investment for energy-efficient technologies (e.g. LED lighting, insulated cool stores, high-efficiency electric motors correctly sized for the task, and precision irrigation).

Electricity generating facilities using wind power, solar power and mini hydropower can be built on agricultural land with negligible impact on productivity if carefully designed.

Waste and residues from primary production enterprises and food processing plants can be used to produce biogas, heat and electricity through encouraging investment by the private sector in proven biomass collection systems and bioenergy conversion plants.

Heat and electricity generated locally can be used directly by farms, fisheries and food processing plants with the owner or operator of the power plant and mini grid selling any surplus electricity to nearby urban communities to help offset the capital costs, thereby resulting in cheaper levelized costs for the benefit of all consumers.

The lowering or removal of fossil fuel subsidies is critical if sustainable energy solutions are to compete. Government subsidies for renewable energy and smart water use schemes can be effective in scaling up new technologies and practices.

Recommendations for stakeholders
Businesses that provide decentralized energy services could receive government support to measure local wind, solar, hydro and biomass resources at a specific location; promote the renewable energy concept to local communities; and reduce the risks involved when investing in new generation facilities.

Water-efficient farming practices such as drip irrigation often need to be coupled with energy-smart technologies. Broad collection and analysis of data can ensure that potential issues, such as overirrigation resulting from lower pumping costs, can be avoided.

Policymakers often lack carefully collected and analysed data to inform them; for example, they need to know in advance what possible impacts the introduction of a new irrigation system will have on water abstraction rates and downstream water users as uptake of the system accelerates.

The introduction of integrated policies to support the water–energy–food nexus approach can benefit from collaboration among all relevant ministries, as well as from vertical collaboration among national, state and local governments.

Partnerships involving research institutes, the private sector and policymakers are essential for commercializing and scaling up successful innovative technologies and systems. These partnerships can be facilitated through knowledge-sharing platforms that help provide relevant information to decision makers, finance agencies and other stakeholders.

Pathways leading to a circular economy can increase productivity at both the small and the large scales of food production, with the necessary sustainable energy inputs provided by supporting development of decentralized energy systems.

The accountability of governments in implementing innovative solutions that help meet their NDC targets requires increased transparency and consultation with experts and the private sector during the decision-making process.

B. Promoting innovative business models

144. The private sector is becoming more actively engaged in supporting energy projects that foster sustainable development in the agrifood sector. However, because private investors seek to maximize the returns on their investment, under some circumstances additional incentives are needed for them to engage in business ventures designed to deliver energy services to communities with limited ability to pay for them. Government subsidies and other financial incentives, for example long-term contracts with renewable energy producers based on the cost of generation of each different technology (e.g. feed-in tariffs that guarantee a minimum price for electricity generated), need to be clearly defined.

145. Innovation and end-user financing are the reasons many business models have been successful. The pay-as-you-go model has largely taken over from microfinance loans in countries that have a relatively high penetration of digital payment technologies (see box 15). From 2015 to 2017, pay-as-you-go systems made up about 80 per cent of the 1.5 million sales of domestic solar PV systems in Africa, Asia and Latin America through around 30 companies (REN21, 2018). As part of their revenue diversification strategy, several off-grid solar PV supply companies in India and East Africa are offering televisions as part of their package as an incentive. Some companies that provide clean cooking facilities also have transformed to a pay-as-you-go business model.

Box 15
Case study: pay-as-you-go decentralized energy system in Senegal

The Vitalite Group is a Belgian commercial social enterprise focused on creating positive social impact through the provision of decentralized energy systems in off-grid rural regions throughout Africa. In Senegal, it operates a private sector start-up that provides autonomous solar home systems aiming to reduce energy poverty in isolated communities. The pay-as-you-go scheme allows customers to avoid the high upfront capital costs of the technology; payments are made at monthly intervals. In addition to tackling energy poverty through an innovative business model, the technology itself reduces the use of conventional energy sources, such as kerosene for domestic lighting and biomass combustion for cooking, thus minimizing health issues linked to indoor air pollution and reducing climate impacts.

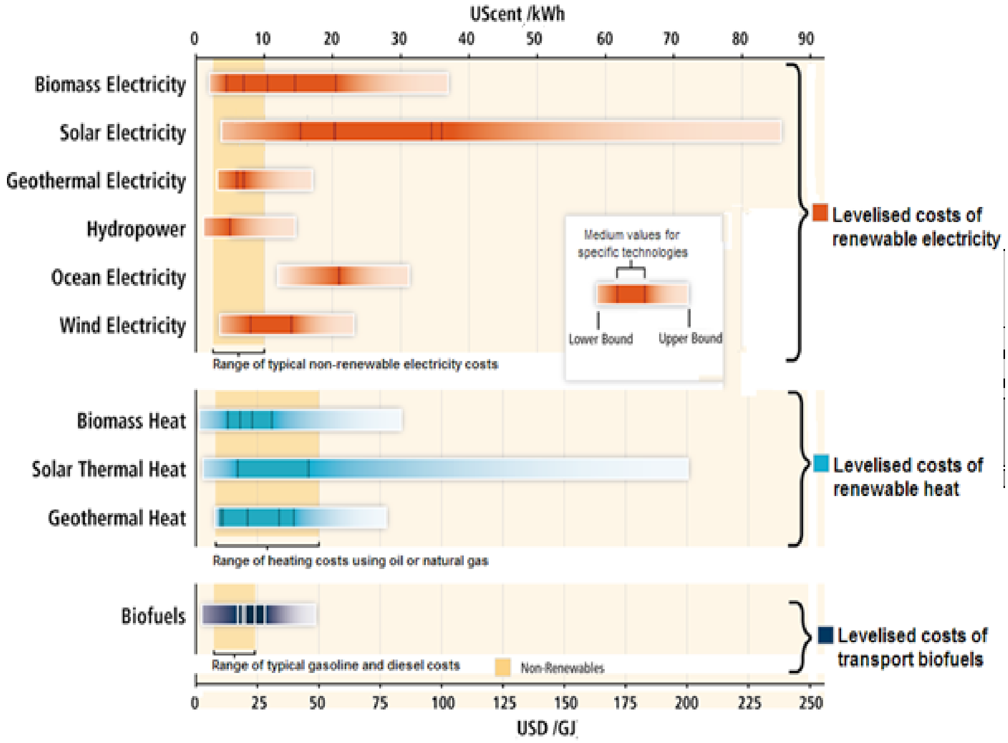
Source: http://xn--snrgie-bvab.com/

146. As the costs of decentralized renewable energy technologies continue to decline, cost-effective options for generating electrical and mechanical power, process heating, and heating water and space along the agrifood chain are becoming more acceptable. These low-carbon technologies can often compete on a levelized-cost basis with production from conventional fossil fuel energy systems under specific circumstances (see figure 12, where the horizontal bars overlap with the vertical range bars of conventional wholesale electricity, heat, gasoline and diesel costs). Renewable electricity generation technologies also compete with diesel, particularly in remote areas and islands where delivery of diesel fuel is costly. A number of businesses have been established specifically to provide decentralized mini grids for rural communities.[19]

19 For example, Island Power Co. (http://islandpower.com.au/#home)

Figure 12

Levelized costs of renewable electricity, heat and liquid biofuels compared with those of fossil fuels



Source: Adapted from IPCC, 2011.

147. The wide range of costs of renewable energy (horizontal bars in figure 13) are attributable to variations, which can be wide, in the availability of local biomass, solar, geothermal, hydro and wind resources (and ocean energy in the future). For example, wind speeds tend to be higher on hills than on flat land, and regardless of their latitude, buildings located in the bottom of a valley may be shaded from the sun at various times of the day. Where good renewable energy resources are available, the installation of renewable technologies can be more economically viable and competitive than extending a national grid or using fossil fuels.

148. Existing policy frameworks and national energy policies do not always respond to the energy needs and capacities of impoverished communities. When developing new policies, the following questions relating to energy access need to be addressed:

a. What renewable energy sources are present?

b. Will the electricity and heat generated be affordable for the community to purchase and make beneficial use of?

c. Is the technology suitable for the purpose, or adaptable to it if not?

d. Is there sufficient local human capacity to install and maintain the technology?

149. From the social perspective, any co-benefits, such as heightened security of water supplies, healthier landscapes, greater biodiversity and improved livelihoods, should be considered when making any policy decisions.

150. Clear financial arrangements between farmers, factory managers and energy operators are required to ensure the quality and the expansion of energy-smart farming systems. Many business arrangements for decentralized energy systems are still in their infancy so their performance is difficult to assess. Examples of these arrangements are as follows:

a. Farmers produce wheat crops and sell the grain while a bioenergy plant operator purchases the straw and sells the heat and power produced from its combustion;

b. Farmers cultivate crops and raise animals for a community biogas plant, but a separate enterprise is responsible for collecting, delivering and feeding manure and crop residues to the anaerobic digester, producing and possibly scrubbing the biogas, and selling the energy products. The farmers receive yearly dividends from the sales of the biogas and obtain cheap fertilizer from the digester effluent;

c. Rural people (typically women participate in such programmes) receive funding from a large local crop-growing organization, such as a tea plantation, to purchase a cow and a calf. The women repay the loan by selling any milk and dung surplus to their domestic demands back to the plantation. This innovative business scheme relies on demands by cropping farms for bio-fertilizer;

d. Householders receive a loan from a plantation company to pay for setting up a domestic-scale biogas system. The loan is repaid by selling surplus dung and/or effluent slurry from the digester to the plantation for use as fertilizer. Once the biogas system installation has been completely paid for, the householder has the option to continue selling the slurry and dung on the market;

e. 'Fee for service' schemes involve energy service companies leasing energy-efficient technologies or offering concession arrangements in which they take a share of the cost savings from the reduced energy demand resulting from the technology.

151. The relatively high capital investment costs involved in farmers installing small wind turbines, mini hydroschemes, solar PV systems, anaerobic digesters and small bioenergy heat and power plants may require microfinancing arrangements to be made available to them by national and local governments, aid agencies and the private sector. The affordability of any proposed new technology needs to be carefully considered on the basis of the average income level within the local community and the ability of local residents and businesses to purchase electricity at retail prices that allow them to remain in business. An extensive discussion about increasing farm revenue and the co-benefits that would be derived from increasing

energy access can be found in the Poor People's Energy Outlook biennial publication (Practical Action, 2018).

152. A number of product distribution models are being used by renewable energy technology companies around the world:

a. Partnerships between companies and institutions;

b. Distributor–dealer channels;

c. Proprietary distribution;

d. Franchise models;

e. Renting or leasing of systems.

153. In recent years, the delivery of energy access strategies has been scaled up through some innovative business models; for example, a private sector model wherein private firms lease solar PV modules, inverters and battery storage to supply AC electricity to consumers who pay for the service provided over two to three years has recently started to displace the donor- or government-driven model of grants or guaranteed prices. Such business models have enabled the commercialization of affordable and reliable renewable energy technologies, helped overcome market failures, and increased the viability of providing energy services to poorer populations that have historically lacked energy access or been unable to afford it (REN21, 2018).

C. Supporting innovations in technologies, policies and investment

1. Innovative technologies

154. Radical changes to global food production systems during the next decade could include the rapid development of novel practices and technologies such as robotics, biotechnology, synthetic meat and milk products, genetic modification, artificial intelligence, virtual reality and big data analysis. New, near-commercial and more efficient technologies are becoming available for use by the agrifood sector in remote areas. These include:

a. Precision farming systems in which fertilizer and water are applied only when and where needed;

b. Drones that apply agrichemicals precisely and can also be used to check the health of crops and livestock;

c. Remote monitoring of soil moisture content and crop health;

d. Robotic milking of cows whenever they choose to be milked;

e. Smart phones to help farmers diagnose crop disease, receive expert advice and check market prices;

f. Energy-efficient cool storage facilities and refrigeration systems, including solar absorption and adsorption technologies;

g. Growing of crops in non-soil media in a controlled indoor environment using diverse, highly technical vertical farming systems in urban locations.

155. Many other innovations not yet commercially viable but close to reaching the demonstration phase could prove beneficial for making the food supply system more sustainable in the long term where access to affordable energy is available.

2. Innovative policies and project replication

156. A coordinated global energy strategy consistent with national policies to bring down the cost of renewable energy technologies and increase their access into impoverished rural communities would encourage more rapid deployment. Many individual projects, often innovative, have been successfully implemented in many countries with co-funding from the GEF, international agencies and the private sector. However, these projects have not always been widely promoted, resulting in lower replication and scaling up than what might have been possible with greater publicity. Rarely are the reasons for a project failing widely publicized, yet failed projects often have the greatest lessons to be learned by proponents of new similar projects (see box 16).

Box 16
Case study: Solar photovoltaic installations in Niue

In the Pacific island country of Niue, around 348 kW peak solar PV capacity had been installed across several sites, including the high school, hospital and airport, by 2013. The systems met around 5 per cent of annual electricity demand. For the population of 1,400, the evening peak power demand was around 580 kW, with diesel generation backup available on the grid. Outages occurred whenever a 50 kW rock crusher was started up. An independent assessment in 2014 by Massey University, New Zealand, found only 80 kWp of installed PV was operational owing to poor system design. This resulted in DC to AC inverters dropping out when low voltage was experienced, and grid instability, in spite of the 180 kW battery storage and diesel gensets. To overcome these problems, additional PV and battery capacity, and controls to monitor power quality (not just electricity output), were installed, leading to almost 10 per cent of diesel fuel and 20 per cent of generation costs being saved.

Source: Stapleton, 2015. More details can be found at https://mro.massey.ac.nz/bitstream/handle/10179/6909/01_front.pdf;sequence=1

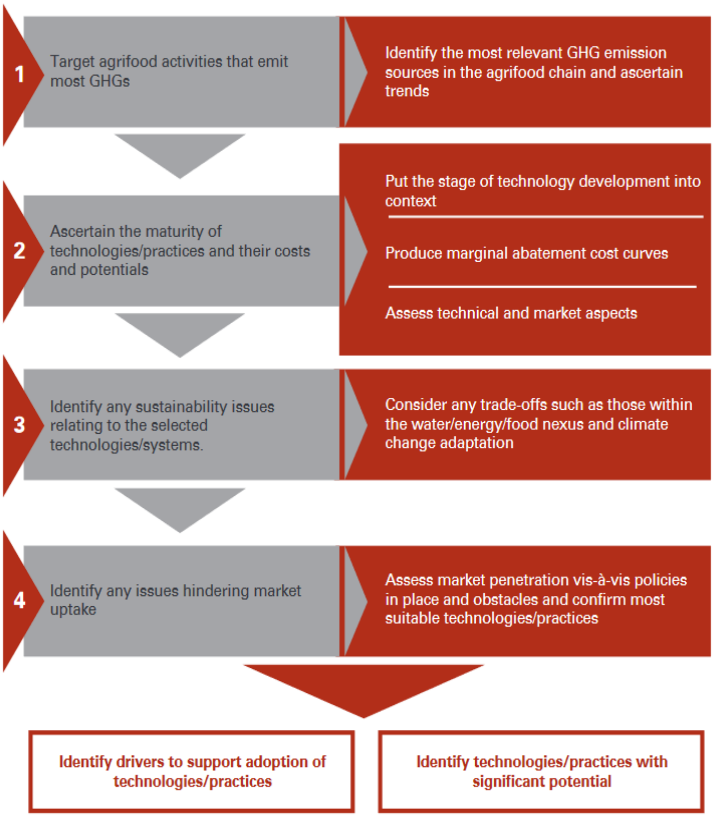
3. Investment priorities

157. A methodology has been developed by FAO and EBRD to enable decision makers to become better informed by identifying potential investments in the many low-carbon, climate mitigation technologies and practices available for deployment along the food supply chain, and have the tools to select and prioritize those most suitable for deployment along the agrifood supply chain (Sims, Flammini and Santos, 2017). The technical parameters, financial

and economic feasibility, local community benefits and sustainability of low-carbon technologies and practices are accounted for when considering and comparing the mitigation potential of a proposed investment under local conditions. The methodology provides a practical means for a country or funding agency to assess and monitor the market penetration of sustainable climate technologies and practices in the agrifood chain (see figure 13). Details of the methodology and a step-by-step guide to using it are provided in (Sims, Flammini and Santos, 2017).

Figure 13

Methodology for prioritizing investments in low-carbon technologies and practices



Source: Sims, Flammini and Santos, 2017.

158. Market penetration is defined as a measure of the adoption of an agrifood technology or practice in a specific market. The FAO and EBRD methodology is useful for estimating the current market penetration, but more important, for assessing the potential for further adoption and hence for reducing GHG emissions efficiently (Sims, Flammini and Santos, 2017). The methodology takes into consideration key features of each technology, including market potential, technical and non-technical barriers to adoption, and unit cost of mitigation (in USD per t CO2 eq avoided). The output is the characterization of a set of technologies and practices that can lead to the identification of 'best bet' investment options for reducing emissions from the agrifood sector based on

local conditions. Moreover, the results include a discussion of policy areas that may need reform, and specifically outline what drivers can be used to promote adoption of the preferred technology options. Using Morocco as a case study of the methodology, barriers that may hinder the adoption of specific climate-friendly technologies as well as policies proposed to remove them and thereby stimulate market penetration were identified (Flammini et al., 2016).

D. Bridging knowledge gaps

159. To transition from conventional to energy-smart food supply systems and to provide greater energy access to many rural communities, a better understanding of the current energy situation in the agrifood chain is warranted. Gaining this understanding requires investment in further R&D, with priorities as outlined below:

a. Data on energy use and related GHG emission factors along the agrifood chain are relatively scarce, especially for small-scale fishing, farming and food processing systems. This lack of information can result in misrepresentation of existing situations and hence mislead policy implementation;

b. Methodologies for collecting more accurate data and analysing energy use and GHG emissions from farms, small-scale capture fisheries and aquaculture, as well as their related post-harvest and supply chains, should be agreed internationally to help reduce data uncertainties;

c. Standardized metrics for measuring GHG emissions from the agrifood chain are currently being negotiated. These would help regulators and stakeholders ensure that efforts to reach targets for reducing GHG emissions are appropriately supported. Different sets of assumptions lead to wide variations in the outputs from life-cycle assessments and hence conflicting conclusions;

d. Integrated farming systems have potential long-term benefits, such as improving the efficiency of water use, maintaining soil quality and reducing energy demands. However, in some situations, measures such as using conservation tillage to reduce tractor fuel consumption can lower productivity in the short term, though yields may recover and stabilize in the longer term as the soil fertility rises. Further analysis and demonstrations of integrated projects on farms are needed over time in order to make optimal policy recommendations;

e. Knowledge of the likely nature and magnitude of possible climate change impacts on both food production and the resource base for renewable energy remains limited. Possible impacts on freshwater resources, biodiversity, land degradation and ecosystems in specific regions remain uncertain;

f. Biomass arising as a co-product of food production and processing operations can be a useful energy resource. However, competition for this resource exists. Methods for assessing the best use of this biomass require greater clarity and a holistic approach;

g. The implications of food losses on energy and water inputs along the agrifood supply chain need further quantification. The high level of uncertainty in the current data has hampered the development of policies and investments to reduce food losses and waste;

h. Synergy between public and private finance to achieve the investments needed for off-grid and distributed energy systems, and to address food security and related climate change challenges, can be better evaluated;

i. The future for big data, artificial intelligence, cloud computing, nanotechnology and the Internet of things to help simultaneously develop and decarbonize the global agrifood sector through scaling up off-grid and decentralized energy systems, implementing circular economy solutions and addressing freshwater supply security, is not yet well understood;

j. The time needed to develop new energy-smart food systems so that they are competitive with conventional systems in terms of productivity, cost and energy intensity is often underestimated. Analysis of the timelines for creating new pathways for delivering these energy-smart systems, establishing appropriate safety nets and adopting effective transition measures would provide policymakers, institutions, financiers and other stakeholders with a better understanding of how to proceed.

160. To bridge the knowledge gaps, public and private investment in R&D for energy and water inputs to the agrifood chain will need to be increased significantly, particularly in low-GDP countries. Private sector investments in R&D and in demonstration projects – driven by the need to respond to the globalization of food commodity markets and the desire to maximize profits – have been directed primarily to large-scale farm and processing systems (FAO, 2011a). Smaller-scale systems have largely been neglected to date.

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