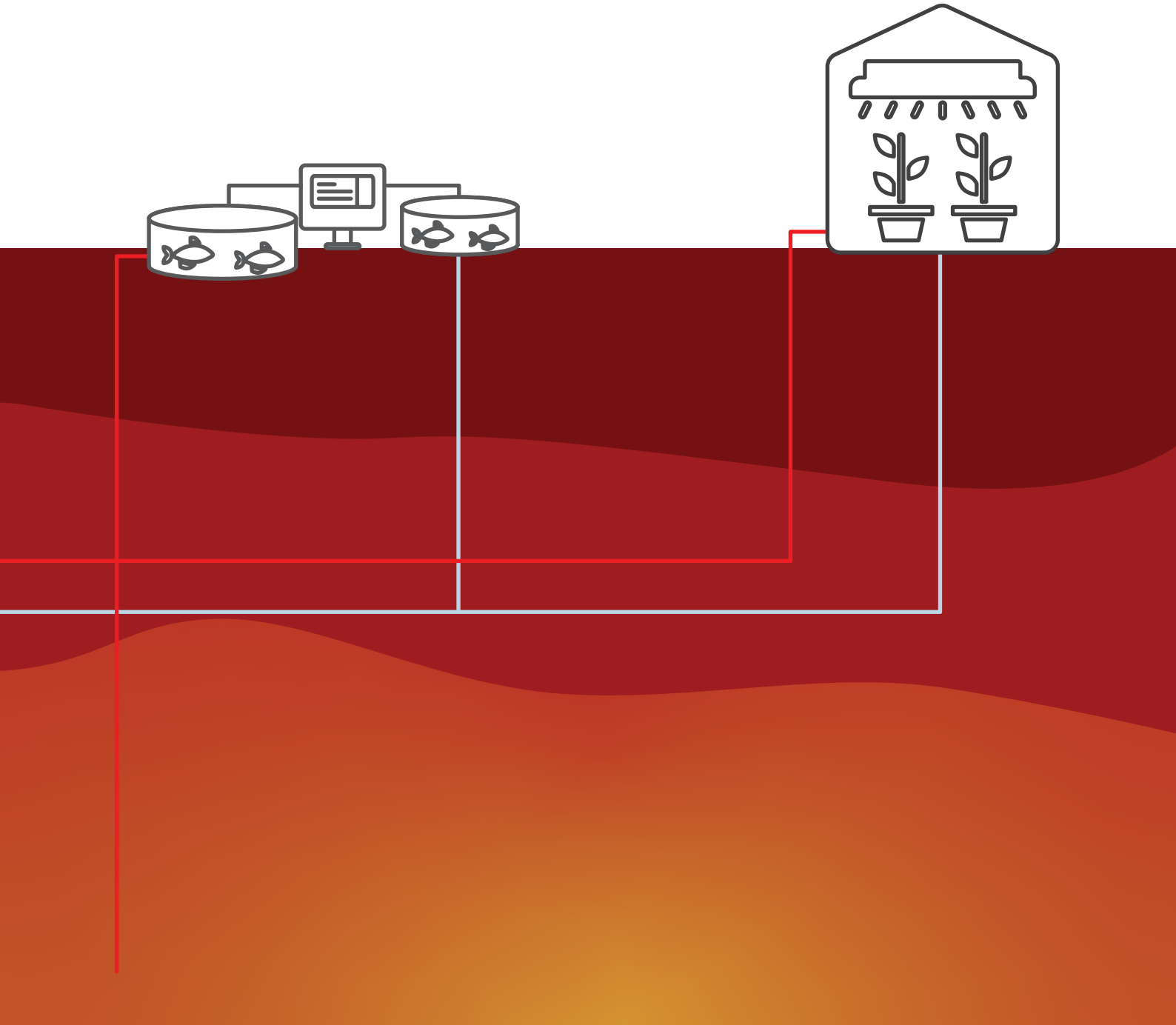
IRENA
International Renewable Energy Agency

Powering agri-food value chains with geothermal heat

A guidebook for policy makers



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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

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Contributors: This guidebook was developed under the guidance of Gürbüz Gönül (Director, IRENA Country Engagement and Partnerships) and Amjad Abdulla (IRENA) and authored by Michelle Ramirez and Jack Kiruja (IRENA), Sylvana Bohrt, Anna Colvin, Alexander LaBua and Hezy Ram (GreenMax Capital Advisors).

For further information or to provide feedback: **publications@irena.org**

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ABBREVIATIONS

°C	degrees celsius
BCR	benefit/cost ratio
CAPEX	capital expenditure
CBA	cost-benefit analysis
CO_2	carbon dioxide
DGA	Deshidratador Geotermico de Alimentos (Mexico)
EUR	euro
FAO	Food and Agriculture Organization of the United Nations
GDC	Geothermal Development Company (Kenya)
GDP	gross domestic product
GIS	geographical information system
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
GRO GTP	Geothermal Training Program under the auspices of the United Nations Educational, Scientific and Cultural Organisation
GW	gigawatt
HPA	heat purchase agreement
INVESTA	Investing in Sustainable Energy Technologies in the Agri-food Sector
IRENA	International Renewable Energy Agency
IRR	internal rate of return
LaGeo	Geotérmica Salvadoreña, S.A. de C.V.
MW	megawatt
MW_{th}	megawatt-thermal
NDC	National Determined Contribution
NPV	net present value
OPEX	operating expenditure
PBT	payback time
PJ	petajoule
SDG	Sustainable Development Goal
SEZ	Special Economic Zone
SICA	Central American Integration System
TJ	terajoule
UHT	ultra-high temperature
USAID	United States Agency for International Development
USD	United States dollar
VAT	value-added tax

EXECUTIVE SUMMARY

The worldwide deployment of renewable energy has seen significant growth over the last decade, driven by increasing awareness of the impacts of climate change and the associated need to reduce fossil fuel consumption and greenhouse gas emissions. Geothermal energy will play an important role in fostering a clean energy transition, as the technology offers a reliable source of baseload power that reduces emissions and improves energy security.

The demand for energy is expected to nearly double globally by mid-century. Meanwhile, the demand for food and water is expected to grow 50%, putting pressure on existing water, energy and food systems (IRENA, 2015). Scaling up investment in renewable energy technologies in agriculture and food ("agri-food") systems is critical to the success of the global energy transition. There are many opportunities for clean energy technologies to support food production, drying, cooling, storage, transport and distribution. Yet, energy use in agriculture and food still relies heavily on fossil fuels, with relatively limited penetration of renewables in these sectors to date (IRENA and FAO, 2021).

The growth in renewable energy, including geothermal energy, has predominantly centred around the electricity sector. However, there is significant potential for using geothermal energy in other end-use sectors through direct-use applications. This is particularly true for agri-food industries, where geothermal can support greater sustainability. In food production, geothermal can be used to regulate temperature and humidity to create the optimal environment for the cultivation of produce. In post-harvest preservation of produce, geothermal energy can be used to support drying, dehydration, cooling and cold storage to minimise spoilage. Geothermal heat is also used to increase the productivity of different applications such as in greenhouse heating, aquaculture, and food processing, among other forms of value addition.

In many developing countries, the unmet demand for affordable and sustainable energy is a key constraint to the development of the agri-food market segment and represents a significant opportunity for countries endowed with geothermal energy to use this resource (FAO, 2015). Agricultural drying via geothermal heat could increase the availability of food by up to an estimated 20% worldwide if the technology is widely deployed and scaled up. Geothermally heated greenhouse agriculture and aquaculture has the potential to further drive food production to meet global needs (IRENA, 2018).

The growth in geothermal energy over the past few decades is a promising development in the global effort to mitigate climate change. Further adoption of direct-use applications, particularly in industries such as the agri-food sector, will be instrumental in supporting the global energy transition and achieving long-term sustainable development goals.

The deployment of geothermal energy for heating applications has grown substantially, increasing 52% in the five years between 2015 and 2020. Greenhouse heating, aquaculture heating and drying represent the main agri-food applications for geothermal energy. Geothermal applications in agri-food value chains are spread across the world, with projects in Africa, Asia, the Americas and the Caribbean, Europe and Oceania. This is enabled by the widespread presence of geothermal resources in different geological and geographical locations.

Among the challenges hindering the use of geothermal energy in agri-food applications are inadequate data on geothermal resources and existing demand, absent or misaligned enabling frameworks, inadequate financing, and lack of awareness, among others. This guidebook provides recommendations to policy makers on the measures that can be implemented to address these challenges and lead to a higher uptake of geothermal energy. These are summarised in the following seven priority action areas (Figure ES1):

Mapping of geothermal resources and co-location with energy demand in the agri-food sector

- Identify and map various sources of geothermal energy – such as wells in existing geothermal fields, hot springs and other surface manifestations, and shallow-ground geothermal sources (*e.g.* hot boreholes). Collect data from these geothermal sources that are relevant to agri-food applications such as temperature, flow rate and chemical composition.

- Identify and map existing agri-food applications or areas with potential for establishing agri-food applications that could use geothermal energy. These data could be shown on maps and integrated with the geothermal resources data using interactive GIS platforms to illustrate the co-location between energy sources and demand to support investment decision making.

Enabling policy, legal and regulatory frameworks

- Develop clear licencing procedures for geothermal direct use or simplify existing licencing procedures, particularly for shallow, low-temperature resources. This could entail establishing a one-stop-shop for the provision of all the licences required to develop geothermal resources for agri-food and other direct-use applications.

- Introduce policy instruments such as heat tariffs, subsidies, fiscal incentives and de-risking/insurance schemes to support the development and adoption of geothermal heating in the agri-food sector.

Cross-sectoral alignment and multi-stakeholder engagement

- Identify different sectors within the economy whose activities can accelerate the deployment of geothermal energy in agri-food systems (*e.g.* energy, agricultural and industrial sectors).

- Identify stakeholders whose interventions could influence the development of geothermal agri-food applications and devise a strategy for engaging them as early as possible to establish synergies and get buy-in (*e.g.* national and local policy makers, manufacturers' associations, communities, etc.)

- Develop master plans for geothermal heat utilisation, taking into consideration the potential uses in different sectors; and aligning the policies of those sectors to achieve the necessary synergies.

- Include geothermal heat applications in energy transition and climate action plans for countries, such as the Nationally Determined Contributions (NDCs) and long-term decarbonisation strategies.

Project development and ownership

- Adapt a set-up model for direct-use operation that suits the prevailing circumstances in a given location (*e.g.* stand-alone systems, cascaded systems and direct-use systems integrated with electricity generation).

- Establish business and ownership models that ensure not only sustainability of the geothermal resource but also an affordable price of energy.

- For each business and ownership model, determine the objectives to be achieved through direct-use applications (*e.g.* profit maximisation, employment creation, sustainable operation practices, etc.) and establish criteria for selecting the most suitable enterprises to meet the objectives.

Access to financing

- De-risk investment in the geothermal agri-food sector by:
    - Establishing risk mitigation schemes for providing risk capital to developers, to enable drilling of new geothermal wells.
    - Mapping the areas that are favourable for utilising geothermal energy in the agri-food sector.
- Develop agri-food applications alongside existing geothermal power plants to utilise excess heat from power generation, thereby eliminating the need to drill new wells which are usually costly. In addition, implement cascading of energy among the geothermal agri-food applications to facilitate sharing of infrastructure such as pipelines, wells, etc., hence reducing exposure to high costs and risks.
- Develop feasibility studies to establish the bankability of geothermal agri-food applications.
- Facilitate understanding among local commercial banks of the financing requirements for geothermal agri-food applications, to enable them to develop financial solutions that are tailored to the needs of agri-food enterprises.

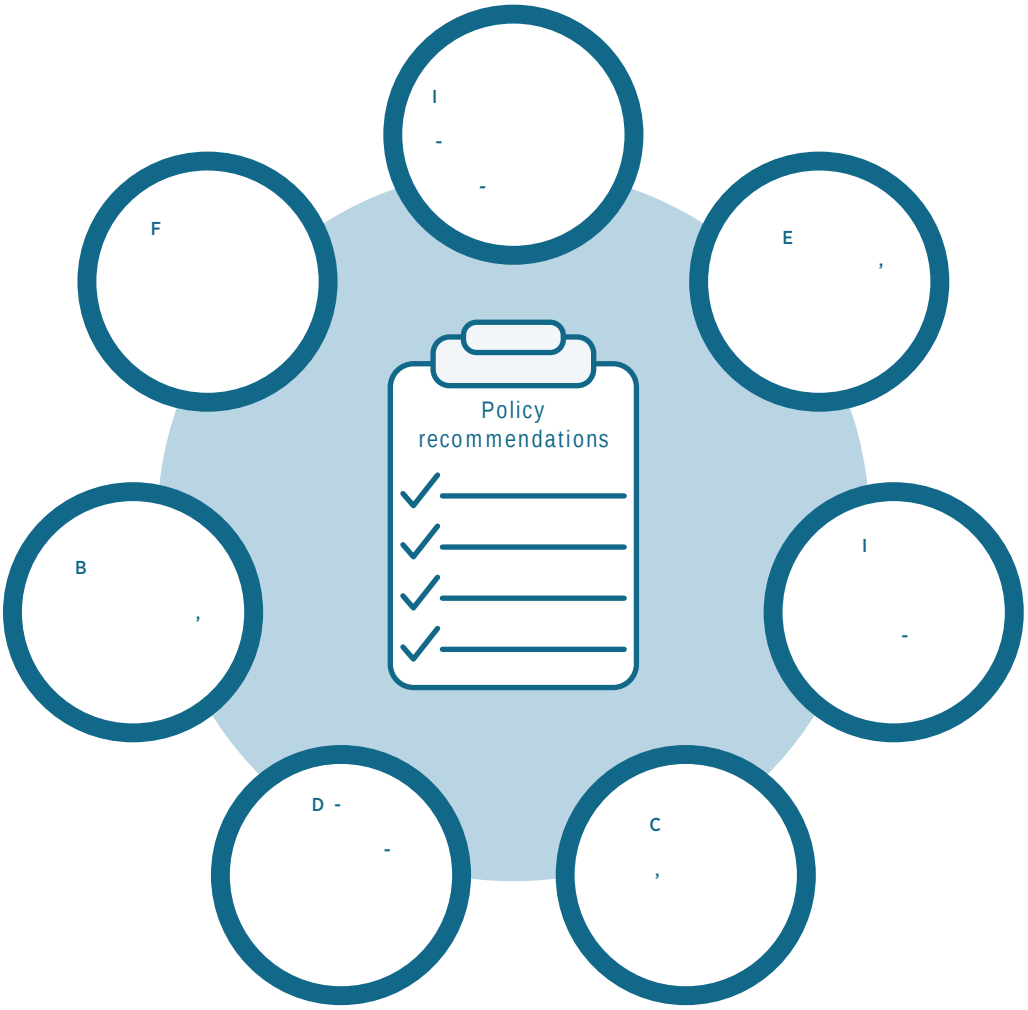
Building local capacity, education and awareness

- Create awareness on the potential and opportunities for geothermal applications in the agri-food sector among various stakeholders at the local level where utilisation of heat takes place.
- In new markets, demonstrate the socio-economic impacts of developing agri-food applications powered by geothermal energy by undertaking cost-benefit analyses to establish not only the financial but also the economic viability of projects.
- Implement pilot projects to demonstrate the technical viability of geothermal heat utilisation in the agri-food sector for the benefit of stakeholders such as investors, communities and policy makers.
- Train and build capacity of not only upstream technical expertise (*i.e.* engineers and scientists who develop the resource) but also national institutions (to enable them to assess the potential for implementing geothermal agri-food projects); service providers and downstream technicians who maintain the agri-food applications; local entrepreneurs and policy makers.

Leveraging technology, innovation and sustainability

- Encourage sustainability practices in the energy (geothermal) and industrial sectors that aim to maximise energy usage and minimise wastage of material through cascading and a circular economy.
- Integrate incubation centres in geothermal utilisation – including by collaborating with research institutions – to promote the development of new products and processes in agri-food, powered by geothermal heat.

Figure S1 Recommendations on priority actions to scale up geothermal deployment in the agri-food sector



The benefits of deploying geothermal direct-use applications in the agri-food sector are wide ranging. Geothermal heat utilisation in agri-food chains can contribute to improved food security and nutrition, reduce food waste, enhance productivity and increase the off-season availability of products. In addition, it supports the establishment of industries that create employment for youth, contributes to the empowerment of women who are the primary food producers in most developing countries, and provides increased income for businesses and farmers, thereby lifting living standards for rural communities. Furthermore, it can contribute to minimising greenhouse gas emissions and to helping the agri-food sector adapt to the effects of climate change (IRENA, 2019).

This guidebook recommends the adoption of a methodology to measure and quantify the socio-economic impacts of deploying geothermal heating in the agri-food sector. The information generated using this methodology could be used to raise awareness on the benefits of geothermal agri-food applications among policy makers, thereby supporting decision making. Finally, the bankability of developing geothermal resources for agri-food applications should be supported by a business case, based on the sale of heat to enterprises. Therefore, a competitive heat tariff that encourages the deployment of geothermal energy would be required by agri-food enterprises. The common methodologies for developing heating tariffs are also discussed in the guidebook.

INTRODUCTION

1.1 Background

Over the last decade, growing concern about the impacts of climate change and the associated need to reduce fossil fuel consumption and carbon dioxide (CO_2) emissions have led to a significant increase in the deployment of renewable energy worldwide. This upward trend has been driven by technological innovation, improved price competitiveness of renewable energy technologies, and enhanced policy and regulatory frameworks that have created an enabling environment for private sector renewable energy market development (IRENA, 2019). There is a critical need for a global energy transition led by clean energy technologies to potentially limit global warming to 1.5 degrees Celsius (°C) by 2050.

Renewable energy now dominates the global market for new electricity generation capacity. In many countries, clean energy technologies have overtaken fossil fuels as the cheapest source of power. In 2020, a record 260 gigawatts (GW) of renewable electricity was installed globally (IRENA, 2021a). Whereas most of this additional capacity was from wind and solar – around 91% – geothermal capacity has been growing steadily over the years. Between 2010 and 2020, a total of 5 053 GW of installed geothermal capacity was added globally, representing an increase of 46.3% and an annual compound growth rate of around 3.5% (Huttrer, 2020). In the coming years, geothermal energy will become increasingly critical in the clean energy transition, as the technology offers a reliable source of baseload power that reduces emissions and improves energy security.

The demand for energy is expected to nearly double globally by mid-century. Meanwhile, the demand for food and water is expected to grow by 50%, putting pressure on existing water, energy and food systems (IRENA, 2015). Scaling up investment in renewable energy technologies in agriculture and food ("agri-food") systems is critical to the success of the global energy transition. It will require an integrated public-private sector approach, extensive capacity development at all levels, and a comprehensive policy and regulatory framework to address the water-energy-food nexus.

Energy is a fundamental input in food systems, both directly and indirectly. There are many opportunities for clean energy technologies to support food production, drying, cooling, storage, transport and distribution. Yet, energy use in agriculture and food still relies heavily on fossil fuels, with relatively limited penetration of renewables in these sectors to date. A recent report by the International Renewable Energy Agency (IRENA) and the Food and Agriculture Organization of the United Nations (FAO), Renewable energy for agri-food systems: Towards the Sustainable Development Goals and the Paris Agreement, outlines a set of priority action areas required to scale up the integration of renewable energy solutions in agri-food systems. Implementation of these priorities would promote energy access/transition and food security while propagating achievement of the Sustainable Development Goals and the Paris Agreement (Box 1).

BOX 1 RENEWABLE ENERGY IN AGRI-FOOD SYSTEMS

Food systems consume a significant amount of energy globally. Up to 30% of world energy use occurs in the agri-food sector. As a result, energy use in food systems accounts for around 30% of the sector's carbon emissions.

Current trends in the use of energy in the agri-food sector show that fossil fuels account for a significant share of the energy consumed. In addition, the penetration of modern energy sources in the sector is still very low, particularly in developing countries. It is therefore critical to transition to the use of renewables in the agri-food sector to promote sustainability in food production. The applications of energy in food systems include primary production, post-harvest handling, storage and refrigeration as well as cooking. These applications promote increased yields, higher incomes, minimal food losses, enhanced health and well-being, and increased resilience to climate change.

Besides the direct benefits of energy use in the agri-food sector, renewables create additional socio-economic and environmental benefits including increasing food production, enhancing efficient use of labour, reducing pollution and greenhouse gas emissions, lowering costs and raising incomes for farmers and entrepreneurs, as well as contributing to inclusivity, gender equality and employment.

Among the high-impact renewable energy applications in the agri-food sector is solar irrigation, which contributes to water access for agriculture by enabling year-round production and resilience to changes in hydrological cycles. Agro-processing using renewables has contributed to lower energy costs in the production of marketable finished goods while protecting the environment, when compared with the use of fossil fuels. Through access to modern clean energy solutions, processing facilities can be decentralised in rural areas, reducing the time required to process the food (*e.g.* as compared to sun drying, which is very common in remote areas). In addition, cold storage and refrigeration of perishable produce such as milk, fish, fruits and vegetables using renewables is promoting the marketing of quality products while minimising post-harvest losses.

The IRENA and FAO report identifies several priority action areas to scale up the use of renewables in agri-food systems:

- Leverage new and existing tools to avail the necessary information on renewable energy potential and agri-food systems to inform decision making.
- Enable financing for renewable energy development and energy end-use sectors, particularly in agri-food.
- Promote a nexus approach to water-energy-food systems to leverage synergies among the different sectors and minimise competition for resources.
- Establish a conducive enabling framework through harmonisation of perspectives and strategies across different sectors to advance energy and food systems.
- Prioritise easily achievable action in the near term to minimise post-harvest losses, enhance circular economy effects, and strengthen the nexus between energy and food, as well as energy and health as part of the green recovery.
- Support innovations in renewable energy technologies to enable further deployment in end-use sectors through dedicated innovation funds and collaborations.

Source: IRENA and FAO, 2021.

Although the impacts of renewable energy use in the agri-food sector are largely similar across all renewable energy technologies, this guidebook focuses specifically on geothermal energy, and in particular on geothermal heating applications.

The growth in geothermal energy deployment has predominantly centred around the electricity sector. However, there is also significant potential for geothermal in end-use sectors through direct-use applications (direct use refers to the utilisation of geothermal resources for purposes other than electricity generation). This is particularly true for agri-food industries, which require a reliable supply of energy (see Figure 3).

Geothermal heat can be used for a wide range of agri-food applications, including, among others, agricultural drying (grains, vegetables, fruit, fish and other agricultural products); heating of greenhouses, soil and water (including for aquaculture); and industrial process heating. In addition, geothermal resources contain by-products such as dissolved minerals, non-condensable gases, brines and steam condensates that can be used for various applications. In many developing countries, unmet demand for affordable and sustainable energy is a key constraint to the development of the agri-food market segment and represents a significant opportunity for countries endowed with geothermal energy to utilise this resource (FAO, 2015).

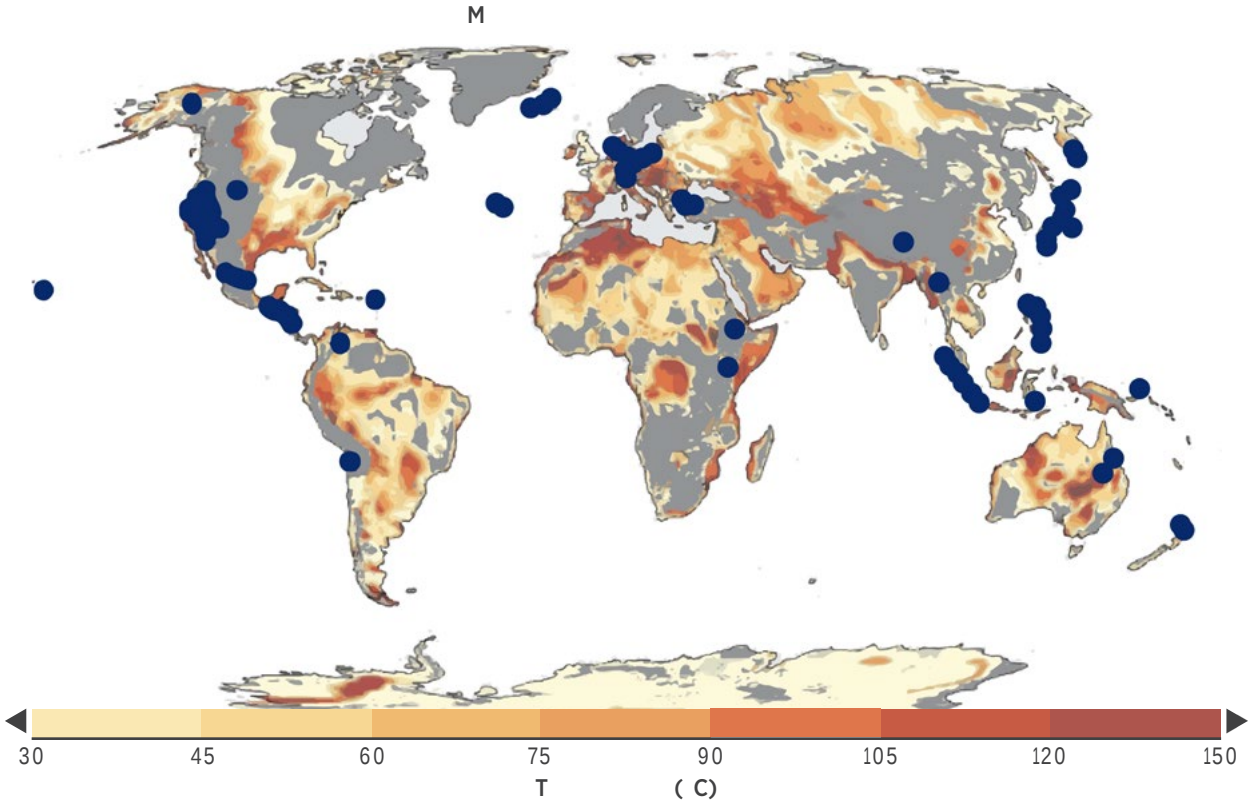
Geothermal energy is widely available around the world and is being used for various applications, subject to the resource temperature. High-temperature geothermal resources (above 150°C) are used mainly for electricity generation, whereas low- and medium-temperature resources (less than 150°C) are more suitable for direct use but could also be used for electricity generation through binary power plant technologies (Dickson and Fanelli, 2004).

The high-temperature geothermal resources occur mainly near areas with high volcanic and tectonic activities such as the Pacific "Ring of Fire", which includes the western United States, Latin America and the Caribbean, New Zealand, the Pacific Islands, Indonesia, the Philippines, Japan and the Kamchatka peninsula (Masum and Akbar, 2020). Other major high-enthalpy geothermal resources can be found along the mid-Atlantic ridge (Iceland and the Azores), the East Africa Rift and parts of Europe.

On the other hand, resources in the low- and medium-temperature range, which are suitable for direct heating applications, are not as constrained geographically compared to conventional high-temperature resources used mainly for electricity generation. These lower-temperature resources can be found not only in volcanically active areas, but also in other geological settings such as sedimentary basins. The widespread occurrence of low- and medium-temperature resources presents an opportunity to develop direct-use geothermal applications potentially in most countries globally.

Figure 1 shows the geographic distribution of the global maximum aquifer temperature at 3 kilometres depth in sedimentary basins (indicative of the broader potential for geothermal direct-use applications), together with locations of geothermal power plants around the world, which coincide with the locations of high-temperature geothermal resources (>150°C). The grey areas are where the sedimentary thickness is less than 100 metres and hence the temperature is not shown (Limberger *et al.*, 2018).

Figure 1 Global maximum aquifer temperature at 3 kilometres depth with locations of geothermal power plants around the world



Adapted from Limberger *et al.*, 2018 and Richter, 2020a.

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Investment in direct-use geothermal projects is increasing, driven mainly by the energy savings associated with using geothermal energy in these applications. In 1995, only 28 countries took advantage of the direct use of geothermal energy; by 2019, this number had more than tripled to 88 countries. The total estimated installed capacity for geothermal direct use in 2019 was 107.7 gigawatts-thermal, representing a 52% increase over the 2015 data. Between 2015 and 2019, the growth in direct use of geothermal energy led to an estimated reduction in CO_2 emissions of 252.6 million tonnes (Lund and Toth, 2020).

Direct uses of heat present an enormous opportunity for the deployment of geothermal energy. The largest installed capacity for direct use in existence today is for heat pumps and district heating, as well as for bathing and swimming. However, great potential also exists in the agricultural sector, which continues to support most rural livelihoods throughout the world. Direct-use geothermal technologies can create job opportunities and boost local productivity in rural areas, among other benefits. For example, geothermal crop drying can help reduce the drying time, preserve the quality of produce, offer skilled and unskilled employment, reduce food waste and improve food security.

Within the framework of the Global Geothermal Alliance[1], IRENA is working with partners to build the capacities of relevant policy makers to promote and scale up the adoption and widespread use of geothermal energy in agri-food systems. The capacity building entails the development of a guidebook for policy makers on powering agri-food value chains with geothermal heat. The guidebook's target audience includes stakeholders in the energy, industrial and agricultural sectors, such as government representatives, geothermal developers, agri-food enterprises, and local communities, among others.

[1] *A multi-stakeholder platform, facilitated by IRENA, for enhancing dialogue, co-operation and co-ordinated action to foster geothermal development worldwide.*

1.2 Rationale

Around 30% of the greenhouse gas emissions from agri-food systems are related to energy use in various stages of the value chain (IRENA and FAO, 2021). Renewable energy solutions, including geothermal heating applications in the agri-food sector, can contribute to climate change mitigation and adaptation efforts on a global scale. Given the wide range of applications of geothermal direct-use technology across multiple end-use sectors, this technology can contribute to the realisation of several United Nations Sustainable Development Goals (SDGs) and support countries to achieve their Nationally Determined Contributions (NDCs) under the Paris Agreement.

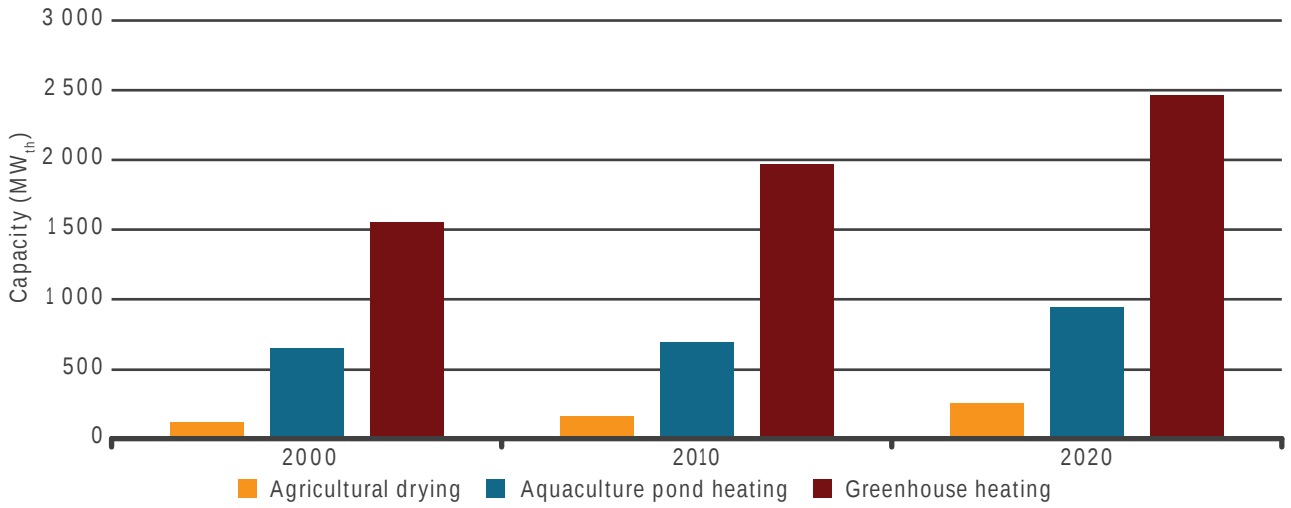
The adoption and scale-up of clean energy solutions such as geothermal energy can replace fossil fuels and reduce emissions across the agri-food sector, thus improving the sustainability of food production, processing, storage, transport and trade. The socio-economic impacts of geothermal heat utilisation in agri-food value chains are examined in further detail in section 2.1 and section 4.1.

Agri-food applications for geothermal heat mainly include agricultural production, processing, drying, cold storage and refrigeration. Examples include heating for greenhouses, fish farms, chicken hatcheries and milk pasteurisation, among others (Guglielmetti *et al.*, 2020). Applying heat and controlling temperature for these processes can increase productivity and yield, increase the resiliency of food systems, support post-harvest preservation and storage, and improve food security and nutrition. These applications are examined in further detail in section 2.2 and as case studies throughout this guidebook.

Figure 2 provides an overview of the growth in geothermal heating capacity worldwide as it applies to the specific agri-food value chains of agricultural drying, greenhouse heating and aquaculture pond heating – three of the most widely used applications of geothermal heat in the agri-food sector. Greenhouse heating has experienced particularly strong growth in recent years, with a capacity increase of more than 60% between 2000 and 2020. Aquaculture heating and agricultural drying also grew steadily over this period.

The use of geothermal energy for electricity generation and direct-use applications is still limited globally. This is due mainly to: a lack of data (both on geothermal direct-use potential and on energy use in agri-food systems); low levels of awareness about the opportunities and benefits for the productive use of energy associated with direct-use technologies; limited financing options due to high upfront costs and resource risk; and the fact that countries have not established enabling conditions for investment in the sector, which in most cases is lacking or inadequate. In this regard, IRENA aims to support countries to increase their capacities to develop and implement policies and regulations that aim to strengthen the enabling environment for geothermal heat applications, including for agri-food applications.

Figure 2 Geothermal heating capacity in three agri-food value chains, 2000-2020



Adapted from Lund and Toth, 2020.

Note: MW_{th} = Megawatt thermal

1.3 Methodology and structure of the guidebook

This guidebook presents the key elements necessary for a more rapid deployment of geothermal heat in agri-food value chains. It analyses the key challenges facing this market segment and proposes solutions, as well as recommendations for policy makers. It also provides an overview of direct-use applications in the agri-food sector together with case studies from around the world that exemplify best industry practices.

Preparation of this guidebook involved extensive desk research, including a detailed review of geothermal direct-use projects, programmes and initiatives around the world (which serve as case studies throughout the guidebook); policy, legal and regulatory frameworks; economic, social and environmental benefits; gaps, challenges and lessons learnt associated with the scale-up of geothermal heat utilisation in the agri-food sector. A consultative peer review process was undertaken with a group of industry stakeholders who reviewed and shared their comments and recommendations on draft versions of the guidebook.
The guidebook is organised into the following main sections:

Section 1: Introduction – this section introduces the use of renewable energy solutions, including geothermal heat (direct use) in the agri-food sector, and provides context for the study.

Section 2: Overview of geothermal heat applications in agri-food value chains – this section describes the benefits of geothermal heat utilisation and its linkages to global climate and sustainable development objectives. It also identifies some of the common direct-use applications in the agri-food value chains (including in agricultural production, processing and post-harvest preservation) and presents examples of specific applications around the world.

Section 3: Guidelines for adopting and scaling up the use of geothermal energy in the agri-food sector – this section identifies seven priority action areas that can support the development of geothermal agri-food applications while highlighting the associated gaps/challenges hindering their adoption and scale-up. The action areas are: mapping of geothermal resources and co-location with energy demand in the agri-food sector; enabling policy, legal and regulatory frameworks; cross-sectoral alignment and multi-stakeholder engagement; project development and ownership; access to financing; building local capacity, education and awareness; and leveraging technology, innovation and sustainability.

Section 4: Tools and methodologies – this section examines how the impacts of geothermal direct use in the agri-food sector are measured based on a cost-benefit analysis to support decision making. It identifies socio-economic indicators specific to agri-food value chains and how they can be quantified to measure the impact of geothermal interventions in the sector. The section also describes the approaches that can be used in establishing geothermal heat tariffs as well as the key elements of a heat purchase agreement.

OVERVIEW OF GEOTHERMAL HEAT APPLICATIONS IN AGRI-FOOD VALUE CHAINS

2.1 Benefits and linkages to sustainable development and climate action

Key benefits of geothermal direct use in the agri-food sector

Geothermal heating applications in the agri-food sector have wide-ranging benefits for the environment as well as multiple stakeholders, including investors, geothermal project developers, local communities and local authorities, among others. Social, economic and environmental benefits for stakeholders are introduced in this section and further developed in section 4.1, which includes a cost-benefit analysis framework to assess socio-economic indicators and benefits resulting from the incorporation of geothermal energy into agri-food value chains.

Environmental benefits result from reduced use of fossil fuels and wood fuels for heating applications. This contributes to climate change mitigation through the increased availability of clean energy, the reduction of greenhouse gas emissions and deforestation. In addition, the operation of geothermal-based systems entails adoption of environmental practices such as re-injection of spent geothermal water back into the reservoir to avoid pollution and enhance sustainability of the resource. Compared to other sources of renewable energy for agri-food applications, geothermal energy has a very low requirement for land per unit of energy produced.

Enterprises using geothermal energy in agri-food applications benefit from lower energy costs and the resulting increased profit margins compared to those using fossil fuels, as geothermal energy could be more affordable under the right conditions. The assurance of a reliable baseload supply of energy from geothermal is an added benefit to enterprises, and, as a result, the need for back-up energy supply is limited. Furthermore, the maintenance costs of these energy supply systems are typically limited to geothermal piping systems.

Geothermal project developers who integrate direct use and electricity generation could benefit from the sale of geothermal heat in addition to electricity sales, which provides an extra revenue stream, resulting in higher returns and reduced financial risks due to diversification of income. The use of excess heat from power generation, as well as energy from wells that are not used for electricity production, can also generate revenue from resources that would otherwise not have been used for any commercial gain. The use of geothermal fluids through a cascaded direct-use mechanism leads to improved efficiency in the utilisation of geothermal resources and can integrate multiple applications with varying temperature requirements (see section 3.4 for different set-ups of direct-use projects).

Local communities benefit directly and indirectly from geothermal heat utilisation both in the application and along the value chain. The development and operation of geothermal heat applications provides employment opportunities for local communities, either during construction, operation or maintenance. Geothermal heating applications used for food production, processing and transformation improve the availability of food and minimise post-harvest losses, which in turn increases crop yield for local farmers and improves food security and nutrition for the community. The establishment of decentralised food processing facilities provides a local market for the food produced by the farmer. Additional benefits for the local community include improved infrastructure development associated with agri-food industries and skills development for local youth in relevant fields (*e.g.* food, agriculture, engineering and finance) to support geothermal and agri-food development. Other indirect community benefits include the development of complementary businesses to provide support services to geothermal agri-food ventures.

Local authorities benefit from new revenue from taxes, business permits and licence fees generated from the establishment of agro-industrial and related businesses along the agri-food value chain. In addition, when the use of geothermal heat displaces fossil fuels, governments benefit from savings by avoiding importation of fossil fuels.

In New Zealand, geothermal energy is being leveraged as a catalyst for economic development at the local level. Box 2 describes some of the benefits that have been realised from geothermal heat application in the agri-food sector.

BOX 2 THE BENEFITS OF GEOTHERMAL HEAT IN NEW ZEALAND'S AGRI-FOOD INDUSTRY

© GNS Science

Miraka's milk processing plant at Mokai on the North Island of New Zealand.

New Zealand is endowed with an abundance of geothermal energy, particularly on the volcanic North Island. A large share of the country's power comes from geothermal energy, and it has a well-established geothermal industry. Geothermal is used both for electricity generation and for direct uses, such as bathing and hot pools, industrial processing of timber and paper, and heating for horticulture, agriculture and fishing industries.

New Zealand's geothermal resource development model aims not only to maximise profits for the developer but also to benefit the communities that occupy the lands where the resources are located and to protect the environment. The indigenous communities in New Zealand, the Maori, participate in geothermal development as shareholders and commercial investors. The revenues generated from the geothermal Investments are reinvested in social programmes for the benefit of the community such as education, health, culture, sports, finance and well-being.

The use of geothermal energy in New Zealand has greatly contributed to the decarbonisation of the economy by displacing around 2 million tonnes of CO_2 annually as of 2016 (Blair *et al*., 2018).

In the agri-food sector, geothermal energy is used to support the food and beverage industry, which is New Zealand's largest export sector.

In the dairy sector, Miraka, a Maori-owned milk processing company located in Mokai, runs on geothermal electricity and uses geothermal heat from the Mokai Geothermal Field in its process heating applications. The plant produces dried milk powders and ultra-high temperature (UHT) products (>135°C to preserve milk for longer). These products acquire the clean, green branding and are exported to more than 26 countries. The milk processor receives milk from 110 local farms and around 60 000 cows, thereby providing the milk farmers with a market for their produce. The factory provides jobs to around 120 employees who contribute to local economic growth (Wairakei Research Centre, 2020).

At the Huka Prawn Park, geothermal energy enhances the production of river prawns by providing an optimal temperature for their growth through the heating of pond water to around 30°C using the energy from a nearby geothermal power plant. As a result, around 8 tonnes of prawns per year are produced from less than 3 hectares of land. The prawn farm provides employment to around 60 people.

Other agri-food applications of geothermal energy in New Zealand include Gourmet Mokai, a glasshouse facility for growing tomatoes and capsicum. The use of geothermal enables the crops to be grown during the winter months, ensuring year-round production. Arataki Honey, a honey producer located in Rotorua, has used geothermal energy for honey processing for several years, resulting in cost-effective operations. The company produces more than 1 000 tonnes of honey annually for domestic and export markets.

Linkages to climate action and sustainable development goals

The increased uptake of geothermal heating applications is closely linked to concerns about climate change, energy security, volatile commodity prices and sustainable economic development. These issues are high on the decarbonisation and sustainability agenda of several nations, including those where geothermal potential exists, particularly in developing countries.

With a rapidly increasing global population, there is an urgent need to increase food production without putting additional pressure on land and water resources. An important nexus exists among water-energy-food, which can be leveraged to sustainably meet the food requirements of the growing population. Due to the production of multiple streams of by-products such as electricity, heat, water (and steam/condensate), mineral elements and gases; geothermal is uniquely positioned to contribute to the enhancement of agri-food systems through the utilisation of these by-products (see section 2.2). Geothermal direct use in agri-food value chains improves energy security, reduces greenhouse gas emissions, promotes resilience in food systems, supports the establishment of a domestic renewable energy industry and supports the realisation of several United Nations Sustainable Development Goals. Where chemical properties allow, geothermal steam condensate and waters provide water for irrigation to support food production.

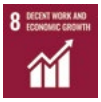
The rise in global temperature due to greenhouse gas emissions has contributed to disruption of the hydrological cycle, which in turn has negatively affected food production in many countries. Rising temperatures also contribute to the accelerated spoilage of food, particularly in rural communities where the use of refrigeration and cold storage is limited. Therefore, geothermal applications in food production and post-harvest processes contribute to the adaptation of food systems to the effects of climate change.

The agri-food sector, particularly in developing countries, is uniquely positioned to enhance inclusivity and empowerment among marginalised demographics such as women and youth. In developing countries, the agricultural sector is the largest employer. Women in those countries play a key role in the production of food, producing around three-quarters of the total (IRENA, 2016a). Enhancing food systems through the use of energy in food production in combination with advanced production technologies will impact women positively. In addition, local agricultural-based businesses that innovate with the use of geothermal energy could provide job opportunities for youth (IRENA and FAO, 2021). The jobs created as a result of geothermal energy applications in the agri-food sector are usually higher-quality, long-term jobs with career development pathways.

Table 1 provides an overview of the role that geothermal agri-food applications play in the realisation of the Sustainable Development Goals.

> "With a rapidly increasing global population, geothermal energy is uniquely positioned to enhance food production without putting additional pressure on land and water resources, among other Sustainable Development Goals."

Table 1 Linkages to climate action and the Sustainable Development Goals

UN Sustainable Development Goal	Description
	SDG 1: End poverty • Due to increased food production, food producers can sell the excess food to boost income. • Value addition of agricultural produce means more income for farmers and employment opportunities. • Agri-food products labelled as "green" due to the use of clean energy and sustainable practices in their production fetch premium prices in the market.
	SDG 2: End hunger • Increased yield from the use of geothermal energy promotes food security. • Food can be grown in environments/conditions when it would naturally not be possible (*e.g.* fruits and vegetables during winter months). • Less food is wasted due to timely processing and cold storage/refrigeration.
	SDG 4: Quality education • Opportunities for higher education are created in relevant fields such as food, agriculture, engineering and finance to support geothermal and agri-food industries.
	SDG 5: Gender equality • Women play a key role in the agri-food sector, particularly in developing countries. Enhancement of agri-food systems through geothermal contributes to improved fortunes for women.
	SDG 7: Affordable and clean energy • Geothermal energy is a clean and affordable solution that provides energy for electricity production or for direct use.
	**SDG 8: Decent work and economic growth** • Geothermal applications in the agri-food sector offer a wide range of opportunities for productive and sustained employment and economic growth. • Geothermal creates high-quality, long-term jobs with career development pathways.
	SDG 9: Industry, innovation and infrastructure • Geothermal energy applications support the development of resilient infrastructure, promote inclusive and sustainable industrialisation, and foster innovation in the agri-food sector.
	SDG 10: Reduced inequalities • Decentralisation of agri-food industries to rural areas where most geothermal resources are found provides opportunities for infrastructure development and access to social amenities in those areas. • Employment opportunities for local communities in the development and operation of direct-use projects serve to increase income and reduce income inequality. • Stimulation of the local economy from direct employment and sales to agro-industrial markets results in improved standards of living.
	SDG 12: Responsible consumption and production • Geothermal energy resources are used more efficiently, including through cascading systems. • Co-location of industries that can exchange energy and materials promotes a circular economy.
	SDG 13: Climate action • Geothermal technologies operate with little or no emissions. • Geothermal energy development can reduce CO_2 emissions when substituting the technology for fossil fuels and can help countries achieve their climate objectives and NDCs.

Source: Frederiksen and Werner (2013).

2.2 Geothermal direct-use applications in the agri-food sector

Energy is a key input in agri-food value chains. In food production, it can be used to power farm machinery, support the provision of inputs (such as fertiliser manufacture and water pumping for irrigation) and regulate temperature and humidity to create the optimal environment for cultivation of produce. In post-harvest preservation of produce, energy can be used to support drying, dehydration, cooling and cold storage to minimise spoilage. Energy is also a key input to other stages in agri-food value chains, such as transport, value addition, retail and cooking.

Geothermal resources provide several energy and non-energy streams that could have multiple applications in agri-food systems. These streams include electricity used to power electrical appliances (*e.g.* pumps, motors, compressors, etc.) for food production, processing, cooling and refrigeration; thermal energy used as process heat in food production, post-harvest treatment, storage and processing; geothermal water (*i.e.* steam condensate and water) used for irrigation; gases (*e.g.* CO_2) used to enhance photosynthesis in greenhouse primary food production; and marketable mineral extracts such as sulphur that could potentially be used for fertiliser production.

Table 2 shows the various uses of geothermal energy in agri-food value chains. However, the focus of this guidebook is on non-electric uses, primarily heat utilisation.

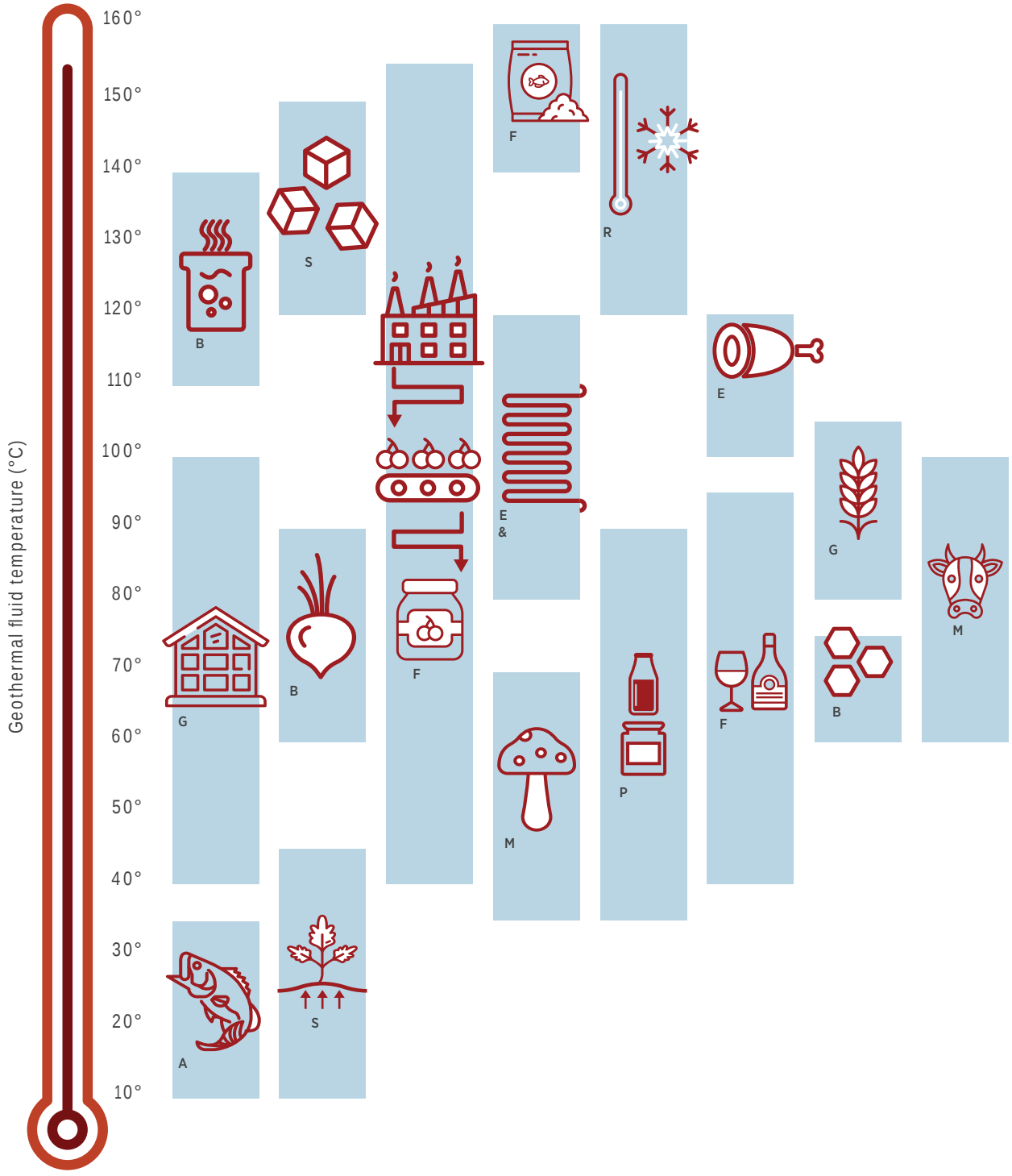
Table 2 Geothermal applications in agri-food value chains

Primary production	Post-harvest and storage	Transport and distribution	Processing	Retail preparation and cooking
• Water for irrigation • Heating of greenhouses and soil warming • Aquaculture heating • Sterilisation of soil, irrigation water and substrate for mushroom culture • Enhancing photosynthesis through CO_2 from geothermal sources • Fertiliser manufacture from sulphur • Running of water pumps using geothermal electricity	• Drying and dehydration of grains, fruits, vegetables, meat and fish, etc. • Cold storage and refrigeration (electric and thermal driven)	• Ice generated using geothermal energy • Electric vehicles charged using geothermal energy	• Process heating applications • Pasteurisation, *e.g.* milk • Sterilisation, *e.g.* food canning • Fermentation and distillation, *e.g.* beer, wines and spirits • Evaporation, *e.g.* milk powder • Powering of processing equipment using geothermal electricity	• Pre-cooking, *e.g.* food canning • Baking

Adapted from IRENA, 2019.

In the agri-food sector, geothermal energy is used to increase the efficiency and productivity of different applications such as greenhouse heating, aquaculture and food processing, among others (Figure 3). The temperature requirement for these applications can largely be met by low- to medium-temperature geothermal resources. For high- and medium-temperature geothermal resources, heat utilisation could be combined with electricity generation.

Figure 3 Lindal diagram of potential uses of geothermal energy in the agricultural sector



Source: Adapted from FAO, 2015.

Agricultural production

Geothermal energy can support agricultural production in various ways. Geothermal heat is used to sterilise soil and irrigation water in agriculture and to regulate temperature and humidity in greenhouses to improve production and enable year-round growing of crops, including off-season or in harsh climatic conditions. Temperature is controlled with geothermal heat for aquaculture, which improves yield, increases the growth rates of species and reduces disease (Climo, 2015).

Greenhouse heating

The most common application of geothermal energy in the agricultural sector is greenhouse heating. Geothermal heating is applied in greenhouses mainly to produce flowers, fruits and vegetables on a large scale, making food available throughout the year. The objective of greenhouse heating is to regulate the temperature and humidity in the greenhouse to provide a conducive environment for crops, resulting in a higher production rate, better-quality crops and reduced incidence of disease.

Low-temperature geothermal resources (<90°C) typically supply the necessary heating for greenhouses, although the level of heating required depends on the crop being cultivated. For example, hot springs allow farmers to construct and maintain geothermal greenhouses year-round in Chena, Alaska. The Chena greenhouse, in operation since 2004, produces hydroponic lettuce, herbs, tomatoes and small fruits. In the winter season, radiant air heat exchangers are used to heat the natural cold air using geothermal energy; the warm air is then ventilated into an interior greenhouse area. The greenhouse is also designed to limit heat loss and to prevent cold air from coming into contact with the plants (Hein, 2012).

The commercial viability of geothermal greenhouse operations depends on several factors, including the type of crop, climate, resource temperature, type of structure, access to markets, etc. The advantage of using geothermal energy is that it regulates the temperature according to the needs of each agricultural product and reduces both fuel and operating costs for greenhouse operators (IRENA, 2019). In certain instances, operators can achieve fuel cost savings as high as 80% compared to traditional energy sources (diesel- or gas-powered generation) – representing around 5% to 8% of total operating costs (NREL, 2014).

Among the countries that use geothermal resources to heat greenhouses are China, Hungary, Iceland, Italy, Kenya, the Netherlands, the Russian Federation, Türkiye and the United States (Guglielmetti *et al.*, 2020; Lund and Toth, 2020; FAO, 2015).

The HEATSTORE project funded by GEOTHERMICA – ERA NET Co-fund includes an innovative system integrating high-temperature aquifer thermal energy storage (HT-ATES) with greenhouses at demonstration and case study sites in the Netherlands (Drijver, Bakema and Oerlemans, 2019). HT-ATES is an innovative technique that allows recovering excess heat from the greenhouses in summer, storing it in aquifers at around 500 metres in depth and eventually delivering it during cold seasons, providing a solution to decarbonise the energy supply for greenhouses, improve energy efficiency (the storage system has an expected recovery factor of 80%) and optimise the sustainability of food production (Drijver, Bakema and Oerlemans, 2019).

Aquaculture heating

Aquaculture involves the farming of fish and other marine organisms in a controlled environment to facilitate their breeding and production. The principal aquatic species raised on fish farms include catfish, salmon, bass, tilapia, sturgeon, shrimp and tropical fish, among others. Geothermal heat can provide a conducive temperature to increase the productivity of aquaculture operations. Fish farms use the energy in geothermal water to heat fresh/marine water in heat exchangers or through direct mixing to obtain the required temperatures for aquaculture. This expedites the growth rate of the organisms, reduces production costs and makes it profitable throughout the year.

The temperature of aquaculture depends on the species farmed but is typically in the range of 15-30°C. Water heated by geothermal is typically used in raceways, ponds and tanks. Besides temperature control, water quality and disease management are critical considerations in geothermal aquaculture (NREL, 2014).

Among the countries reporting the use of geothermal energy in aquaculture are China, France, Greece, Iceland, Israel, Italy, New Zealand, Switzerland and the United States (Guglielmetti *et al.*, 2020; Lund and Toth, 2020; FAO, 2015). Iceland is a world leader in geothermal aquaculture and has developed some of the most advanced facilities, as described in Box 3.

BOX 3 GEOTHERMAL AQUACULTURE IN ICELAND

Iceland's largest aquaculture centre in Tálknafjörður, Iceland, which uses geothermal heat in its fish farming operations.

Iceland is endowed with abundant natural resources. In 2019, the country's natural resources accounted for 22% of its gross domestic product (GDP) and around 73% of exports. Fisheries is the second largest industry in Iceland behind tourism and transport. Although the role of agriculture in the country's economy has declined, recent efforts have been made to increase exports of agricultural products accompanied by an uptake in the use of geothermal heat in greenhouses (Iceland Chamber of Commerce, 2020).

Due to the cold climate in Iceland, large-scale industrial aquaculture operations in the country use geothermal heat. Arctic Fish is one of Iceland's recent success stories in this sector. In 2019, the company opened an aquaculture facility in Tálknafjörður in the West Fjords. The facility uses a recirculating aquaculture system and is among the only water recovery operations of its kind (McDonagh, 2019). Arctic Fish chose Tálknafjörður as the location for its facilities because of its proximity to natural hot springs indicating a widespread source of geothermal heat. Arctic Fish is the premier Icelandic enterprise to implement a full water recycling aquaculture system. It has the technology to regulate heat and light optimally to facilitate ideal breeding conditions.

Iceland's aquaculture industry is known for its sustainable practices and holistic use of fish by-products. Haustak, an Icelandic dried-fish products company based in Reykjanes resource park, uses geothermal heat from a power plant for drying products. Among the products dried are fish heads, bones and offcuts that were previously disposed of as waste but are now marketed to Africa. Due to properly controlled drying, the shelf life of these products is as long as two years (Haustak Dried Fish Products, 2021).

Another fish by-product, the skin of cod fish, is being used by an Icelandic biomedical firm to treat wounds by stimulating tissue regeneration, due to the high level of omega-3 on the fish skin. The skin is obtained from sustainably sourced fish and processed using renewable energy (Kerecis, 2021).