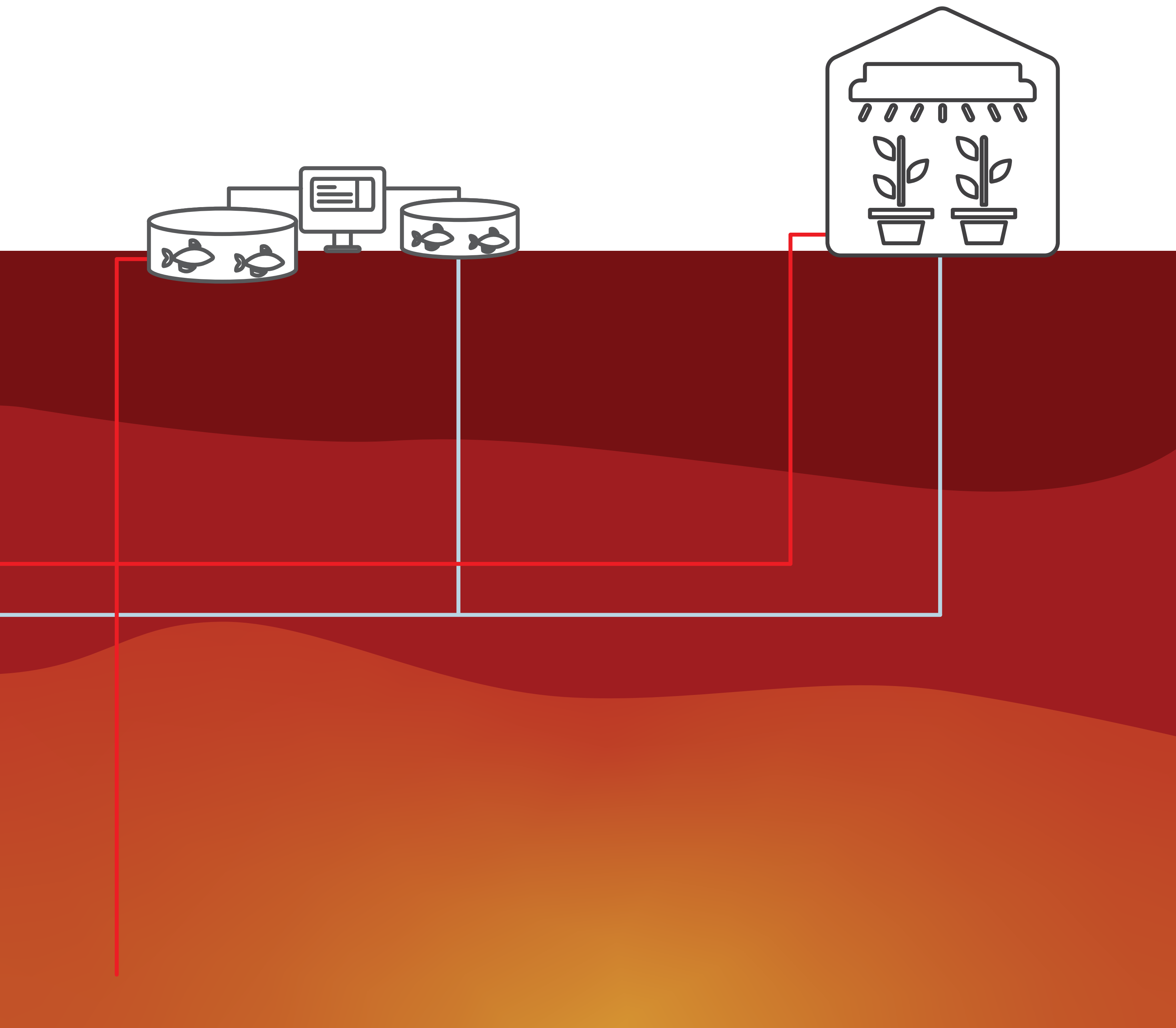
IRENA
International Renewable Energy Agency

Powering agri-food value chains with geothermal heat

A guidebook for policy makers



ISBN: 978-92-9260-441-7

Citation: IRENA (2022), *Powering agri-food value chains with geothermal heat: A guidebook for policy makers*, International Renewable Energy Agency, Abu Dhabi.

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**

Acknowledgements

IRENA is grateful for the valuable contributions of the members of the advisory group of geothermal experts created from the constituency of the Global Geothermal Alliance (GGA) and other institutions involved in geothermal utilisation in the agri-food sector.

Inputs and feedback were received from the following experts: Héctor Miguel Aviña and Eduardo Perez Gonzalez (Autonomous National University of Mexico), Manon Stover (Baseload Capital), Peter Omenda (Consultant), Aida Antonieta Flores and Jose Salvador Handal (El Salvador – CNE), Oliver Dubois (FAO), Jacques Varet (Géo2D), Steve Grasby (Geothermal Canada), Ana Lucia Alfaro Murillo and Rafael Edgardo Parada Perez (GIZ), Guðni Axelsson (GRO GTP), Cristian Irias (Honduras – SEN), Volkan Öztürk and Ufuk Şentürk (JESDER), Paul Ramsak (Netherlands Enterprise Agency – RVO), Maria Carla Lourenço and Luís Nuno Duarte da Silva (Portugal – Directorate General for Energy and Geology), Maged Mahmoud (Regional Center for Renewable Energy and Energy Efficiency – RCREEE), Luca Guglielmetti (University of Geneva), Andrea (Andy) Blair (Upflow Ltd), and Elin Hallgrimsdottir and Joeri Frederik de Wit (World Bank ESMAP).

Valuable input was also provided by the following IRENA colleagues: Aliz Crowley, Jin Kyung Jeong, Paul Komor, Divyam Nagpal, Bishal Parajuli, Pablo Ralon and Ali Yasir.

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**

This guidebook is available for download: **www.irena.org/publications**

CONTENTS

FIGURES

TABLES

BOXES

PHOTOGRAPHS

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).

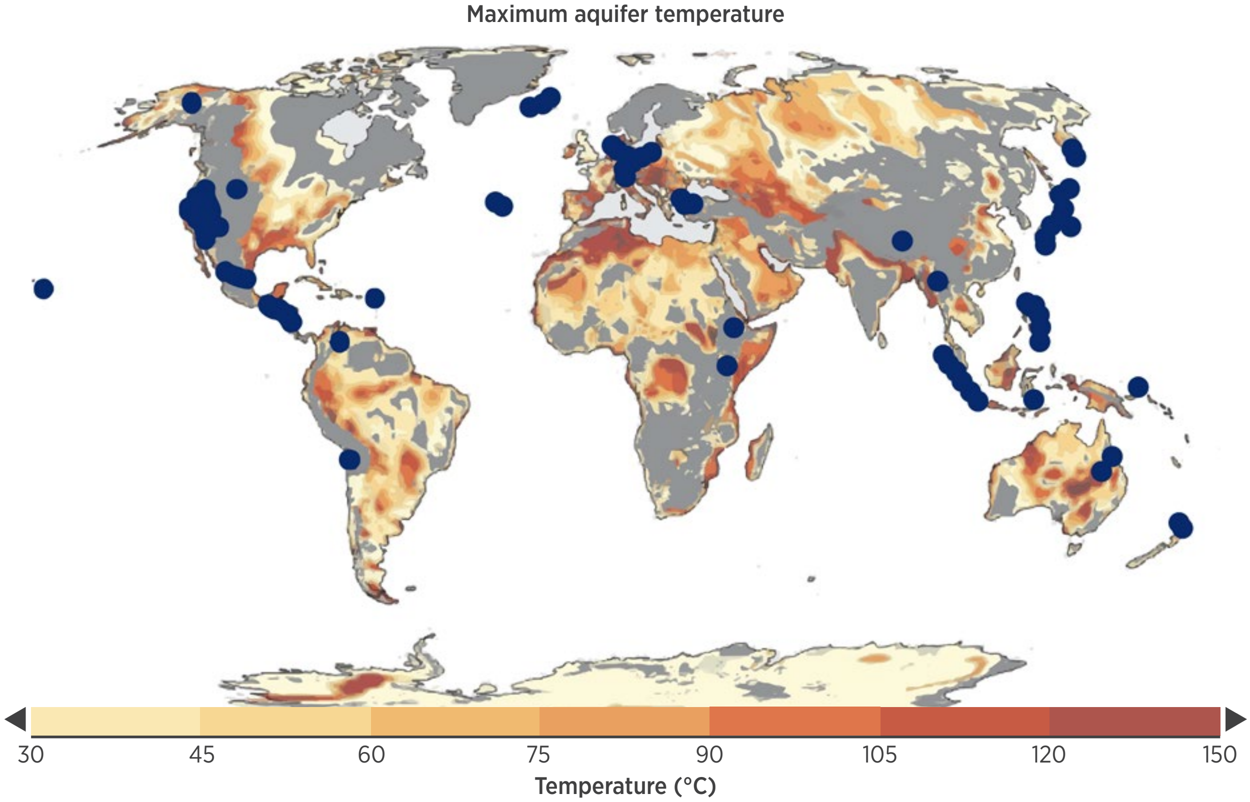
Geothermal energy is widely available around the world and is being used for various applications, subject to the resource temperature. High-temperature geothermal resources (above 150°C) are used mainly for electricity generation, whereas low- and medium-temperature resources (less than 150°C) are more 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.

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

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.

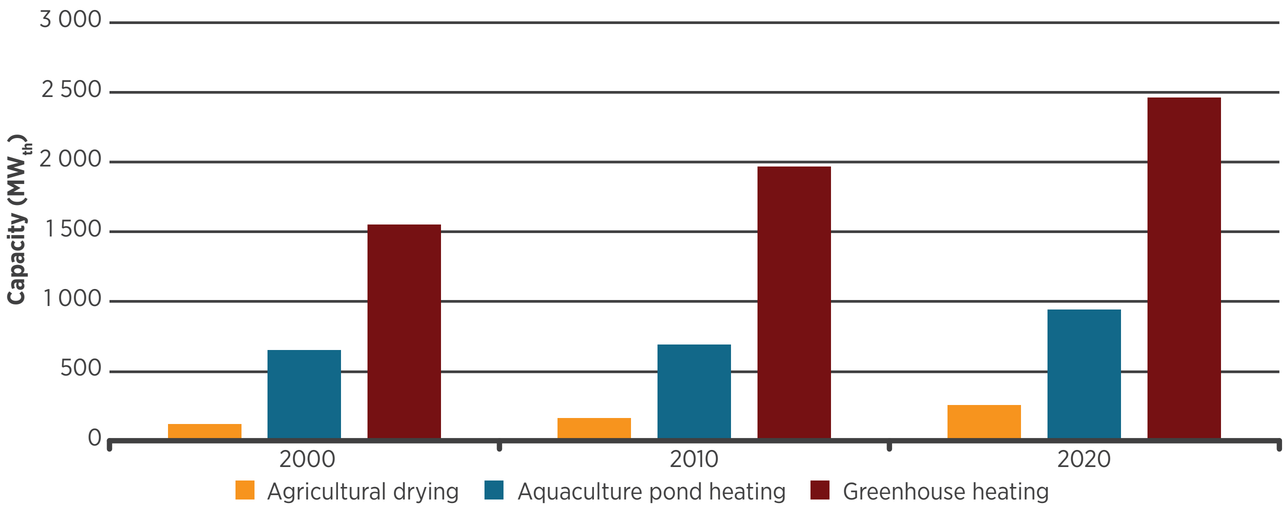
The adoption and scale-up of clean energy solutions such as geothermal energy can replace fossil fuels and reduce emissions across the agri-food sector, thus improving the sustainability of food production, processing, storage, transport and trade. The socio-economic impacts of geothermal heat utilisation 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.

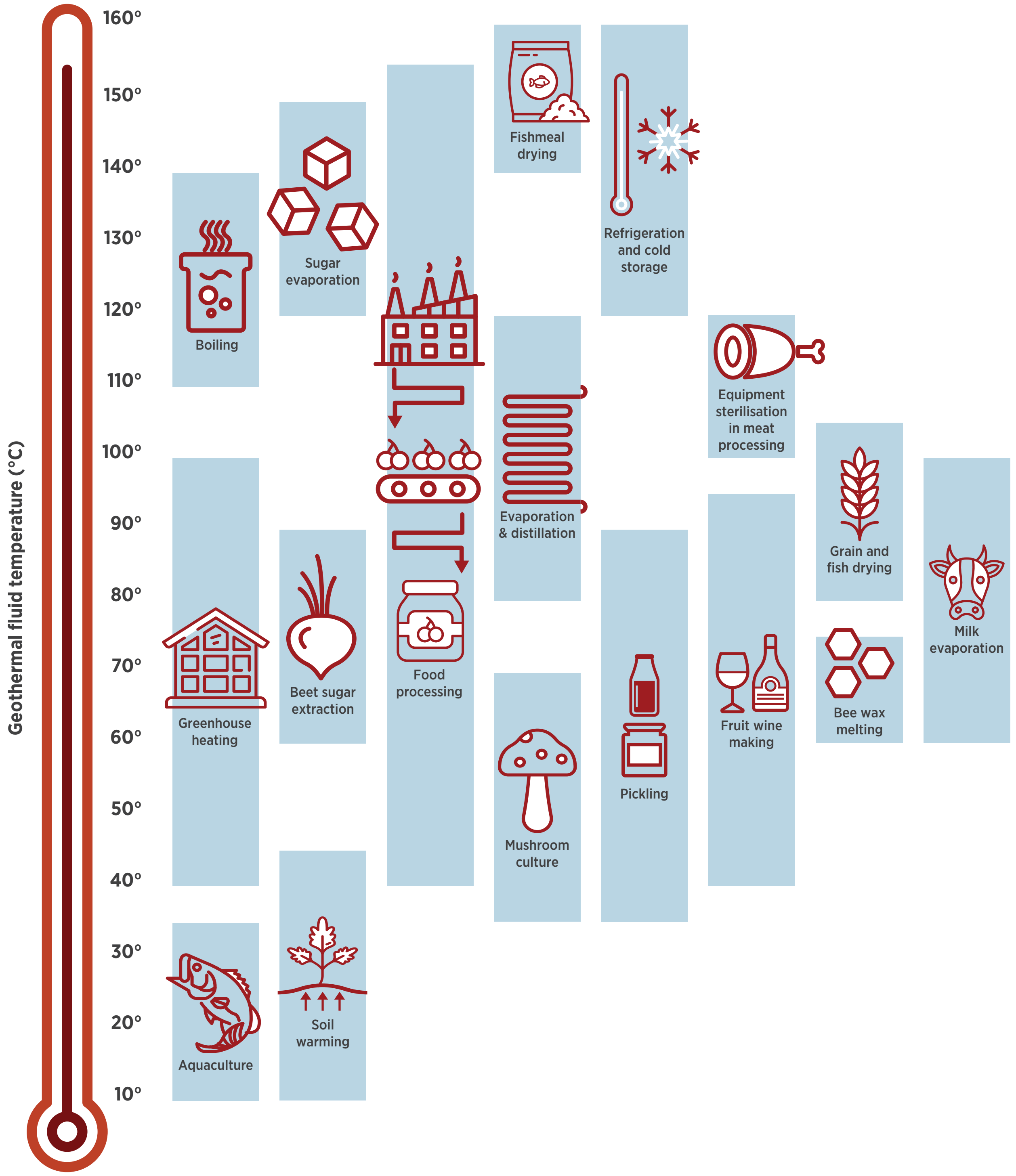
Table 2 Geothermal applications in agri-food value chains

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).

Photograph 1 Mushroom cultivation from geothermal heat in Kamojang geothermal field, Indonesia

© Surana *et al.*, 2010

Photograph 2 A geothermal milk pasteuriser at the Menengai geothermal field, Kenya

© GDC, Kenya

Mushroom cultivation

A crucial part of the mushroom cultivation process is sterilisation of the growth medium to kill any potential biological contaminants before mushrooms begin to grow. Mushroom cultivation typically requires heat in the range of 40-70°C.

In the Kamojang geothermal field in West Java, Indonesia, geothermal energy was successfully used in this sterilisation process (Photograph 1). In addition to mushrooms, further research was carried out on the sterilisation of potato-growing media. Geothermal heat was a substitute for oil fuel, leading to significant reductions in costs and emissions (Surana *et al.*, 2010).

A similar mushroom-growing pilot project was previously launched at Los Humeros geothermal field in Mexico in the 1990s, which aimed to use excess geothermal heat in a food production operation to reduce production costs. The replacement of fossil fuels with geothermal steam ultimately lowered pasteurisation, incubation and production costs, while better control of temperature and moisture conditions resulted in increased production (Rangel, 1998).

Agricultural processing and value addition

Food processing can include process heat applications such as evaporation, fermentation, canning, pasteurisation, sterilisation, and drying and dehydration after initial processing (*i.e.* transformation to other commercial products). Unlike agricultural production activities, industrial processing activities usually require higher temperatures. Agricultural processing using geothermal heat enables farmers to deliver larger volumes of finished goods to markets (Climo, 2015).

Milk pasteurisation

Milk is a product that can spoil quickly due to its enzymatic activity and microbial growth and thus requires timely processing to keep it fresh. The dairy industry can use geothermal hot water for milk pasteurisation as well as geothermal steam for UHT pasteurisation and milk powder production through evaporation and drying.

Geothermal heat can be used at around 60-80°C to pasteurise milk and get rid of most microbes. Most geothermal resources can provide this kind of temperature. The issue that requires more attention is cooling the treated milk to around 3-4°C for storage. This can also be achieved by using geothermal heat – but requires a higher temperature

(>120°C) to provide the cooling effect using the absorption cycle refrigeration technology. Milk with longer shelf life can also be produced by pasteurising the milk using higher-temperature geothermal fluids (>130°C). In this case, the milk can be stored for several weeks after it is brought to the market. On the other hand, milk powder production requires high-temperature geothermal steam (>200°C).

The use of geothermal heat in milk processing has taken place in Iceland (dating back to the 1930s) and in the United States (Klamath Falls, Oregon) and is currently ongoing in Italy, New Zealand (Lund, 1997) and Romania. A milk pasteurisation demonstration project also exists in Kenya (Photograph 2), and a cheese production project in Honduras.

Post-harvest preservation

Energy is a key input into post-harvest preservation of produce. Geothermal heating applications can support drying and dehydration as well as cold storage and refrigeration of produce to minimise food waste and spoilage. Improved post-harvest preservation decreases spoilage of produce for local farmers and allows them to sell raw materials to agriculture-based industries.

Agricultural drying and dehydration

Agricultural drying and dehydration are among the two most prominent uses of geothermal energy in the agri-food sector. One way for farmers to reduce waste and ensure food availability throughout the year is through the drying of agricultural products (fruits, vegetables, fish, meat, cereals, etc.). The heat required for the drying process can typically be obtained from hot water from geothermal sources. This process often has an advantage over using hydrocarbons and electricity in food processing, especially in cases where the cost of producing the geothermal hot water and steam is low.

A variety of crops are suited for drying and dehydration using temperatures that can be supplied by geothermal energy. These include cereals (maize, rice, wheat, etc.), tomatoes, onions, garlic, carrots, mushrooms, apples, mangoes, pears and dates, among others (Box 4). In 2020, around 15 countries were using geothermal energy for drying of various crops (Lund and Toth, 2020).

BOX 4 GEOTHERMAL FRUIT DEHYDRATION IN MEXICO

© Geofood, Mexico

Mango geothermal dehydration in processing facilities in Mexico.

A food dehydrator at Los Azufres, Mexico was installed in 1995 and had the capacity to dehydrate an average of 400 kilograms of fruit and produce 40 kilograms of dry fruit. The temperature inside the dehydrator was 60°C.

The Geothermal Food Dehydrator (Deshidratador Geotérmico de Alimentos, or DGA) project was developed by the Institute of Engineering of the National Autonomous University of Mexico (IIUNAM, by its acronym in Spanish) with financing from the Mexican Centre for Geothermal Energy Innovation (CeMIE-Geo, by its acronym in Spanish). The first prototype of the food dehydrator, the DGA10 model, is a dehydrator that was operated by running hot air through the dehydrating chamber, a horizontal section (3 metres long) with the capacity to process 10 kilograms of fruit in 15 hours.

The DGA is located in Domo de San Pedro Geothermal Field and is managed by DGA de Nayarit. It has three geothermal drying chambers for food dehydration with the capacity to process 3 000 kilograms/batch/day of alimentary pulp, which produces up to 900 kilograms/batch/day of processed dry fruit. The fruits dehydrated at the plant Include jack fruits, mangoes, pineapples and tomatoes. Around 50 people from the local area are employed directly at the dehydration plant (90% women), and around 60 people derive employment indirectly from the plant.

Cold storage and refrigeration

Cold storage and refrigeration are necessary to preserve the quality of agricultural produce and reduce spoilage, particularly for perishable crops such as tubers, fruits and vegetables. The loss of food in the agri-food value chains due to spoilage could be as high as 20% on average in regions with low penetration of cold storages (FAO, 2019). Consequently, cold treatment is required at every step of the agri-food value chain to minimise losses.

Cold storage can serve multiple purposes in agri-food value chains, including refrigeration for agricultural produce, which can reduce losses and increase output. Geothermal resources in the range of 80-150°C can be used to provide cooling for cold storage and refrigeration through the absorption cycle, with higher temperatures increasing the efficiency of the process (Uwera *et al.*, 2015). Absorption cycle equipment is particularly compatible with geothermal energy, as it uses heat to drive the working fluid through the system. It is capital intensive but has low operating costs, making it more suited for medium- to large-scale operations (IRENA and FAO, 2021).

As a result, geothermal-powered absorption cooling is technically feasible. However, its commercial application to the agri-food industry remains limited around the world. This is because of the small-scale nature of the cooling requirements in most existing geothermal agri-food applications. Geothermal heat pumps can also provide a sustainable cooling solution that is more energy efficient than conventional cooling systems.

Geothermal agri-food applications around the world

In the agri-food sector, geothermal heat applications can support food security, provide employment, contribute to gender equality and boost rural economic development. Developed countries that have implemented geothermal agri-food applications include Japan in Asia; Bosnia and Herzegovina, Greece, Hungary, Iceland, Italy, the Netherlands, Poland, Romania, the Russian Federation, Serbia, the Slovak Republic, Switzerland and Türkiye in Europe; the United States in North America; and Australia and New Zealand in Oceania (Lund and Toth, 2020).

Direct-use agri-food applications also occur in developing countries. These include: Algeria, Kenya and Tunisia in Africa; China, Indonesia, the Philippines, Thailand and Vietnam in Asia; El Salvador and Guatemala in Central America; Mexico in North America; and Argentina and Chile in South America. However, the level of utilisation in developing countries is low compared to developed countries, with the exception of China (Lund and Toth, 2020).

Europe

Europe is a leading market for geothermal heating and cooling of residential and commercial buildings at the individual and district scales, as well as for industrial applications. Geothermal systems are found mainly in low- to medium-temperature deep sedimentary basins throughout mainland Europe. Larger geothermal power plants are found in diverse geologic settings in Iceland, Italy, Portugal (Azores Islands), the Russian Federation and Türkiye; smaller binary power plants occur in Austria, Belgium, Croatia, France, Germany, Hungary and Romania (Richter, 2020a).

Agri-food applications that utilise geothermal heat are widespread throughout Europe (Guglielmetti *et al.*, 2020; Lund and Toth, 2020; FAO, 2015), notably:

- greenhouse heating in Iceland, Italy, Hungary, the Netherlands, the Russian Federation and Türkiye;
- aquaculture heating in Iceland, Italy, Poland, Romania, Serbia, the Slovak Republic and Switzerland;
- spirulina cultivation in Greece, Iceland and Italy;
- crop drying in Greece (vegetable/fruit dehydration), Iceland (seaweed and fish drying) and Serbia (grain drying); and
- industrial applications in Bosnia and Herzegovina, Iceland (salt extraction) and Italy (milk processing); as well as in Greece, Iceland and Italy (wine making and beer brewing).

North America

In North America, geothermal power production occurs in the western United States (California, Idaho, Nevada, New Mexico, Oregon and Utah), Alaska and Hawaii. Canada has great potential to develop low- to medium-temperature geothermal resources, especially to support remote northern communities, but it has yet to install a power plant or implement agri-food direct-use applications as of 2021. Direct use of geothermal resources (excluding heat pumps) in the United States has remained nearly static over the past decade, with the closure of several industrial facilities (*e.g.* onion/garlic dehydration in Nevada) offsetting growth (Boyd, Sifford and Lund, 2015). Geothermal heat applications in the US agri-food sector include the following (Lund and Toth, 2020):

- greenhouse heating at 44 locations across 9 US states mainly growing potted plants and flowers and some organic vegetables;
- 51 fish farming and 2 alligator farming facilities in 10 states, as the United States is a global leader in aquaculture; and
- winery facilities in California, New York, Virginia, and Wisconsin and a brewery in Oregon (Boyd, Sifford and Lund, 2015)[2].

[2] *Trout Springs Winery: www.troutspringswinery.com/sustainability.html;*
Pearmund Cellars: www.pearmundcellars.com/pearmund-cellars-history/;
and Sheldrake Point Winery: https://sheldrakepoint.com/wp-content/uploads/2020/07/Sheldrake-Point-Winery-Goes-Geothermal.pdf

Oceania

New Zealand´s Taupo Volcanic Zone is the locus of geothermal power production within Oceania. There are cascaded geothermal heat applications at several power plants within this zone, and there is a growing emphasis on expanding geothermal direct-use businesses in New Zealand (*e.g.* planned milk processing at Kawerau geothermal field and a planned brewery at Wairakei geothermal field). Agri-food direct-use applications in Oceania include (Daysh *et al.*, 2020; Lund and Toth, 2020):

- greenhouse heating in New Zealand;
- aquaculture in two locations in Australia and two locations in New Zealand;
- drying of alfalfa in New Zealand; and
- milk processing at Mokai geothermal field.

Asia

In Asia, geothermal resources are mainly located along the Ring of Fire archipelago and include countries such as Chinese Taipei, Indonesia, Japan and the Philippines, as well as China and Thailand. China has rapidly become the world leader in geothermal heat utilisation. The main direct-use applications in China include geothermal heat pumps, aquaculture and agricultural crop drying. Other agri-food direct-use applications in Asia include the following (Lund and Toth, 2020; FAO, 2015):

- greenhouse heating in China and Japan;
- aquaculture in China (farms and fishponds), Indonesia (catfish), Japan (tilapia, shrimp), Jordan (tilapia) and Vietnam (fish farming);
- crop drying in China, Indonesia (beans and cereals at the Kamojang Geothermal Field, coffee bean and tea leaf drying), Japan (vegetable drying) and Thailand (bananas, chili, garlic, maize, tobacco, peanut drying at Sankamphaeng and Fang geothermal fields) and the Philippines (coconut meat); and
- industrial applications in India (food processing), Indonesia (mushroom cultivation at Kamojang geothermal field, copra processing to make coconut oil) and Vietnam (salt extraction).

Photograph 3 Greenhouse utilising geothermal heat in Menengai, Nakuru, Kenya


© Geothermal Development Company

Eastern Africa

Geothermal resources in this region are found mainly along the East Africa Rift – which runs through 13 countries and can be geographically split into the eastern and western branches – as well as in the Comoros Islands. The eastern branch has dominantly high-temperature volcano-hosted geothermal systems apt for flash steam power plants and cascaded direct-use applications, whereas the western branch has dominantly low- to medium-temperature fault-hosted systems apt for binary power plants and direct-use applications.

Despite significant geothermal potential in the region, Kenya is the only country with reported agri-food direct-use applications. However, great potential exists in other East African countries, where the agricultural sector remains a key economic driver. The existing direct-use applications in agri-food value chains in the region include the following:

- agricultural drying: *e.g.* drying of grains and pyrethrum flowers at Eburru, Kenya; and
- a direct-use demonstration facility at Menengai, which extracts heat from a low-pressure well not suitable for electricity generation. The pilot project entails a range of geothermal-heated applications, including heating for a greenhouse (Photograph 3), aquaculture unit, milk pasteuriser and grain dryer.

Latin America and the Caribbean

The Latin America and the Caribbean region has significant geothermal potential, with most of the resources located in the following geographical locations: Central America and Mexico (Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua and Panama), the Andes Mountains of South America (Argentina, Bolivia, Chile, Colombia, Ecuador, Peru and Venezuela) and the Eastern Caribbean states and territories (the Commonwealth of Dominica, Grenada, Guadeloupe, Martinique, Montserrat, Saint Kitts and Nevis, Saint Lucia, and Saint Vincent and the Grenadines). The majority of the geothermal resources are magmatically heated high-temperature systems.

El Salvador, Guatemala and Mexico lead the Latin America region in agri-food applications with geothermal heat supplied by shallow wells or integrated with operating geothermal power plants. Chile leads the Andes Mountains of South America subregion in agri-food applications supplying heat from geothermal heat pumps. Direct use of geothermal energy for agri-food systems has yet to be implemented in the Eastern Caribbean states and territories. There is growing interest among many stakeholders in the Latin America and the Caribbean region for expanded geothermal heat use, application of geothermal heat pumps and an improving investment climate.

Examples of geothermal agri-food applications in the region are presented below.

El Salvador

The state-owned geothermal developer Geotérmica Salvadoreña, S.A. de C.V. (LaGeo) has local community projects for agri-food applications using direct utilization of geothermal fluids in both the Ahuachapán and Berlin geothermal fields. The direct-use projects are implemented by LaGeo's non-profit FundaGeo, a social foundation operating since 2006 to implement corporate social responsibility initiatives to benefit local rural communities (González *et al.*, 2019). FundaGeo provides local communities with surplus geothermal by-products (steam, steam condensate and heat from re-injection water) as well as seed capital, training, and infrastructure for productive uses and income-earning potential (ESMAP, 2019; González *et al.*, 2019).

At Ahuachapán geothermal field, geothermal steam is used for handmade candle-making, and steam condensate is used to water coffee plants as well as in beekeeping to process honey. At Berlin geothermal field, fruits such as apples, bananas, coconuts and pineapples are dehydrated for sale and consumption by the local community, with an estimated installed capacity for agricultural drying of 1.7 megawatts-thermal (MW_{th}) and 21 terajoules (TJ) per year of energy (Rodríguez and Herrera, 2005). A newly constructed coffee dryer will be used by neighbouring communities. The coffee drying process will use heat from separated geothermal water of 170°C obtained from a re-injection pipeline. Following heat extraction for the direct-use process, the water must be returned to the same pipeline at temperatures no less than 150°C to avoid silica scaling downstream in the steam field and wells (Photograph 4).

Photograph 4 Local community projects using geothermal energy by-products in El Salvador

Production of handmade candles with geothermal steam (left), coffee irrigated with steam condensate (centre) and coffee drying with re-injection water (right) in El Salvador.

Guatemala

There are two agri-food geothermal direct-use projects near Amatitlan geothermal field. The San Michkael Geothermal Mini-Industrial Park pilot demonstration project produces hot water and steam from shallow wells, which is used to dehydrate food, grains, fruits and vegetables, to produce handmade candles and to provide hot and cold water production for multiple industrial uses. Cold storage and other cascaded applications are being evaluated (Paiz, 2021).

In 1999, the company Agroindustrias La Laguna built a demonstration plant adjacent to the Amatitlan geothermal field. The plant dehydrates apples, bananas, chili peppers mangoes, pears and pineapples. Geothermal heat is supplied for the dehydration process by a downhole heat exchanger in a shallow well drilled to 120 metres depth that was not capable of producing fluids (Merida, 1999). The energy used in agricultural drying is estimated at 0.5 MW_{th} and 12 TJ per year (Lund and Toth, 2020).

Mexico

In Mexico, the majority of direct-use applications are in balneology (health and therapeutic applications) and space heating. In the agri-food sector, geothermal heat is being used for greenhouse heating and fruit-drying applications (see Box 4: Geothermal fruit drying in Mexico). Geothermal heat utilisation was first pioneered by the Federal Electric Commission through a series of pilot projects to demonstrate the technical feasibility of direct-use applications of geothermal heat in three operating geothermal fields: Cerro Prieto, Los Azufres and Los Humeros. The pilot projects included office heating, heated greenhouses, a fruit and vegetable dehydrator, bulb germination, accelerated flower production, an edible fungal nursery and wood drying (Casimiro and Pastrana, 1996).

Andean region of South America

In Chile, geothermal heat pumps are used for heating applications in aquaculture, greenhouses and the wine industry. A pilot project in southern Chile uses geothermal energy to support year-round growing and harvesting of crops in geothermal-heated greenhouses in Puerto Aysén, a remote town where it is cold and rainy for much of the year, complicating access to local fresh vegetables. In Argentina, limited use of geothermal heat occurs at three sites for aquaculture and greenhouses (Lund and Toth, 2020).

Eastern Caribbean

Direct use in the Eastern Caribbean is currently limited to non-agri-food applications such as swimming and bathing. However, there is growing interest in agri-food applications including potential for crop drying (*e.g.* bananas, cacao, seaweed and sugar cane / rum). The Organization of Eastern Caribbean States recently commissioned a direct-use study across the Eastern Caribbean islands with the support of the government of New Zealand (Ephraim, 2020).

GUIDELINES FOR ADOPTING AND SCALING UP THE USE OF GEOTHERMAL HEAT IN THE AGRI-FOOD SECTOR

This section provides an overview of the key components of direct use of geothermal heat in agri-food systems and recommended measures for policy makers to scale up the adoption of this technology. The seven priority areas covered are: 1) mapping of geothermal resources and co-location with energy demand in the agri-food sector; 2) enabling policy, legal and regulatory frameworks; 3) cross-sectoral alignment and multi-stakeholder engagement; 4) project development and ownership; 5) access to financing; 6) building local capacity, education and awareness; and 7) leveraging technology, innovation and sustainability. The section also identifies gaps and challenges hindering the scale-up of direct-use technologies in the agri-food sector and provides possible solutions and corresponding case studies to exemplify how the identified barriers can be addressed.

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

Various types of geothermal energy resources can be used for agri-food applications over a range of depths and temperatures. These include low- medium- and high-temperature geothermal fluids that can be obtained from shallow or deep reservoirs. Geothermal fluids may reach the surface of the earth as hot springs or fumaroles, or through wells drilled to access the geothermal reservoirs.

In volcanic geologic settings (*e.g.* along rift valleys and the Ring of Fire or on volcanic islands), deep resources tend to have higher temperatures; however, in sedimentary basins (*e.g.* in continental Europe), deep resources have lower temperatures. There are various classification schemes of geothermal resources by depth, temperature, geological setting and other characteristics (Williams, Reed and Anderson, 2011). For purposes of utilising geothermal resources for direct-use applications, the following classifications are most applicable:

Depth

- Surface manifestations of geothermal fluids occur as hot springs, fumaroles, steaming ground, mud pots and geysers.
- Shallow geothermal resources occur in the near sub-surface down to a few hundreds of metres in depth.
- Deep geothermal resources in volcanic regions can be hosted between 1 000 and 3 000 metres depth, while sedimentary basin-hosted geothermal systems can be found at depths exceeding 5 000 metres.

Temperature

- High-temperature geothermal resources are liquid-dominated, two-phase or vapour-dominated systems generally considered to be greater than 150°C.
- Medium-temperature geothermal resources are generally liquid-dominated systems and considered to be in the range of 100-150°C.
- Low-temperature geothermal resources are liquid-dominated and generally considered to be less than 100°C.

The temperature available from the geothermal resource will to a large extent influence the choice of the direct-use application to be developed. Generally, the main sources of geothermal energy for agri-food applications may include the following:

- hot water available as a by-product from binary plants and flash steam plants before being re-injected;
- hot water or steam from sub-commercial geothermal wells (*i.e.* where pressure/temperature is too low to support electricity generation);
- hot water or steam from wells located at uneconomical distance from existing power plants;
- excess steam from existing geothermal wells, which is not used for electricity generation;
- outflow from geothermal reservoirs such as hot springs and fumaroles;
- water from boreholes with elevated temperature;
- hot water co-produced with oil and gas or from repurposed oil and gas wells; and
- energy from shallow ground or ground water at shallow depth, in combination with heat pumps to boost the temperature.

A key challenge facing the geothermal industry is that most geothermal resources suitable for direct use are largely unexplored. It is often the case that inadequate data are available for these resources, which cannot justify the drilling of geothermal wells. However, in many instances these resources may be located close to agriculturally productive areas. In addition, these resources may occur at shallow depth and hence can be developed more easily and at a lower cost than deeper geothermal resources. Drilling new wells for direct-use projects poses a financial challenge, as it is often cost-prohibitive for small-scale direct-use projects. Therefore, integrating geothermal agri-food applications into electricity generation projects to use either separated brine in cascade operation, geothermal fluids from sub-commercial wells, or excess steam and hot brine from the electricity generation can minimise drilling risks.

As an initial step, the development of digital data portals, online databases, interactive GIS maps and analytical tools can help to identify potential areas with geothermal resources suitable for direct-use applications. As highlighted in Box 5, many countries and regions have developed these types of tools to support initial identification of sites with techno-economic potential for direct-use applications. The interactive maps and analytical tools facilitate geothermal direct-use resource assessments for potential investors at the regional, national and local levels. These platforms do not replace in-depth technical feasibility studies; rather, they provide an initial overview of the geothermal potential for a given location or region. Digital portals are useful to policy makers to raise awareness of geothermal solutions, promote accelerated geothermal development and encourage development of new areas.

BOX 5 INTERACTIVE DIGITAL GEOTHERMAL MAPS AS RESOURCE ASSESSMENT TOOLS TO SUPPORT INVESTMENTS

Examples of interactive web-based maps, analytical tools and digital data portals that have been developed at the regional level (East Africa, Central Europe) and national level (Mexico, Hungary, the Netherlands, the United States, Canada and Switzerland) are presented below:

- **Africa Geothermal Inventory Database (AGID; East Africa)** is an online digital data repository and web GIS information sharing platform for 13 countries in East Africa. The UN Environment AGID provides a centralised hub for geothermal information available to public, private and other stakeholders. The database promotes the development and use of geothermal energy resources with the objective of catalysing investment in geothermal projects. The GIS map viewer contains information on participating countries, geothermal sites, power plants, organisations, laboratories, equipment and human resources in the East Africa Rift. AGID was launched in 2014, while the map viewer was created in October 2016 and last updated in September 2017.

- **Danube region geothermal information platform (Central Europe)** is a regional portal to provide data and information about geothermal energy in the Pannonian basin, which includes six countries and territories (Bosnia and Herzegovina, Croatia, Hungary, Romania, Serbia and Slovenia). The portal was designed in 2019 by the Danube Region Leading Geothermal Energy project – an international consortium of geological surveys, university, industry, and development agency partners – to promote sustainable use of the largely untapped deep geothermal energy resources in the Pannonian basin as well as to foster collaboration and exchange of ideas among geothermal industry stakeholders across the Danube Region. In addition, the portal was created to raise awareness among policy and decision makers on the advantages of geothermal energy as a solution for decarbonising the heating sector. The portal contains an online map viewer, which provides access to information on spatial-referenced datasets (boreholes, maps, etc.), as well as thematic modules on knowledge sharing, benchmarking, geologic risk mitigation, legislation and licencing, and a glossary and decision tree.

- **National Inventory of Clean Energies (INEL; Mexico)** is a user-friendly, publicly accessible online statistical and GIS platform that provides information about the use and potential of geothermal energy and other renewable energy sources. The platform is available in Spanish and English, and all data are downloadable. The INEL was compiled by the Ministry of Energy (SENER) in collaboration with the Federal Electricity Commission (CFE) in accordance with the mandate for its creation in the Energy Transition Law of 2015. The INEL consists of three components for each renewable technology: 1) an inventory of generation, 2) an inventory of estimated potential and 3) GIS map information on resource potential. The two inventories each include interactive analysis tools; user queries by geographic region, technology, proven or probable classification, generation capacity or data source; location of power generation sites; and statistics on installed capacity and generation. The geothermal GIS map information on resource potential comprises geothermal permits and concessions, heat flow measurements in wells, and a nationwide map of sub-surface temperature. Although much of the geothermal information pertains to electricity generation, the map of geothermal potential is also useful for evaluating direct-use projects. The purpose of the INEL is to provide information to potential investors, researchers and policy makers and generally promote electricity generation using clean energy sources. It is intended to serve as a tool for government decision makers on policies, legal frameworks, economic incentives and financing to facilitate the use of clean energy. The website application was last updated in August 2018.

- **Hungarian geothermal system (Hungary)** is a user-friendly and publicly accessible web-based platform that provides geological, hydrogeological and geophysical and well data on geothermal energy resources in Hungary. It was created in 2020 with the intention to assist policy makers and national and international investors to perform the preparatory work necessary for new projects in Hungary, as well as to support academic and general public interest. The portal contains digital map data as well as analysis modules to provide assistance during all stages of project development. Building on the results of the Danube Region Leading Geothermal Energy project, the analysis tools include benchmarking (evaluation of thermal water management and utilisation practices in the areas of licence management, technology, environment and social aspects), decision trees (decision points during project development related to geothermal resources, market, licencing and funding) and risk mitigation (identifying geologic risks and appropriate mitigation measures).

- **ThermoGIS (Netherlands)** is a public, web-based GIS system that provides aquifer and sub-surface temperature maps derived from geothermal, oil and gas well data. ThermoGIS was created in 2010 with the main goal of supporting companies and the government to develop geothermal energy in the Netherlands. A tool to calculate techno-economic potential for direct-use heating applications (excluding electricity generation) can be used for feasibility studies and site selection. The economic feasibility analysis uses a discounted cash flow model that incorporates cost parameters and the Dutch SDE+ energy production subsidy scheme, among others. The online platform is intended to assist policy makers to promote accelerated geothermal development and encourage development of new areas. As the geothermal heating industry grows, new well data become available every year and ThermoGIS is updated regularly (Vrijlandt *et al*., 2019).

- **National Renewable Energy Laboratory (NREL)** Geothermal Prospector (United States) is a visual mapping tool that integrates geothermal-related geospatial data from universities and government agencies in the United States. The interactive map includes information on existing geothermal resources as well as those under exploration. It also contains Information on low-temperature geothermal resources. In addition, the mapping platform has an analytical screening tool to visualise wells and perform a geological, technical and socio-economic resource assessment.

- **Canadian National Geothermal Database (Canada)** is an online, open-source platform that provides downloadable digital map layers that serve as tools for assessment of the resource potential and for supporting investment decisions. The platform aims to improve accessibility of information to mitigate exploration and investment risk, reduce fragmentation of data collection, increase reliability of data and provide knowledge of Canada's geothermal potential.

- **Geologic database of Switzerland (Switzerland)** is an online, open-source platform that provides downloadable digital map layers including datasets specific for geothermal resources. Heat data are calculated from the temperature gradient (average value around 30 Kelvin per kilometre) and heat conductivity of the rock (average value around 3 watts per metre-Kelvin). The database also shows the temperature distribution and position of the faults at different fixed depths and on selected surfaces representing seismic marker horizons, or isotherms. The horizon surfaces are taken from the GeoMol15 geological 3D model and the temperatures from the GeoMol15 temperature model, which is composed of regular cells that are 1 000 x 1 000 x 100 metres in size. The temperature block model is derived from a finite element (FE) method temperature model, which is based primarily on 31 vertical temperature profiles, and the horizon surfaces are derived from the Seismic Atlas of the Swiss Molasse Basin (Sommaruga, Eichenberger and Marillier, 2012). The FE temperature modelling method assumes conductive heat flow only and does not consider convective heat flow. The GeoMol15 and associated temperature model are available for online viewing with the GeoMol Viewer*.

* See: *map.geo.admin.ch.*

Performing resource assessments for direct-use projects should also ensure that there is sufficient demand for the energy, considering that the energy (heat) should be used in the vicinity of the resource area. Integrating geothermal direct-use technology into agri-food value chains requires geographically aligning the agri-food market or industrial application with the geothermal resource. The temperature of the resource must also align with the upper-limit temperature requirement of the desired application. Furthermore, adequate flow rates of the geothermal fluid must be achieved to supply the required energy capacity for the desired application, while the chemical composition of the fluids must be conducive for utilisation.

There are two approaches to achieve this multi-component alignment of geographic location, temperature, and flow rate, either starting with the direct-use application or starting with the geothermal resource:

- **Resource push (engineering optimisation of the application):** Perform a local technical assessment of the geothermal resource at the site of an existing agri-food facility and an engineering assessment of the facility itself to evaluate its heat and/or power requirements. Unless the facility is fortuitously located near a known geothermal system, the most suitable technologies are often lower-temperature direct-use applications (less than 60°C) being supplied with energy from shallow hydrothermal wells, which could integrate heat pumps. Lower-temperature applications include aquaculture, geothermal greenhouses, soil warming, irrigation and mushroom culturing. These types of agricultural applications are more prevalent worldwide because of their lower geothermal resource temperature requirement.

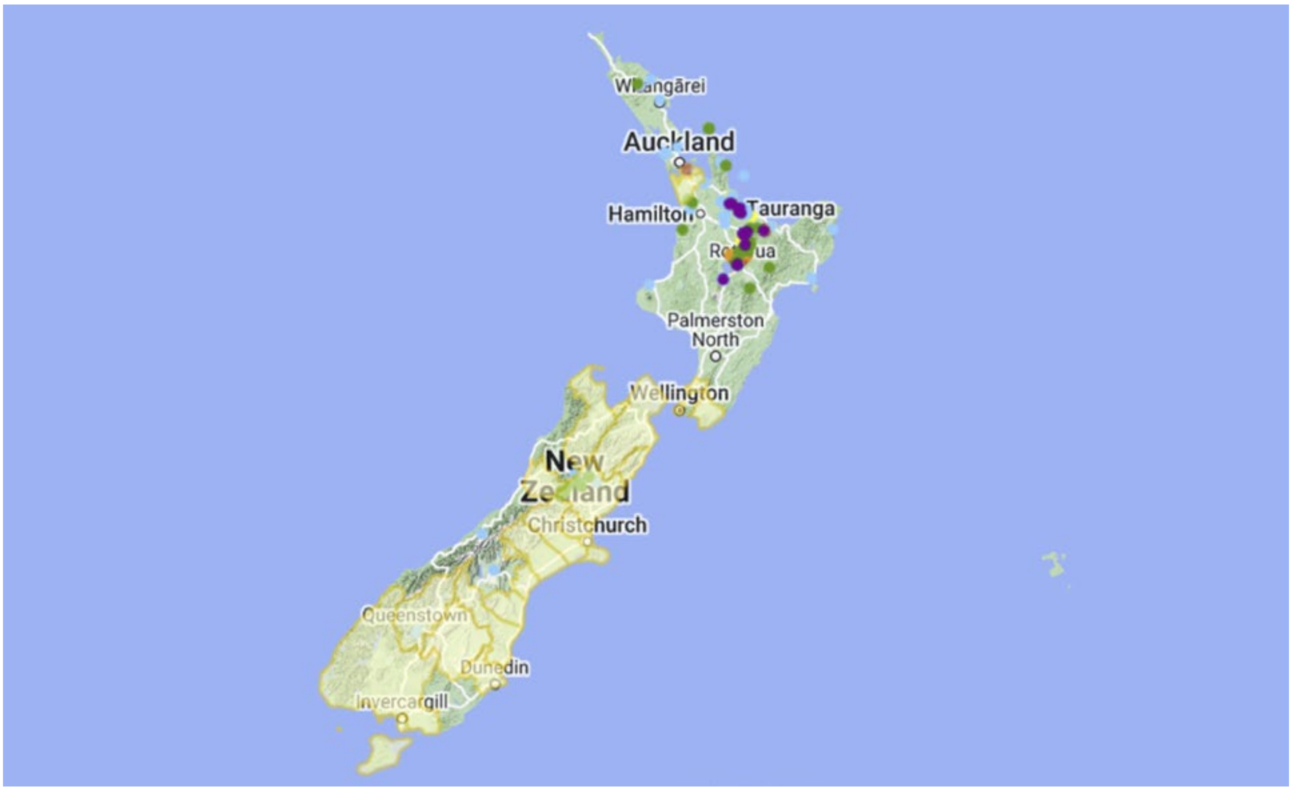
- **Industry pull (opportunistic use of the resource):** Perform a regional technical assessment to identify the most favourable sites to produce geothermal energy and attract industries to relocate there. This could also entail carrying out an assessment of the potential geothermal agri-food applications around an area with known geothermal potential. For example, the Icelandic company Arctic Fish (see Box 3) chose Tálknafjörður as the location of its facilities because of its proximity to natural hot springs (Richter, 2019a). At Eburru in Kenya, steam from an existing shallow well drilled in the 1950s is used to provide energy for drying pyrethrum flowers grown locally. The steam exiting from the dryer is then collected, condensed and used to provide potable water to the community (Ndetei, 2016).

During the initial project evaluation, it can be challenging to identify potential agri-food markets and geographically match the application with the geothermal resource. This can be addressed by either optimising the engineering in an existing facility to suit the resource or by relocating the industry to favourable locations where hot springs and existing or planned geothermal developments can provide heat for agri-food applications. This matching process can be facilitated by carrying out pre-feasibility studies that map out the potential agri-food industries located around geothermal resource areas. These types of studies can include identification and mapping of key value chains that could benefit from geothermal energy, location of existing facilities that could switch to geothermal energy, and availability of critical infrastructure – for example, roads, power supply, and access to markets for agri-products.

In 2013-2014, the Powering African Agriculture project was implemented in Kenya by the US Agency for International Development (USAID) and Kenya's Geothermal Development Company (GDC) to support the use of geothermal energy along agri-food value chains. During the project, pre-feasibility studies were carried out to assess the potential of five agri-food value chains found along the Kenyan Rift that could benefit from nearby geothermal resources – *i.e.* the dairy sector, greenhouse cultivation, aquaculture farming, crop drying and the livestock sector (USAID and GDC, 2014). These pre-feasibility studies included market study, supply and demand analysis, energy requirements, re-location potential and financial analysis.

The use of online databases of geothermal potential with interactive maps discussed in this section can integrate critical datasets on agri-food to support decision making on investments. These maps point investors and policy makers to areas with the greatest potential to co-locate geothermal and agri-food applications. In New Zealand, a geothermal database was developed showing the various applications of geothermal energy on an interactive map. As shown in Figure 4, most of the direct-use applications, including aquaculture, greenhouse and industrial uses, are in the Northern Islands, where the main geothermal resources are found.

Figure 4 Interactive geothermal use map of New Zealand



Source: GNS Science, 2021.

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

3.2 Enabling policy, legal and regulatory frameworks

The integration of geothermal energy into agri-food systems requires co-ordinated government policy and regulation. Coherent government policy serves to align objectives, mobilise public and private sector support, facilitate investment and maximise benefits. Governments play a critical role in supporting the uptake of geothermal energy in agri-food systems by setting targets and standards, raising awareness, building capacity, investing in technological innovation and developing infrastructure to improve market access (IRENA and FAO, 2021).

Some of the main policy instruments designed to attract investment to and facilitate the development of the geothermal direct-use projects include heat tariffs, subsidy mechanisms, tax incentives, risk mitigation schemes and insurance programmes.

- The establishment of a mechanism to develop a competitive heat tariff incentivises the generation of heat from geothermal energy. Heat tariffs determine the price at which thermal energy will be sold to agri-food enterprises. An ideal tariff is one that is acceptable to both the enterprises and the geothermal developer and could be used to enhance the bankability of the energy supply business and support the developers to obtain financing for the project (see section 4.2).

- In cases where the cost of geothermal heat generation is higher than alternatives available in the market, a subsidy scheme may be instituted to compensate operators of heat plants for the difference between the cost of generating renewable heat and the prevailing market price of heat from alternative sources. In the Netherlands, the Sustainable Energy Production and Climate Transition (SDE++) provides financial support to operators of renewable energy technologies, including geothermal energy. The scheme provides subsidies to operators of renewable or carbon-reducing technologies in the generation of electricity, heat and gas for a duration of up to 15 years depending on the technology. By 2020, the programme (and its predecessor, SDE+) had benefited 18 geothermal projects, providing a subsidy of EUR 0.023 (USD 0.026) per kilowatt-hour for geothermal heat (Ramsak, 2020).

- Tax incentives are another policy tool that can be applied to both the geothermal and agri-food sectors. Tax exemptions on the purchase of equipment and components lower the system costs for operators. Tax incentives can also be applied to support the sustainable operation of agri-food businesses, particularly in the early years of operation – for example, through income tax holidays, among others. In the United States, federal and state tax credits have supported the development of geothermal direct-use applications. In Indonesia, under the Omnibus Law enacted in 2020, incentives are in place that remove the requirement for geothermal direct-use licence holders to pay production fees (SSEK, 2020).

- Government- and private sector-sponsored risk mitigation and insurance schemes improve the financial viability of geothermal direct-use projects by reducing the drilling risk for project developers. The choice of mitigation scheme depends largely on the maturity of the geothermal markets in a given country/region, with grant-based schemes being established in nascent markets while insurance-based schemes are more suitable for mature markets with a large portfolio of projects. France has had a drilling insurance system in place since 1982 that compensates developers for up to 90% of the cost of a well if the flow rate or temperature of the well is insufficient to sustain the project (USAID and GDC, 2014). The Dutch geothermal risk guarantee fund, established in 2009, provides for the compensation of developers at a rate of 85% of the total project cost in case of failure. The fund, which supported 11 geothermal projects between 2009 and 2020, encouraged significant geothermal project development in the country (IRENA, IEA and REN21, 2020). Similarly, in Iceland, the government provides loans and guarantees to cover exploration and drilling activities, with the loans converting into grants if drilling fails to result in a financially viable project (USAID and GDC, 2014).

The Geothermal Risk Mitigation Facility (GRMF) in Africa and the Geothermal Development Facility (GDF) in Latin America are funds that offer similar risk mitigation for geothermal project development in their respective regions. Although these facilities have focused on geothermal power generation to date, they plan to expand their mandates to also include direct-use applications (Boissavy, 2020).

GeoFutures is a facility with an initial focus in East Africa (Ethiopia and Kenya) that aims to leverage private sector underwriting to de-risk geothermal developments. GeoFutures incorporates a grant-based facility, GreenInvest, that aims to catalyse the participation of private insurance in the facility. However, the facility will focus on power projects when it becomes operational.

The GEORISK Project recommends the development of national insurance schemes across Europe to cover the risks associated with the exploration, development and operation of geothermal power projects across Europe.
Legal and regulatory frameworks for geothermal direct use vary greatly by country. A clear framework for awarding concessions for the development of geothermal resources is essential. Regulations also need to be developed around land use, access to sub-surface rights, and environmental and social considerations. Unlike geothermal electricity generation, which in some countries is usually regulated by a specific law and accompanying regulations, direct-use regulations are either absent or are spread among different related laws covering energy, water, the environment, etc. Several countries have recently enacted legal reforms, for example, Mexico´s Geothermal Energy Law of 2014 and Ethiopia’s Geothermal Proclamation of 2016; others are in the process of modifying geothermal legislation – for example, Chile (Box 6) – to simplify approval processes for shallow, low-temperature geothermal direct-use projects.

Other countries without geothermal legal frameworks in place have recently drafted or are in the process of drafting (*e.g.* Colombia) new legislation to encompass both electricity generation and direct use. In Europe, many countries have developed their own national direct-use guidelines, best practices or standards (*e.g.* Finland, Germany and Sweden) (Haehnlein, Bayer and Blum, 2010). Establishing a “one-stop-shop” in government to streamline regulations can further support the development of geothermal projects, as well as the integration of any associated regulations in the agri-food sector.

Examples of legal and regulatory frameworks for geothermal energy that support direct-use applications include the following:

- In Ethiopia, geothermal legislation was enacted to provide a framework for the licencing of geothermal resources for electricity generation and direct-use applications. Licencing of direct-use projects is restricted to resources of up to 120°C. This distinction between licencing for geothermal electricity generation and for direct-use projects is unique among neighbouring countries of the East African Rift (IRENA, 2020).

- In France, a registry system is used to implement a simplified approval regime (online registry declaration) for projects of between 10 metres and 200 metres in depth, less than 25°C temperature and less than 500 kilowatt-thermal net power generation, with the intention of alleviating the regulatory burden for shallow, low-temperature geothermal projects (Fraser, 2013).

- In Hungary, in cases where no groundwater is extracted, geothermal projects occurring between 20 metres and 2 500 metres do not require a concession, whereas projects exceeding 2 500 metres in depth do (Boda, 2016).

- In Indonesia, under the 2020 Omnibus Law, the central government stipulates the procedures and standards regarding geothermal direct-use projects. Local governments are required to issue business licences for the direct use of geothermal resources (SSEK, 2020).

"Policy instruments such as heat tariffs, subsidy mechanisms, tax incentives, risk mitigation schemes and insurance programmes may be designed to attract investment and facilitate the development of geothermal direct-use projects"

BOX 6 IMPROVING THE LEGAL FRAMEWORK TO FACILITATE GEOTHERMAL DIRECT USE IN CHILE

Chile initially attracted international private investments for electricity generation from high-temperature geothermal resources, following the establishment of a legal framework for a geothermal concession system in 2000 (law) and 2004 (regulations), which was later modified in 2015. As a result, the 48 megawatt (MW) Cerro Pabellon geothermal power plant in northern Chile was commissioned in 2017, making it the only commercial-scale geothermal plant in South America (Huttrer, 2020).

Chile is currently modifying its geothermal law to support the development of shallow geothermal direct-use projects, including geothermal heat pumps, which have made inroads in the country over the past 25 years. However, Chile has not gone through the industry boom seen in the use of heat pumps worldwide. It is anticipated that simplifying the regulatory framework for shallow, low-temperature geothermal resources will promote project development.

The geothermal concession law and regulations for Chile do not distinguish between large and smaller-scale projects, requiring the same technical, economic and administrative requirements. Under the new proposed modifications to the law, shallow direct-use projects would be exempt from the concession system. Instead, a National Registry system would be established for shallow (less than 400 metres deep) and low-temperature (less than 90°C) direct-use projects. The modifications to the geothermal law were approved by the National Congress in March 2020 and are pending approval in the Senate. It is anticipated that agro-industrial applications involving fish farming, greenhouses and vineyards would benefit from increased investment in geothermal direct use following these regulatory improvements.

On the other hand, the World Bank has been supporting the Ministry of Energy of Chile since 2017 to remove specific legal, social and market barriers and improve geothermal market conditions. The Technical Assistance for Sustainable Geothermal Development Project for Chile has two components: 1) improving the existing policy and regulatory framework and strengthening the management skills to boost investment in geothermal energy; and 2) enhancing market conditions to promote the sustainable development of the geothermal energy sector (World Bank, 2021).

The proposed new legislation and the World Bank's assistance seek to grow the use of heat pumps in Chile. In recent years, as the country's geothermal power industry has stagnated due to obstacles to remain competitive in the energy market, there has been a shift towards shallow geothermal direct-use heating and cooling applications with ground-source heat pumps. Traditionally, shallow direct use in Chile has focused on thermal spring spa tourism. Most of the spas are fed by surface springs, while only a few use shallow wells. However, Chile has an enormous untapped potential for direct use beyond spa tourism.

Geothermal heat pumps were first used in 1996, and in 2020, 61 heat pump projects were reported (Lund and Toth, 2020). It should be noted that the use of heat pumps in Chile is not due to the development of regulatory frameworks, as the introduction of heat pumps in 1996 was prior to the geothermal law (2000) and regulations (2004), and World Bank assistance (2017). In 2019-2020, the Ministry of Energy of Chile and Germany's GIZ carried out a market study of the heat pump industry in Chile (GIZ, 2020a). The study identified around 40 companies involved in the supply chain for geothermal heat pumps, including fabrication, importation, engineering, field testing, drilling, installation, inspection and certification.

In addition to space heating and cooling of homes, hotels, and schools, geothermal heat pump agro-industrial applications include greenhouses, fish farming and wine manufacturing. Two pilot projects in southern Chile – a geothermal greenhouse and a heating system for a public school – have shown the potential to reduce pollution as an alternative to wood-burning stoves, improve agro-industry energy efficiency, and grow and harvest crops year-round in remote areas with snowy winters (Lund and Toth, 2020).

3.3 Cross-sectoral alignment and multi-stakeholder engagement

One of the challenges associated with the development and implementation of policy, regulatory and legal frameworks for geothermal direct-use applications is the lack of co-ordination among key public and private sector stakeholders. This is critical because in most cases, geothermal developers, who have the necessary information about the potential of the resource for direct use, do not include direct use in their business models. Therefore, aligning geothermal development plans with the plans for other sectors such as agricultural or industrial sectors that require thermal energy for their operation can catalyse direct-use agri-food development (IRENA, 2020).

Cross-sectoral alignment

One way of achieving cross-sectoral alignment is through the development and implementation of a geothermal heat master plan or sector roadmap with capacity targets, provisions, guidelines, standards and associated regulations for geothermal heat utilisation. A national roadmap can identify appropriate technology options, policy measures, available financing mechanisms, capacity building, training and public engagement needed to grow the sector and achieve economic, environmental sustainability and emission reduction goals through direct use of geothermal energy.

Above all, a national geothermal roadmap serves to align the priorities of multiple stakeholders across various sectors of the economy – *i.e.* geothermal project developers, agri-food industry players and beneficiary end users or communities. A sector master plan or roadmap provides clarity and predictability for all market actors, notably for investors and companies that need to consider multi-year plans involving capital expenditure or borrowing. This in turn fosters private sector participation by de-risking and mobilising financing and stimulating both demand and supply for direct-use investments and projects. Table 3 presents examples of geothermal direct-use roadmaps at the national and regional levels.

> "Geothermal heat masterplans or sector roadmaps can support the alignment of geothermal development plans with those for other sectors while also identifying appropriate technology options, policy measures, available financing mechanisms, capacity building and other enablers"

Table 3 Geothermal direct-use roadmaps

COUNTRY Roadmap / Program	Description
Uruguay	**CTCN – Uruguay National Roadmap for Direct-Use Geothermal Energy** • Published in 2020, this roadmap aims to increase the deployment of low-temperature geothermal in the industrial, residential and commercial sectors in Uruguay. • The document analyses the current status of geothermal energy in the country, identifies existing barriers to implementation and proposes measures to overcome them.
Mexico	**SENER – Mexico Technological Roadmap for Direct Use of Geothermal Heat** • Published in 2018, this roadmap provides detailed information regarding direct-use development including cascaded applications and heat pumps in Mexico. • The document further outlines the main challenges for implementing direct-use projects and proposes potential solutions and strategies. • The roadmap envisions growth in installed geothermal direct use capacity to 3 800 MW_{th} by 2030.
Canada	**Direct-Use of Geothermal Resources in British Columbia** • Published in 2016, this study focusing on British Columbia, Canada identifies and evaluates potential direct-use opportunities in 63 communities.
New Zealand	**Low Temperature Geothermal Energy Roadmap: Fostering increased use of New Zealand's abundant geothermal resources** • Published in 2011, this roadmap aims to facilitate the uptake and use of low-temperature geothermal across New Zealand. • The document outlines gaps and barriers to development, as well as providing recommended actions and initiatives.
	**Geoheat Strategy of AOTEAROA New Zealand** The strategy covers the period 2017 to 2030 and aims to achieve two main objectives: • Realise a 7.5 petajoule (PJ) annual increase in the use of geothermal heat in new projects by 2030. • Create 500 new jobs in new projects due to the use of geothermal heat by 2030.
Netherlands	**Netherlands Geothermal Energy Master Plan** • Published in 2018, this plan establishes a foundation for increasing production of geothermal energy in the Netherlands from 3 PJ to 50 PJ in 2030 and more than 200 PJ in 2050. • The document also sets a target that by 2050, geothermal energy will supply an estimated 65% of the demand for heat in greenhouse horticulture. • The master plan builds on related public policy initiatives in the sector, such as the Geothermal Action Plan, 2011 and the Acceleration Plan for Geothermal Energy in Horticulture, 2014.

Source: CTCN, 2020; SENER and CeMIE-Geo, 2018; Hickson *et al.*, 2016; Climo and Carey, 2011; Stichting Platform Geothermie, 2018.

As part of the energy transition, countries are developing Nationally Determined Contributions (NDCs) and long-term low-carbon strategies to reduce their carbon emissions towards net zero. During the NDC process, countries revise their decarbonisation commitments on a regular basis to establish more ambitious targets. Through this process, countries can support the decarbonisation of their agri-food sector through the inclusion of geothermal energy as a source of clean energy. As an example, China intends to develop clean energy heating technologies, including from geothermal (China-NDC, 2021).

Furthermore, the alignment of local priorities to national policies could support the realisation of economic development at the local level. In the case of New Zealand, the policy of developing energy resources to benefit local businesses has contributed to the development of direct uses in the country, as demonstrated in Box 7.

BOX 7 ALIGNING LOCAL DEVELOPMENT STRATEGY TO NATIONAL PRIORITIES IN NEW ZEALAND WHILE LEVERAGING GEOTHERMAL ENERGY

The government of New Zealand has developed an economic model that focuses on driving growth at the regional and local levels by empowering businesses. With regard to energy, the policy prioritises the development of energy projects that contribute to local productivity as opposed to serving the national grid. This policy is Implemented through the regional and district development agencies.

In the Bay of Plenty region in New Zealand, geothermal energy was identified as one of the key resources that could be leveraged to support economic development. The region's latest strategic economic plans identified geothermal as a key pillar for development and proposed the establishment of ecosystems (clusters) around existing geothermal installations.

In the district of Taupo, in the Bay of Plenty region, the local development agency developed a strategy that aimed to position the district as a centre of geothermal excellence. Among the activities the agency Included in the strategy are:

- "Adding Heating in Primary Production" as a focus area in the 2012 strategic plan;
- Backing the establishment of the position of a geothermal business lead for the Bay of Plenty region;
- Identified areas of alignment between the district's economic plans and the New Zealand Geoheat Strategy, which include the establishment of a geothermal cluster consisting of a centre of excellence for geothermal, a geothermal heat park and a strategic plan for Wairakei.

The working strategy of the district development agency focuses on building partnerships among the various stakeholders involved in the Taupo economic strategy and leveraging on their strengths. Its efforts in identifying opportunities for investment, attracting investors and creating awareness have resulted in the development of the Miraka milk processor, Geo40 silica extraction and Rogue Bore Brewery.

Source: Hawker-Green, Blair and McCaw, 2020.

Multi-stakeholder engagement

The development of geothermal direct-use projects may involve multiple stakeholders. These may include the project operator, geothermal resource developer, interested local entrepreneurs, and government agencies, among others. Identification of stakeholders that might have an interest in the project is a crucial first step. Classification of the stakeholders based on their influence and importance to the success of the project should be carried out and a strategy for engaging each category devised. The stakeholder engagement process should be well structured to maximise the impact of the synergies that exist among stakeholders for the benefit of the project.

In most cases, the majority of the stakeholders may lack sufficient information about the geothermal resource potential and the opportunities for its application in the agri-food sector. Therefore, at the initial stages, the developer could take a leading role in co-ordinating the other stakeholders and creating awareness about the potential applications, as is the case in Kenya with GDC and KenGen.

Government agencies can mobilise public funds and provide risk mitigation options, including from donor agencies and development partners, establish new regulations and standards, design policy instruments to attract investments in the geothermal agri-food sector, offer access to affordable financing and build local capacity – all of which create new private sector business opportunities to utilise geothermal heat in agri-food value chains. The public sector can also lead the rest of the market by launching pilot projects to demonstrate the viability of direct-use technologies, particularly in countries with nascent geothermal markets.

In Central America, Germany's GIZ is playing a leading role to build capacity on the development of geothermal agri-food and industrial applications; so is the United Nations Environment Programme (UNEP) in East Africa.

In the Netherlands, geothermal associations and the public sector collaborated to develop the geothermal energy master plan, while in New Zealand, the implementation of direct use is structured to include a governance and action group, led by a dedicated co-ordinator.

Other stakeholders such as local communities may provide the workforce needed while enterprises become customers of the geothermal energy. Direct-use geothermal energy applications can provide beneficiary communities with economic opportunities and can also support the development of local industries with the right partnerships in place.

Table 4 summarises the main stakeholders and their stake in the development of agri-food projects utilising geothermal energy.

Table 4 Key project stakeholders and their potential roles

Stakeholder	Role during the engagement process
National government ministries/ agencies	• Develop relevant policies and regulations (including incentives) and ensure that they are aligned across multiple sectors. • Provide funds to de-risk projects and develop capital-intensive infrastructure. • Provide relevant infrastructure (access roads, water, sewerage services, etc.) to support the development of geothermal agri-food enterprises. • Provide licences for geothermal projects. • Provide relevant information about existing geothermal resources and their characteristics.
Local authorities	• Provide land for the development of agri-food projects. • Provide relevant infrastructure (access roads, water, sewerage services, etc.) to support the development of geothermal agri-food enterprises. • Provide permits for businesses to operate. • Support efforts to attract businesses to establish around the geothermal resource areas (including incentives).
International/ regional development organisations	• Support capacity building through the development of knowledge products and promoting exchange of experiences and best practices towards the establishment of enabling frameworks for geothermal agri-food enterprises. • Provide development and risk financing and support the establishment of demonstration projects.
Geothermal developers	• Conduct exploration and drilling to ensure that geothermal energy for utilisation is available. • Create awareness about the potential opportunities and benefits of using geothermal energy in the agri-food sector. • Provide necessary information about the geothermal characteristics to the potential investors and authorities. • Provide supply-side support to the customers with regard to connections, operation and maintenance, metering and billing. • Ensure that customers always have adequate supply of geothermal energy according to their requirements. • Establish a tariff for geothermal heat considering the investment and operating costs.
Investors and financiers	• Provide financial support for the establishment of bankable agri-food projects. • Tailor financing to the needs of the agri-food enterprise operations.
Customers of geothermal heat	• Establish and manage agri-food enterprises that require geothermal energy. • Pay for the use of geothermal energy in the operation of thermal process within their enterprises.
Local communities	• Engage constructively with other stakeholders for the acceptance of the projects. • Provide raw materials to the agri-food enterprises. • Provide the workforce for the agri-food enterprises.

Box 8 presents the approaches applied in New Zealand to achieve synergies among the different stakeholders involved in the development of direct uses.

BOX 8 STAKEHOLDER ENGAGEMENT IN THE DEVELOPMENT AND IMPLEMENTATION OF A GEOHEAT STRATEGY IN NEW ZEALAND

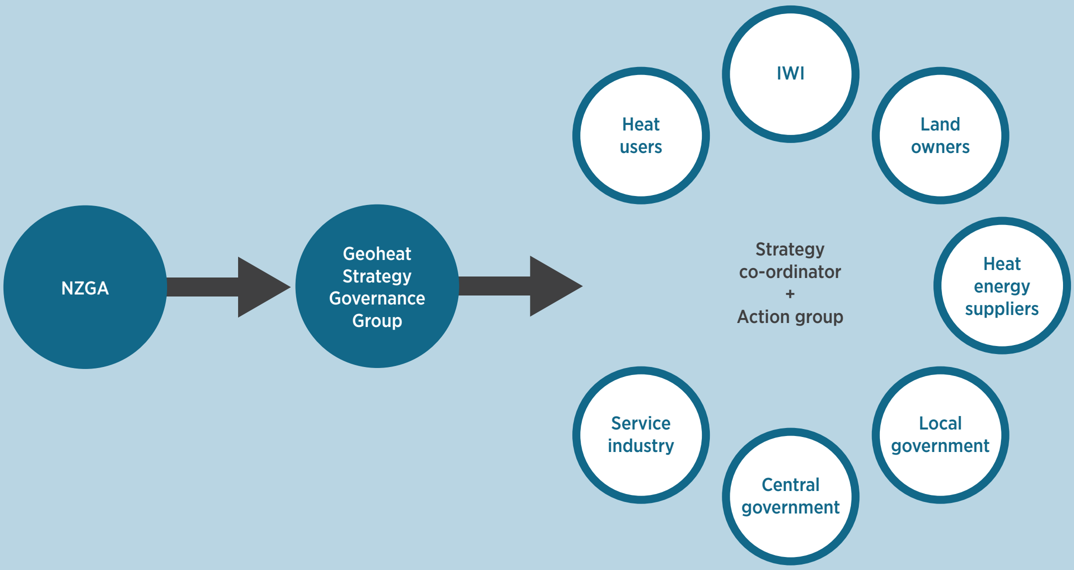
New Zealand is one of the countries that has developed a structured approach in the development and implementation of geothermal direct-use applications. The process involved the participation of multiple stakeholders through several consultation meetings and workshops, which resulted in the publication of the New Zealand Geoheat Strategy in 2017. Among the stakeholders involved in the consultation process are:

- local communities represented by the Maori
- government agencies represented by ministries, science experts, regional and local authorities, regional and local development agencies
- geothermal industry representatives, including power generators and heat customers
- the New Zealand Geothermal Association.

The strategy's host is the New Zealand Geothermal Association, which together with GNS Science co-ordinated its development.

The strategy also includes a governance structure to oversee its implementation, as shown in Figure 5.

Figure 5 New Zealand Geoheat Strategy governance structure



Source: NZGA, 2017.

A strategy co-ordinator is responsible for the delivery of the outcomes and works hand-in-hand with the governance group composed of cross-sector representatives, an action group composed of interested individuals, as well as other interest groups from various sectors.

See: *www.nzgeothermal.org.nz/downloads/Geoheat_Strategy_2017-2030__Web_Res_.pdf*

3.4 Project development and ownership

The establishment of direct-use applications entails the development of the geothermal resource to make the energy available on the surface for utilisation, as well as the development of the agri-food applications that use the energy. In the case of electricity generation, a greenfield geothermal project may take several years to actualise due to the need to carry out extensive exploration and resource assessment activities. This development could take up to seven years or more to actualise. A typical geothermal project begins with surveys and exploration activities, which can take at least two years, followed by test drilling (around 1-2 years), project planning (around 1 year), field development, construction and commissioning (at least 2 years).

While the geothermal resource and infrastructure are being developed, planning around the agri-food business can take place concurrently. In the case where a geothermal power plant already exists, integration of direct uses could take a much shorter time. Similarly, the development of direct uses utilising shallow geothermal resources or surface manifestations may also result in quicker realisation of projects.

Direct-use project set-up and ownership models

The direct-use applications can be developed either as stand-alone independent systems, cascaded direct use systems or integrated with geothermal power generation. The stand-alone systems usually access shallow, low- to medium-temperature resources, whereas cascaded and integrated direct-use systems require deeper wells to access the required medium- to high-temperature resources.

Stand-alone direct-use systems

Stand-alone systems are individually developed projects that utilise geothermal heat and are not necessarily co-located with other geothermal energy utilisation projects. Stand-alone projects may access naturally occurring geothermal fluids or may require drilling of new geothermal wells. Depending on the temperature requirements of the thermal processes involved, a stand-alone project may require a low-temperature resource or higher-temperature resources. Usually, for financial viability, stand-alone projects will use naturally occurring geothermal fluids or may involve drilling shallow wells, which in most cases produce low- medium temperature fluids. Stand-alone projects could also use existing deep wells located in sites that do not support electricity generation, or those drilled for other purposes, such as oil and gas. The development of stand-alone projects usually involves lower costs, lower resource risk and substantially less development time.

Cascaded direct-use systems

Cascaded systems consist of two or more direct-use projects that utilise geothermal energy from the same stream of hot water or steam. The stream of hot water or steam must have adequate temperature and flow rate to meet the energy requirements of all the direct-use applications connected to it. In a cascaded system, the projects or thermal processes that require higher temperatures are located upstream, while those with lower temperature requirements are located downstream. A successful cascaded system should ensure that the inlet temperature of the stream reaching the last application is the same or higher than that required for its thermal processes. Due to the drop in temperature between one process and the next, cascaded systems will typically require medium- to high-temperature resources and may involve drilling of geothermal wells. A cascaded system may also use low-medium temperature resources where the direct-use applications have low temperature requirements.

The key advantages of cascaded systems include potential access to higher-quality resource in terms of temperatures and flow rate; shared cost of development (*e.g.* drilling and infrastructure development costs); potentially lower heat tariffs due to shared operating costs; efficient utilisation of the geothermal resource due to subsequent extraction of heat by downstream processes; and higher socio-economic impacts to the local communities as a result of many applications established in the locality. The downside to the cascaded systems is higher investment cost of development and exposure to higher resource risks in case of drilling new wells. In addition, proper planning of energy distribution is required to ensure that customers located downstream get access to sufficient energy. This may result in complex contractual agreements between customers and the geothermal developers.

Integrated geothermal direct-use and electricity generation systems

In some cases, the stand-alone and the cascaded direct-use applications can be developed alongside electricity generation activities. The direct-use applications may utilise the excess energy contained in geothermal waters after electricity generation, energy from sub-commercial wells, energy from wells located at an uneconomical distance from the power plant, or excess steam and hot water that is not used for generating electricity. Usually, the integrated direct-use systems use medium- to high-temperature geothermal fluids, which are also suitable for electricity generation. The Integrated direct use applications can be operated in a cascaded manner because of the availability of higher temperatures. Nonetheless, individual direct-use applications, particularly those with large-scale operations or those requiring high temperatures, may also be integrated.

Integrated systems have similar advantages and disadvantages as the cascaded systems. However, in instances where the direct-use application is established alongside an existing power project, the added advantage is that the initial drilling costs and resource risks are avoided. Other advantages include the possibility to establish a mini-grid to provide captive power to the direct-use applications, resulting in a lower cost of power and the establishment of a circular economy built around the activities of the enterprises. In addition, due to the high temperature and high flow rate of fluids from electricity generation, more enterprises can be connected, resulting in higher and diversified revenue streams for the developer from the sale of heat and other by-products such as minerals and non-condensable gases. As with cascaded systems, management of the downstream operations could pose challenges during operations.

Unless geothermal resources are easily accessible, it is often cost-prohibitive for agro-industry projects to undertake the drilling of new deep wells without significant government incentives, *i.e.* grants, subsidies, tax reductions and risk mitigation schemes (see section 3.5). The Netherlands is an example of where multiple types of government policies and tools were instrumental in generating an enabling environment to stimulate the growth of the geothermal greenhouse horticulture industry (IRENA, 2019). Applications that require high temperature are more frequently developed from systems that integrate direct use and electricity generation rather than as stand-alone direct-use projects.

Overall, a significant level of investment and time may be required to establish a geothermal agri-food project. The main ownership models that can be applied to develop direct-use geothermal projects in agri-food industries are summarised below.

- Full ownership: Under this model, the owner of the geothermal well(s) develops the respective direct-use applications. This model works for stand-alone, cascaded or integrated projects. The Wabuska Geothermal Power Plant in Nevada, United States has been operating since the 1980s. Excess heat from the power plant keeps a fish farm warm year-round. Similarly, the owner of a geothermal field in Chena, Alaska uses the hot water for a greenhouse on-site to grow vegetables. This model allows the project developer to optimise the performance of the entire operation (*i.e.* to decide how to use the geothermal resource). Another operating direct-use project in the agri-food sector that uses this model is the Caldiran geothermal project, where tomatoes are grown in one of the coldest regions in Türkiye (Richter, 2020b).

- Heat purchase agreement (HPA): Under this arrangement, there is a split between the owner of the resource and the user of the energy to support the direct-use application. The two parties enter into an HPA (see section 4.2), which defines the legal obligations for each party to the agreement, whereby one party provides the energy that the other party pays for. Such a contractual arrangement addresses the built-in conflict whereby the supplier of energy is cognisant of the need to sustain the geothermal resource while maximising profits from the sale of heat, while the owner/operator of the direct-use operation requires a reliable supply of energy at a low price. An example is the HPA entered into between Ormat and Conagra foods in Nevada, United States to dry onions.

- Partnership: In certain cases, the parties decide that it is best if their interests are fully aligned. Hence, both parties enter into a joint venture or partnership that can be structured in different ways. The partnership can own all of the assets in the project – both the resource and the direct-use application. The economic interests of the parties usually follow the value of the contributed assets. This partnership can be owned equally or not at all. The parties share one goal: to maximise the profitability of the project while sustaining the operation for a long period of time. Other forms of partnership include arrangements whereby each party remains the owner of its assets but allows the partnership to use its assets. In this case, it is customary that the energy supplier will be paid a percentage of the sales of the product that uses the geothermal energy during production, processing, etc. This model can be found, for example, in Iceland, where the owner of the Blue Lagoon shares some of its revenues with the supplier of the geothermal effluent from a nearby power plant.

Project identification and prioritisation

In some cases, with multiple potential direct-use applications, it might be necessary to select which application is best suited for development based on the objectives of the resource developer. For example, in the case of a public developer, the objective may be to derive maximum benefits for the local community from the geothermal resource. In this case, the developer may wish to encourage the development of direct-use applications that use locally available raw materials in order to create markets for the farmers or promote job creation for the local community by attracting enterprises with labour-intensive operations. Other objectives that the developer may wish to promote include maximising profits from the sale of geothermal by-products to generate multiple streams of income, promoting a circular economy and sustainable business practices, among others.

The renewable energy food community of Tuscany, Italy was established in 2009 to promote production of food products using sustainable methods. The members of the community include companies that source a significant share of their energy for production from renewables, mainly geothermal. The companies are also expected to obtain the raw material from Tuscany and manufacture the final products in the same region. Therefore, the community is characterised by short supply chains as well as sustainability in food production and processing (CCER, 2021).

In Kenya, the public geothermal developer, GDC, promotes the development of direct use with a focus on environmental sustainability and socio-economic empowerment for local communities. During an initial assessment of potential direct-use applications in the country, GDC with the support of USAID identified several applications or activities that would be most relevant and provide maximum benefits across a portfolio of geothermal fields. To facilitate cross-cutting comparisons among the identified applications, a weighted scoring methodology was applied to rank them, as presented in Box 9 (USAID and GDC, 2014).

> "Geothermal project developers may select direct use projects for implementation based on the objectives they wish to fulfil such as profit maximisation, environmental and resource sustainability, and promotion of local socio-economic development."

BOX 9 CRITERIA FOR RANKING AND SELECTION OF DIRECT-USE APPLICATIONS

Kenya has a portfolio of 14 high-temperature geothermal areas earmarked for development as well as several low- and medium-temperature prospects. The establishment of direct use is high on the agenda of geothermal developers in the country, including for GDC, which holds several concessions. A guidebook for direct use developed by GDC with the support of USAID in 2014 proposed a methodology for selecting the most suitable direct-use applications for the country using weighted scores. The methodology used by GDC was based on the following criteria:

- Existence of a geothermal resource with known characteristics and potential to co-locate direct-use applications;
- Process energy that a direct-use application requires, in terms of temperature and flow rate. The higher the requirements, the less the favourability of the application;
- Market demand of the commodity to be produced from the application, taking into account existing and potential domestic and international markets;
- Potential for private investment in the application based on the complexity of implementation / return on investment;
- Potential of the application to generate employment for local communities;
- Socio-cultural appropriateness of the application for the beneficiary community;
- Impacts of the application on the environment;
- Potential to replicate the application in several geothermal fields.

In the Kenyan context, each criterion was assigned a weighted score, as shown in Table 5.

Table 5 Weighted scoring criteria for selection and ranking of direct-use applications

Indicator	Weighted scoring (%)
Geothermal resource potential to support direct-use applications	20%
Process energy requirement of the direct-use applications	15%
Market demand of the commodity to be produced	15%
Investment potential	15%
Employment potential	15%
Socio-cultural fit for beneficiary community	10%
Environmental impacts	5%
Replicability potential	5%
Total weighted score	**100%**

According to these weighted criteria, a portfolio of potential direct-use applications was evaluated and ranked in order of their favourability. Table 6 summarises the preliminary ranking of the potential direct-use applications that are optimal for Kenya according to the criteria. The study concluded that greenhouse heating, aquaculture heating, dairy processing and crop drying would yield positive results across most, if not all, of the ranking criteria.

Table 6 Ranking of potential geothermal direct-use applications in Kenya

Direct-use application	Thermal process	Temperature requirement (°C)	Common source of energy	Overall ranking
Greenhouse heating	Temperature and humidity control	55	None	Excellent
Aquaculture	Pond heating	32	None	Excellent
	Fish drying	45	Solar	Good
	Cold storage and refrigeration	120	Electricity	Good
Milk processing	Milk powder	200	Wood/oil	Good
	UHT milk	140	Wood/oil	Good
	Cheese making	135	Wood/oil	Good
	Pasteurisation	110	Wood/oil	Good
	Butter	130	Wood/oil	Good
	Milk chilling	120	Electricity	Good
Large-scale drying	Cereals	90	Wood/oil	Good
	Tea	150	Wood	Good
	Nuts	50	Nut shells	Good
	Fruits and vegetables	50	Wood	Good
Small-scale drying	Cereals	45	Solar	Good
	Fruits and vegetables	50	Solar	Good

Adapted from USAID and GDC, 2014.

Kenya is one of the leading countries worldwide in geothermal development and has a long track record of electricity generation from geothermal resources. The country also has very ambitious plans to develop geothermal heat utilisation applications to support economic development, particularly through industrial and agri-food applications. Stakeholder engagement, especially with government agencies and local communities, is seen as key to the realisation of direct uses in the country. The main direct-use projects earmarked for development are envisaged to take the form of industrial parks with multiple cascaded applications, integrated with electricity generation. Government agencies are expected to play a critical role in the realisation of these projects.

3.5 Access to financing

Geothermal projects have traditionally benefited from various sources of financing, including equity, loans and grants. The early exploration stages of geothermal development are considered high risk due to resource uncertainty before the resource is established through exploration / confirmation drilling. Public finance options, including government budgetary allocations as well as risk mitigation schemes, have been implemented in many countries to navigate this early phase of development, with the recognition that the economic benefits of geothermal development to the country often outweigh those of private investors. In more mature geothermal markets, private insurance schemes have also been developed to provide risk mitigation for early-stage geothermal development. The later stages of project development, including plant operations, are usually financed through debt and equity, among other sources of funds.

Table 7 presents a summary of clean energy financing mechanisms applicable to the development of geothermal projects. It should be noted that these financing options are generally for geothermal project development and do not necessarily apply to the integration of geothermal energy into the agri-food sector.

Table 7 Clean energy financing mechanisms

Financing mechanism	Description
Pure grants	This is a form of supporting instrument whereby the supporting entity provides funding to risky activities such as initial exploration and initial drilling. The grantors are typically governments or international development organisations that wish to foster the development of geothermal in a given country or region. Grants have no strings attached as long as the work is performed as contemplated. This type of financing is exclusive to the initial stage of geothermal projects.
Contingent grants	This financial instrument is a variation on pure grants, whereby the grant has some conditions associated with it. Contingent grants are typically provided during the exploration and initial drilling stage. If drilling is unsuccessful, the grantee has no monetary obligations; if the operation is successful (*i.e.* the drilling activity funded by the grant leads to a project coming online), however, the grant converts into a loan that the grantee will repay over time. The rationale here is that the proceeds from this grant/loan can be recycled to provide support to more projects.
Risk mitigation	There are two types of mechanisms to encourage investors to engage in the drilling phase: **Insurance:** The insured pays a one-time premium prior to the start of drilling. Once the drilling is complete, the well is tested as agreed upon in advance. If the results are not satisfactory (*i.e.* if the well was drilled according to the agreed-upon parameters and is dry), the insurance company will pay the insured a one-time payment to cover the cost of the well(s) and associated expenses. **Grants:** Under this mechanism, the qualified applicants can obtain a grant covering the costs of the initial drilling and other related expenses.
Concessional loan	A concessional loan is a loan at below-market conditions – *i.e.* lower interest rate, longer maturity and no or very light securities and collaterals. This instrument is available at later stages of project development when part or all of the resource has been fully developed. Hence, the proceeds from the loan will be used to construct the facility. The loan will be repaid from the profits of the operation. National development banks typically provide such loans because they can borrow at very low rates and are not mandated to maximise profits as the first priority (vis-à-vis commercial banks).
Project financing	Once the drilling phase of a geothermal project is completed and has passed the necessary acceptance tests, it can use the combination of equity and debt for further financing requirements. In developing countries, multilateral or regional development banks typically offer project debt (*e.g.* African Development Bank, International Finance Corporation, etc.). Equity is usually provided by investors focused on emerging markets. Project financing allows the project assets as the only collateral for the financing but can be time consuming and expensive.

Adapted from Boissavy, 2020.

Access to financing is one of the main barriers to geothermal direct-use project development. Public financial resources tend to be limited, especially in developing countries, and it can be difficult to raise funds for direct-use geothermal projects, especially stand-alone projects. Funding from multilateral institutions and development banks has traditionally focused on geothermal electricity production, which can achieve greater scale.

In the wake of energy transition and climate action, various financing options have been made available to support the increased deployment of clean energy technologies. These include the various climate finance options and tailored financing sources available from international financial institutions and bilateral institutions, among others. In addition, several countries have designed catalytic financing schemes to stimulate economic growth following the recession caused by the COVID-19 pandemic. Geothermal development, including direct use, could benefit from the funding opportunities created by these financing options. For instance, IRENA co-ordinates two multi-stakeholder project facilitation platforms that support renewable energy investments (Box 10).

BOX 10 RENEWABLE ENERGY PROJECT FACILITATION PLATFORMS CO-ORDINATED BY IRENA

Climate Investment Platform (CIP)

The CIP is an online multi-stakeholder platform that was established in 2020 by IRENA, the United Nations Development Programme (UNDP), and Sustainable Energy for ALL (SEforALL), in co-operation with the Green Climate Fund (GCF). The platform allows for the registration of renewable energy projects requiring support as well as investors/financiers interested in supporting projects that are furthering the energy transition. The CIP aims to support renewable energy projects, which are aligned with the achievement of the Paris Agreement and the Sustainable Development Goals, to obtain the necessary financing. The platform provides a holistic approach to project facilitation including support for the establishment and implementation of ambitious climate commitments and enabling frameworks at the country level, matchmaking between projects and investors as well as risk mitigation through technical assistance to achieve bankability.

Following a selection process based on a set of criteria, 26 projects have so far been earmarked for financial matchmaking support through the CIP platform as of December 2021. Through the matchmaking process, more than USD 1 billion is estimated to be mobilised to implement the projects.

Source: CIP, 2021.

Energy Transition Accelerator Financing Platform (ETAF)

In 2021, IRENA and the United Arab Emirates, through the Abu Dhabi Fund for Development (ADFD), established the ETAF Platform, a USD 1 billion facility to support the energy transition by addressing existing financing gaps. The facility aims to provide co-financing or co-investment to all sizes of projects in developing countries on demand.

The ETAF platform was established with seed capital of USD 400 million from the ADFD and envisages raising the balance from multiple stakeholders during 2022-2023 and leveraging IRENA expertise to support project developers.

The ETAF platform is the successor to the IRENA/ADFD facility, which was operational between 2013 and 2020 and supported 26 renewable energy projects, mainly in developing countries.

Source: ETAF, 2021.

As described in section 3.2 and section 3.3, among the first steps that countries can take to attract private investment to the geothermal direct-use sector is to develop and implement clear and transparent policies, legal and regulatory frameworks; combined with the development and alignment of plans to integrate geothermal heat utilisation in the end-use sectors. This includes regulations for extracting and utilising geothermal heat (*e.g.* how extraction rights will be awarded and for how long; what environmental and social permitting requirements and procedures need to be established for projects, etc.).

Public-private partnerships are an effective method of sharing the costs and risks of project development depending on who is best suited to bear them, such as those associated with drilling and exploration, and development of enabling infrastructure. While the private sector may be unable to take on the same level of risk as the public sector, it brings in innovative business practices and specialised expertise in project development that the public sector may lack (IRENA, 2021b). Risk mitigation schemes that have historically been used to support geothermal electricity generation can be adapted by the public and private sector as tools to support direct-use project development (Boissavy, 2020).

One way to reduce the financing requirements of direct-use projects and improve their bankability is to develop the projects alongside pre-existing geothermal power projects to utilise excess heat from power generation through cascading systems or available heat from sub-commercial and uneconomically located wells. This approach limits the direct-use facility's exposure to drilling risk and costs and shortens the duration for project development. In addition, where cascaded systems are developed, the risk of investment is greatly minimised due to sharing of infrastructure by several operators.

Furthermore, the direct-use projects can benefit by making use of existing infrastructure developed for the electricity project such as obtaining thermal energy from re-injection pipelines (see section 3.4). An example is the coffee dryer that utilises 170°C brine from the re-injection pipeline at Berlin geothermal power plant in El Salvador (see section 2.2). In the case of Iceland, the geothermal developer HS Orka provides companies located in the Resource Park with access to hot brine and non-condensable gases for use in their direct-use operations. In Türkiye, the development of infrastructure to support greenhouse heating is financed by the government through a programme supported by the Ministry of Agriculture and Forestry.

Feasibility studies and pilot projects also play an important role in securing financing for geothermal direct-use applications in agri-food systems. Feasibility studies are key in determining the bankability of direct-use projects through assessment of their technical, legal, social, environmental and financial viability. For example, in Kenya, pre-feasibility studies were carried out to assess the viability of using geothermal energy in the milk and meat value chains.

Governments act as facilitators of social and economic development to improve the welfare of citizens. The assessment of the socio-economic and environmental impacts of geothermal agri-food applications to local communities could further increase awareness of their benefits, resulting in acceptance by policy makers and the communities, particularly if the impacts are positive. This could in turn unlock financing from governments and other development partners for key infrastructure to support direct-use projects. To properly demonstrate the benefits of using geothermal heat, the assessments should consider the impacts along the entire value chain for products produced within a given area – for example, fruits, vegetables, fish and livestock, among others.

Scaling up growth in geothermal direct use will require not only public financing but also partnerships with local commercial banks that can provide financing in local currency. As with any infrastructure project, financial structuring is key to the success of the project, as financiers need a "bankable" project that they can support. Facilitating local financial institutions to understand the financing requirements of direct-use projects by developers and other industry stakeholders could enable potential financiers to structure and tailor financial products for this sector. As an example, the Turkish Ziraat bank provides loans with terms tailored to the needs of local geothermal-heated greenhouse projects (Box 11).

Another important financing solution is to improve market intelligence to de-risk and optimise geothermal energy investments in food chains. This can be achieved in two ways:

- by mapping the locations where geothermal energy solutions have the best chances to bring about potential agricultural yields – similar to what has been done for solar energy in Uganda's maize value chain (Shirley *et al.*, 2021); and

- as a complement to mapping, by undertaking a comprehensive cost-benefit analysis of geothermal energy investments in food chains – similar to what the FAO has done for solar and biogas (Sims *et al.*, 2015).

BOX 11 GEOTHERMAL GREENHOUSE LOANS IN TÜRKIYE

IGeothermal heated greenhouse in Türkiye

Geothermal heat plays a central role in food production in Türkiye. While most geothermal electricity production takes place in western Türkiye, geothermal greenhouses boost the local economy in the Caldiran-Ayrancilar region of eastern Türkiye. Caldiran is the coldest region of the country, where temperatures can reach -40°C, but this has not impeded the local population from producing vegetables. The greenhouses obtain hot water from several geothermal wells found in the area, with geothermal heat maintaining indoor temperatures in the greenhouses above 15°C. Top-quality tomatoes, eggplants and cucumbers are produced in these greenhouses.

The geothermal potential of Türkiye can support greenhouse heating with geothermal resources for an area of 30 000 hectares. However, for this to be achieved, state-sponsored projects are needed, and incentives must be provided. With the efforts of the Geothermal Power Plant Investors Association, the Agricultural Specialized Organized Industrial Zone (TDIOSB) project was implemented to support agricultural production in industrial facilities used in the processing of vegetables and livestock. Once projects are included in the investment programme, the necessary financing for the infrastructure is covered by the Ministry of Agriculture and Forestry, with exemptions provided for value-added tax (VAT). As of 2021, TDIOSB had 46 projects within its scope, including a 71.7 hectare project in Aydin, where 20 000 tonnes of tomatoes were being produced annually, employing 750 people; and greenhouse cultivation activities in Kütahya, where 35 000 tonnes of tomatoes are produced annually, employing 1 100 people.

Another geothermal greenhouse is owned by Caldiran Geothermal Inc., built in 2016 with support from the Turkish Ministry of Agriculture and Forestry. This geothermal greenhouse, located at an altitude of 2 050 metres, has the capacity to produce 1 000 to 2 000 tonnes of tomatoes and is marketed under the brand Agravan. These products are sold locally and exported to Georgia, the Russian Federation and the United Kingdom. The facility employs 40 people in the Ayrancilar community. The participation of women has also increased in this type of work – something that is not common in Türkiye – with 30 women currently working in the facility (Richter, 2020b).

Private banks have created incentives for investors in the geothermal greenhouse sector in Türkiye. In 2019, the Turkish bank Ziraat launched a loan package for geothermal greenhouse heating projects to increase interest in the development of projects focused on greenhouse cultivation. Loan packages offer flexible options for investors, such as a principal grace period of up to two years, and investment loans can be valued for up to seven years, depending on the repayment period. Ziraat Bank also offers credit packages for existing greenhouses that need to invest in modern geothermal infrastructure (Richter, 2019b).

3.6 Building local capacity, education and awareness

Although the concept of direct use is not new, the utilisation of geothermal heat in the agri-food sector, among other direct-use applications, is still in its early stages of development in most countries. Awareness raising about the benefits and opportunities associated with direct-use geothermal technologies is therefore critical for policy makers, entrepreneurs and communities. Given that geothermal heat, unlike electricity, can only be used locally, awareness creation should be targeted at the local level. In addition, expertise is required to establish and operate geothermal-based projects. This can be built through education institutions or technical capacity building programmes.

In countries with established geothermal direct-use applications, the technical and financial viability of direct-use projects are better understood, as successful geothermal heating projects demonstrate the benefits and viability of such technologies to policy makers and beneficiary communities. However, this is not the case in most countries. Therefore, awareness creation should entail demonstration of the benefits that can be derived from the implementation of agri-food applications powered by geothermal energy. In this regard, a methodology for assessing the socio-economic costs and benefits of implementing geothermal direct-use projects in the agri-food sector is presented in this guidebook (see section 4.1). The methodology provides a quantitative and qualitative measurement of the economic, social, financial and environmental impacts of geothermal direct-use projects based on a set of indicators that are specific to these types of projects.

Pilot projects could also be developed to help demonstrate the technical viability and to some extent provide indications for the commercial viability of direct-use heating technologies. Pilot projects are critical in the collection of necessary data that could help improve the confidence of investors when making investment decisions. Once potential beneficiary end users, policy makers and communities are shown an actual project whose data proves successful operations, the level of awareness and acceptance of the technology increases.

Different types of expertise are required to develop geothermal projects, including geoscientists and drilling engineers at the resource level, environmental and social experts, project managers, policy makers and financiers (see Box 12). Partnerships with international, regional and local institutions are important to be able to provide training and certification programmes for technical experts, service providers and the downstream workforce to operate and maintain projects. Capacity building and entrepreneurship support will also need to be provided to local industries (*e.g.* farmers, artisans) to help raise awareness and develop local skills in the geothermal and agri-food sectors. In addition, training and capacity building of relevant public institutions should provide extensive support in the areas of policy making and decision making, besides imparting technical or commercial knowledge.

For countries without sufficient prior experience in geothermal applications in the agri-food sector, it is important to improve the capacity of national institutions to assess potential applications, stimulate investment and implement projects. Building institutional capacity can be achieved through training activities, as well as through the provision of tools/software, joint research, and pilot and demonstration projects.

In East Africa, several technical assistance programmes have been implemented in the region to support the development of geothermal direct use. In 2013, USAID supported Kenya's GDC to develop a methodology for identifying and prioritising direct-use projects. This support resulted in the development of pre-feasibility studies for a number of agri-food value chains as well as a direct-use demonstration centre in Menengai geothermal field. The UK Department for International Development through the East Africa Geothermal Energy Facility (EAGER) supported Uganda to identify potential direct-use opportunities that can be developed alongside electricity generation to improve the economics of geothermal projects. An assessment of direct-use opportunities in Djibouti, Ethiopia, Kenya, Rwanda, Tanzania and Uganda was carried out beginning in 2020 by the Climate Technology Centre and Network (CTCN) with the support of the United Nations Industrial Development Organization (UNIDO).

In Central America, Germany's GIZ is running a programme to support the countries in the sub-region to build capacity for industrial and agri-food uses of geothermal energy, as described in Box 12.

BOX 12 GIZ TECHNICAL ASSISTANCE IN CENTRAL AMERICA

In 2016, Germany's GIZ established a regional programme to promote and advance the use of geothermal heat in Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua and Panama. GIZ implemented the programme on behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ) and in collaboration with a local counterpart, the Central American Integration System (SICA, by its acronym in Spanish). The programme also has international partnerships with the International Geothermal Association (IGA), the Bundesverband Geothermie (BVG) and the World Bank (GIZ, 2020b).

The first phase of the project, Promotion of Geothermal Energy in Central America (FoGeo-1 by its acronym in Spanish), was implemented from 2016 to 2020. The objective of the programme was to support capacity building and development of an enabling environment for investment to facilitate the implementation of agricultural and Industrial application of geothermal energy. As part of the project, the technical, commercial and social feasibility of select pilot projects were assessed for cascading and stand-alone opportunities in Costa Rica, El Salvador, Guatemala and Honduras (GIZ, 2020c).

The second phase of the project, Geothermal Heat Utilization for Industrial Processes in SICA Member Countries (GEO II), started in 2020 and will last until 2023. This phase of the programme focuses on implementing pilot projects through policy dialogue, adaption of regulatory frameworks, knowledge dissemination, capacity building, stakeholder collaboration and project development (World Bank, 2018). Not only will these pilot projects demonstrate the potential to lower energy consumption costs for agro-industry, but they are also intended to have social and economic impacts in terms of job creation and sustainable local community development (Alfaro, 2021).

Around the world, there are many international, regional and national training centres or programmes that provide geothermal capacity building, including (but not limited to) the following:

- **Africa Geothermal Centre of Excellence (AGCE)** was founded in 2017 as an initiative from the UN Environment Programme, with the support of the Icelandic government and geothermal developers in Kenya, to provide geothermal training courses to the African region. The AGCE training courses held in Kenya include a module on direct-use technologies.

- **Andean Geothermal Centre of Excellence (CEGA)** in Chile is a collaboration among academic researchers from universities in Chile to develop scientific knowledge on geothermal resources through academic research programmes, sometimes in collaboration with private developers, on topics related to low- and high-enthalpy geothermal resources, direct use as well as societal aspects of geothermal energy.

- **CeMIE-Geo** is an academy-industry alliance with the support of the Secretariat of Energy of Mexico and the National Council of Science and Technology to promote and accelerate the use and development of geothermal energy in Mexico. The consortium includes several universities, scientific research institutes, as well as public and private companies.

- **East Africa Geothermal Energy Resource (EAGER) Facility (2015-2018)** was funded by the UK government and aimed to support investment in geothermal power generation in Ethiopia, Kenya, Rwanda, Tanzania and Uganda through technical assistance and capacity building programmes at the national level. The facility also supported preliminary assessment of developing direct-use applications alongside electricity projects to improve their financial viability.

- **Fraunhofer Institute for Energy Infrastructures and Geothermal Energy (IEG)** in Germany is a think-tank that strives for energy transition. One of its main projects is geothermal paper drying. The aim of the project is to develop steam for drying paper and to ensure sustainable paper manufacturing by using geothermal energy in the drying process.

- **Geothermal Institute:** University of Auckland is a New Zealand-based institute that provides research, consultancy and training, among other geothermal-related services, within the country and externally. It also offers master's programmes in geothermal-related subjects.

- **iiDEA Group** from the Engineering Institute of the National Autonomous University of Mexico (UNAM) is an applied geothermal energy research group developing technology for agriculture, fishing, home heating, food industry applications and power generation. The group aims to find sustainable solutions to the water-energy-food nexus. iiDEA Group was instrumental in the development of a geothermal drying facility in Mexico.

- **Sino-Icelandic Geothermal Training Program** is offered at the Sinopec Management Institute in Beijing, China. The programme is focused on training Chinese geothermal experts in the development and use of low- to medium-temperature geothermal resources for heating.

- **The University of El Salvador** offers a Diploma in Geothermal Energy in Latin America. The four-month programme was developed in collaboration with the GRO Geothermal Training Programme (GTP) (Box 13) and the Nordic Development Fund. The programme, delivered in Spanish, aims to strengthen the technological and scientific knowledge of institutions, companies and personnel working in the field of geothermal energy throughout Latin America.


© GRO Geothermal Training Programme

GRO GTP students visiting a greenhouse facility in Iceland.

BOX 13 GRO GEOTHERMAL TRAINING PROGRAMME (GTP), ICELAND

The GRO Geothermal Training Programme (GTP) in Iceland is one of the premier internationally recognised training programmes for capacity building of the global geothermal workforce. The development of geothermal energy requires diverse sets of skills across a variety of geoscience and engineering disciplines. However, there are few university-level geothermal degree programmes, and most training occurs on the job within companies and research institutions. Therefore, the GRO GTP uniquely provides postgraduate geothermal training to professionals from developing countries.

The programme's mission is to assist developing countries in Africa, Asia, and Latin America and the Caribbean in strengthening the capacities of their workforce at an individual and institutional level, aligned with achieving the Sustainable Development Goals.

The GTP offers several types of capacity development:

- A six-month-long training programme in Iceland is offered annually. Scientists and engineers who are practicing professionals from across the globe come to Iceland to attend introductory lectures, receive specialised training and conduct a final research project. The trainees have access to the multidisciplinary research facilities of the host organisations, *i.e.* Iceland GeoSurvey (ISOR) and Orkustofnun (National Energy Authority of Iceland). The programme has graduated over 710 fellows as of 2021.

- An M.Sc. and Ph.D. scholarship programme at the University of Iceland and Reykjavík University is eligible for graduates of the six-month training programme who have not already received advanced university degrees.

- Workshops and short courses are offered in selected countries in Africa (since 2005), Central America (since 2006), and Asia (since 2008) to reach a wider audience and promote co-operation among industry experts.

Direct use of geothermal energy is a key module in the GTP-sponsored programmes. The participating students receive academic and technical guidance from Icelandic as well as Icelandic-trained experts during the programmes. During the six-month training programme in Iceland, students are introduced to direct use through lectures and field visits to facilities using geothermal heat, such as greenhouses, aquaculture and fish drying facilities. In addition, the students who specialise in geothermal utilisation have the option of carrying out research on any aspect of geothermal heat use, including for agri-food applications. The short courses and workshops also usually incorporate a module on geothermal direct use. Some students graduating from the M.Sc. and Ph.D. scholarship programme have developed their thesis around direct-use-related themes.

In 2021, the GTP conducted its first online geothermal course with a focus on Africa. The course covered topics on geothermal potential, economic viability of electricity generation and direct-use applications in Africa. The course was aimed at decision makers in GTP partner countries, attracting around 200 participants from 32 countries. Similar online courses for Asia and Latin America and the Caribbean were also planned.

3.7 Leveraging technology, innovation and sustainability

The use of geothermal energy for electricity generation extracts only a portion of the energy obtained from the geothermal resource, while the rest is often re-injected back into the ground with the spent brine. Direct uses, including geothermal agri-food applications, present an excellent opportunity to utilise the geothermal resource sustainably by extracting more energy from the brine before it is re-injected. Geothermal heat applications encourage the implementation of innovative technologies designed with an eye towards enhancing sustainability.

For instance, practices that cascade energy through various thermal processes that require energy at different temperature levels ensure that as much energy as possible can be extracted from the geothermal resource. A stream of hot water or steam containing geothermal energy is passed from one thermal process to another, with each process extracting the amount of energy it requires. Processes that require higher temperature are located upstream, while those with lower temperature requirements are located downstream.

In an effort to create a society without waste and enhance sustainability, it is possible to create processes that not only cascade energy but also promote re-use of each other's waste by-products, resulting in circular processes. The pioneer concept of a society without waste was demonstrated in Kalundborg, Sweden, in the 1950s. Designed around a 1 500 MW coal-fired plant, the Kalundborg Industrial Park provided a blueprint of an industrial symbiosis network in which neighbouring companies collaborate to make use of each other's by-products and share resources, thereby reducing waste streams.

This concept of industrial symbiosis was adopted in Iceland as an eco-industrial park and expanded through the integration of geothermal energy as a renewable resource. The development of the Svartsengi Resource Park in Iceland on the Reykjanes peninsula was formed after a combined geothermal heat and power plant opened operations there in 1976. The park hosts an array of services including, but not limited to, the Blue Lagoon spa, a dermatology clinic that integrates the use of geothermal mineral, a biotech unit for algae production and a methanol manufacturing facility that uses CO_2 from the geothermal resource as a raw material. The nearby Reykjanes Resource Park offers fish-drying facilities among other activities. The Resource Park is in the process of expanding operations with the inclusion of new companies that can use the by-products of the geothermal plants including waste heat, dissolved minerals and non-condensable gases.

Eco-industrial parks offer a model for utilising geothermal resources through innovative practices to generate further revenue streams and reduce waste. These facilities act as incubation centres for innovation in the energy-food nexus. The principles of this design and the role that geothermal can play in driving sustainability and new innovative technology can be applied to current and future direct-use applications.

In Europe, the food production industry is still innovating ways to reduce its carbon footprint. The GEOFOOD project is an initiative between partners from Iceland, the Netherlands and Slovenia that seeks to integrate horticulture and aquaculture into a net zero waste production system heated using geothermal energy. The objective of the GEOFOOD project is to uncover the potential of low-temperature geothermal fields for food production and processing. This initiative focuses on the advantages of circular food production, such as optimisation of energy and nutrient use, water treatment, and waste recovery processes when geothermal heat applications are implemented in agribusiness.

Innovations are ongoing in different countries to enhance the growth of algae using geothermal energy. The heat from geothermal provides a conducive environment for the optimal growth of the algae, while geothermal CO_2 is used to enhance photosynthesis, resulting in a negative carbon footprint. Furthermore, growth of algae in these conditions results in low freshwater consumption and low land usage in comparison to conventional production methods (Mannvit, 2020) (Photograph 5). The algae so produced is used for animal and fish feeds, extraction of high-value micro-nutrients and manufacture of cosmetics. In addition, researchers working on the development of antimicrobials in New Zealand were reported to be studying thermophiles – micro-organisms growing at elevated temperatures – and the possibility of extracting their molecules for the manufacture of antibiotics (Royal Society of Chemistry, 2018).

Photograph 5 Algae production in photobioreactors

Table 8 provides a summary of the key actions necessary for accelerated geothermal applications in the agri-food sector, the existing challenges, and possible solutions, drawing on lessons learnt from successful projects around the world.

Table 8 Summary of challenges, gaps, recommendations and lessons learnt to support the use of geothermal heat in agri-food systems

Challenge/gap	Description	Recommendations/lessons learnt
Mapping of potential supply and demand of geothermal energy for agri-food systems	Inadequate data exist on the availability of geothermal resources suitable for direct use. Shallow geothermal resources, which could be developed more easily than deeper geothermal resources for direct use, are largely unexplored.	• Collect data on geothermal resources from various sources. • Develop mapping tools to integrate the available geothermal data to inform policy making (digital data portals, online databases, interactive GIS maps and analytical tools will all help map out potential areas with geothermal resources suitable for direct-use applications). • Focus on development of shallow geothermal resources for direct-use applications in agri-food systems. • Identify agri-food value chains that can benefit from the use of geothermal energy due to their co-location with geothermal resources. This could be represented in maps.
Policy, legal and regulatory frameworks	Laws and regulations to support the development of geothermal projects may be inadequate or lacking. Policy instruments to support the integration of geothermal energy into agri-food systems may be inadequate or lacking.	• Establish adequate and simplified licencing procedures for geothermal direct-use projects and clearly defined regulations. • Develop and implement policy instruments to encourage the deployment of geothermal heat in the agri-food sector.
Cross-sectoral alignment and multi-stakeholder engagement	Policies of different sectors whose involvement is required to implement direct-use projects are usually non-aligned. Numerous stakeholders are involved in the development of direct-use projects.	• Develop cross-sectoral, integrated planning approaches to facilitate the adoption of geothermal energy into food systems and to align public and private sector priorities (*e.g.* with master plans or roadmaps for geothermal heat utilisation. • Identify the various stakeholders in direct-use project development and devise a strategy for their engagement as early as possible.
Project development and ownership	The duration for geothermal project development is lengthy. Opportunities exist for sharing of infrastructure such as wells and energy delivery pipelines among various agri-food applications.	• Identify development models that promote sharing of infrastructure to minimise cost and exposure to individual projects and achieve quicker development time frames. • Leverage geothermal resources that can be easily harnessed to enable faster development of projects, *e.g.* low-temperature (shallow) geothermal resources, excess heat from power plants, etc. • Support integrated planning frameworks that include infrastructure development. • Define the objectives of direct-use projects as early as possible and identify enterprises that advance the objectives.

Challenge/gap	Description	Recommendations/lessons learnt
Access to financing	Geothermal project development has high upfront costs and risks. Public financial resources are limited, especially in developing countries. Multilateral and international bank funding is mainly focused on geothermal electricity production projects. Demonstrable feasibility of direct-use projects is lacking in many developing countries.	• Establish risk mitigation schemes to minimise the exposure to losses by geothermal developers. • Develop laws and regulations that encourage the deployment of geothermal heating, including simplified licencing procedures for geothermal direct-use projects. • Develop direct-use projects alongside existing power projects to utilise excess heat through cascading systems or available heat from sub-commercial wells. • Assess the socio-economic benefits of deploying geothermal heat in agri-food projects to demonstrate the potential to improve the livelihoods of local communities. • Launch pilot projects to demonstrate the technical/financial viability of direct-use technologies and associated business models. • Partner with local banks and build their capacity to finance direct-use projects using local currency financing. • Leverage technical assistance and matchmaking platforms to connect investors/financiers with bankable projects.
Building local capacity, education and awareness	There is a shortage of local skilled geothermal workforce in the public and private sectors. Awareness is limited about the potential and benefits of direct-use applications to improve the socio-economics of local communities.	• Partner with international, regional or local institutions to provide training and certification programmes for the downstream workforce to develop, operate and maintain direct-use projects. • Raise awareness on the benefits and feasibility of direct-use projects among policy makers, communities and private sector agri-food industries. • Identify best practices and promote exchange of experiences and knowledge among countries and training centres at a regional level. • Build the capacity of public institutions to identify direct-use opportunities and assess their financial as well as socio-economic viability.
Leveraging technology, innovation and sustainability	There is a need to use resources sustainably and minimise wastage. Innovation should be nurtured to enable the creation of new products and processes.	• Encourage sustainability practices in the energy (geothermal) and industrial sector that aim to maximise energy use 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 through innovation.

TOOLS AND METHODOLOGIES

4.1 Assessing socio-economic impacts of geothermal direct use in agri-food value chains

The incorporation of geothermal direct use into an agri-food application impacts a diverse group of stakeholders along the agri-food value chain, encompassing investors, developers, farmers, local authorities, local communities, households and individuals. Section 2.1 introduces how these stakeholders can benefit financially, socially and environmentally from the incorporation of geothermal energy into agri-food businesses, while this section provides a methodology to measure the impacts of those benefits (here referred to as socio-economic benefits).

This methodology underscores the importance of net socio-economic benefits contributing to project viability, beyond financial profitability. Notably, it provides decision makers with a semi-quantitative approach to incorporate socio-economic factors into business cases. Lastly, it informs decision makers of the relevance of non-financial benefits in the geothermal agri-food value chain, further encouraging the adoption of energy policies that promote geothermal direct use in agri-food projects.

As businesses seek to mainstream sustainability in their operations, this methodology will be a useful tool for measuring the non-profitability related metrics such as social and environmental aspects. In particular, the business case for geothermal direct use in the agri-food industry must analyse the impacts of these aspects on enterprises, energy suppliers, the environment and society in general. This methodology could be applied, for instance, during feasibility studies, both by state-owned developers and publicly funded projects as well as by privately sponsored projects. For each geothermal energy supply scenario, the development of a business case should be performed to assess financial profitability, employment potential, new market opportunities, energy savings and CO_2 reductions, among others. Not only does geothermal energy technology have the potential to lower operating costs and improve financial profitability, but social, environmental, health and well-being benefits can make geothermal an even more attractive renewable energy alternative.

Geothermal energy brings multiple socio-economic benefits compared to several other conventional technologies. Particularly, when compared to natural gas and other fossil fuel technologies, geothermal creates more jobs on a per megawatt basis. Not only are these jobs more numerous, but they are of better quality and longer-term in nature (GEA, 2010). Box 14 provides insights on the employment potential within the geothermal sector in the wake of the energy transition.

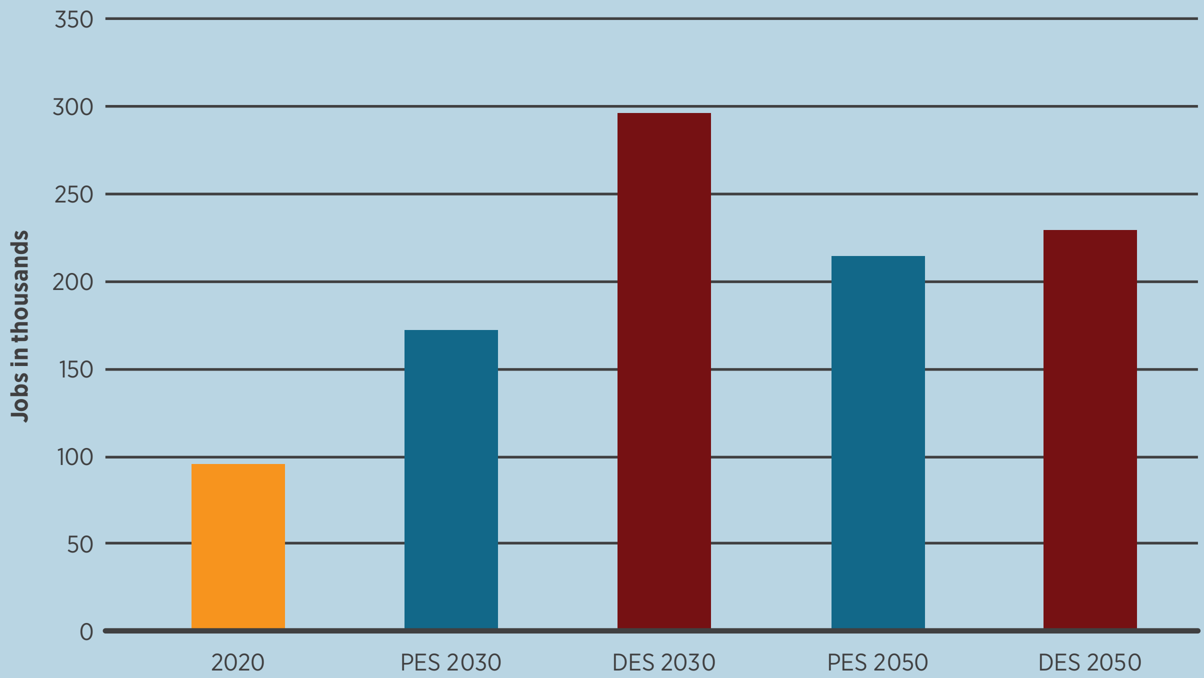
BOX 14 GEOTHERMAL JOBS OUTLOOK

IRENA has been assessing the socio-economic impacts of renewable energy technologies on various fronts since 2011. These include benefits related to jobs and skills development, inclusivity and gender empowerment, GDP, value creation at the local level and welfare improvement in general, among others. The IRENA studies assess the impacts of renewable energy deployment today and make projections to 2030 and 2050 for the global, regional and in some cases national scale.

IRENA's *Annual jobs review* (2021) shows that geothermal technology created 96 000 jobs in 2020. The European Union holds the largest share, with 40 000 jobs, which includes around 8 700 jobs in heat pumps in the region. The United States is the second largest jobs provider with 8 000 direct jobs, followed by China with an estimated 3 000 direct and indirect jobs (IRENA and ILO, 2021).

IRENA's flagship report World energy transitions outlook: 1.5°C pathway, launched in 2021, provides a roadmap to limit global temperature rise to 1.5°C and estimates the socio-economic impact of this energy transition on economies and societies (IRENA, 2021a). The report looks at two different scenarios: the Planned Energy Scenario (PES) and the Decarbonising Energy Scenario (DES). The PES provides the current policy and target pathways, while the DES provides the energy transition pathway needed to meet the 1.5°C goal. To achieve the DES, the report suggests that geothermal will play a significant role in the energy transition to 2050. In terms of total primary energy supply, the share of geothermal will increase from around 0.7% today to over 8% in 2030 and almost 10% in 2050 to meet the climate goals. In the process, the technology will create 296 000 jobs in 2030 and 229 000 jobs in 2050, as shown Figure 6.

Figure 6 Geothermal jobs in 2020, and projections to 2030 and 2050



Source: IRENA, 2021a.

In addition, geothermal sites tend to be located in remote or rural areas. This helps support local communities or workforces. This is particularly relevant for many developing countries, which have abundant geothermal resources and also face a dire need to revive rural economies.

This section recommends a cost-benefit analysis methodology for assessing the impacts of deploying geothermal energy in agri-food systems. A cost-benefit analysis considers the attractiveness of investments by quantitatively determining if the benefits outweigh the costs. Next, this section identifies socio-economic indicators that are specific to the geothermal agri-food sector and describes how the indicators can be monetised (when possible), or alternatively evaluated qualitatively, in the cost-benefit analysis. This approach to assessing socio-economic impacts builds on the work of IRENA (2016b) and the FAO and GIZ (2018; 2019).

Methodology for assessing the socio-economic benefits of geothermal applications in the agri-food sector

A methodology for assessing the socio-economic impacts of utilising renewable energy solutions in the agri-food sector using a cost-benefit analysis was developed by the FAO and GIZ through the project Investing in Sustainable Energy Technologies in the Agrifood Sector (INVESTA) (Box 15) (FAO and GIZ, 2018; FAO and GIZ, 2019). The INVESTA cost-benefit analysis methodology is a four-stage financial and economic feasibility analysis that provides a framework that is adapted and applied here for geothermal direct-use technologies in agri-food value chains. The first stage consists of a brief project description including institutional, economic, technological and social aspects as well as a description of the geothermal direct-use application and technology. The second stage is the financial analysis, which serves as a foundation to carry out the economic analysis in the third stage. It involves the identification of a benchmark scenario (usually a fossil fuel alternative) against which the geothermal scenario will be compared. Finally, in the fourth stage, a sensitivity analysis is carried out to assess risks during all project phases.

"Beyond financial profitability, other socio-economic indicators should be quantified and incorporated into business cases that inform policy makers of non-financial benefits from integrating geothermal energy in agri-food value chains"

BOX 15 INVESTA COST-BENEFIT ANALYSIS METHODOLOGY

The Investing in Sustainable Energy Technologies in the Agrifood Sector (INVESTA) project, carried out by the FAO in collaboration with GIZ, developed a methodology to comprehensively assess the costs versus benefits of introducing innovative and sustainable renewable energy technologies in agri-food value chains in emerging economies (FAO, 2018). The methodology was initially applied at the project level to selected case studies using biogas and solar energy solutions in vegetable, milk and rice value chains (FAO and GIZ, 2018). Subsequently, the methodology was applied at the national level in four countries (Kenya, the Philippines, Tanzania and Tunisia) to measure macro-scale impacts and identify enabling frameworks to support investments in energy-smart agri-food chains (FAO and GIZ, 2019). This four-stage methodology consists of:

1. Feasibility analysis of the given renewable energy technology;

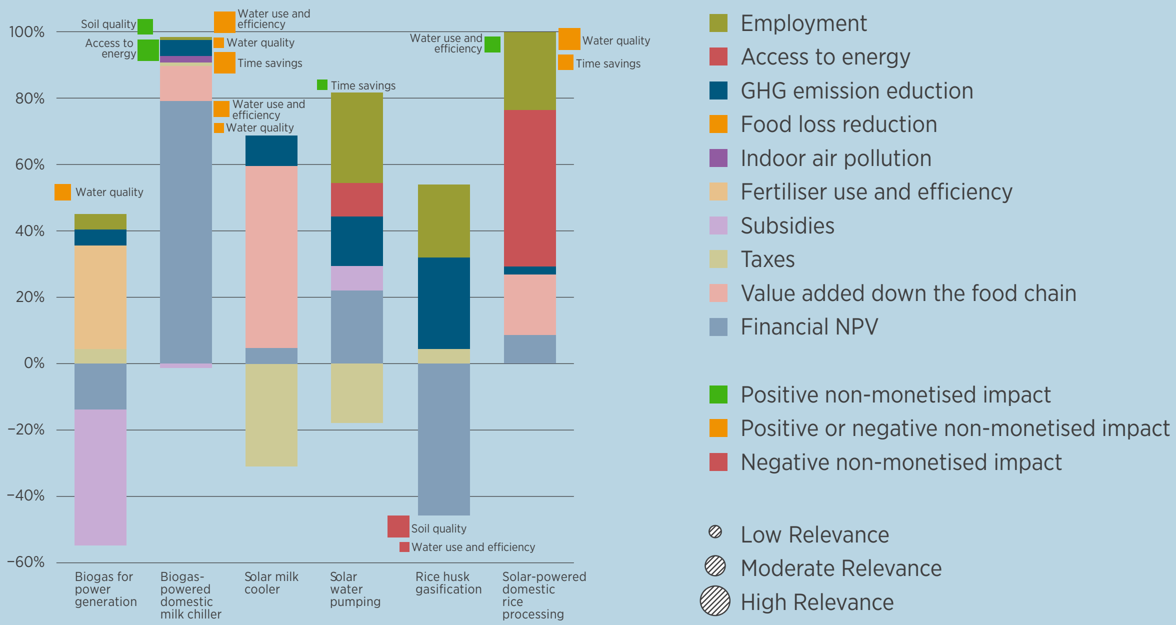
2. Financial analysis to assess financial profitability, *i.e.* financial returns of the specific project to Investors;

3. Economic analysis that monetises all socio-economic benefits and costs to assess economic profitability, *i.e.* the financial and social returns of the project to society; and

4. Sensitivity analysis of project risks and uncertainties.

Figure 7 shows the results of the economic INVESTA cost-benefit analysis methodology as applied to six case studies using solar and biogas renewable energy technologies to demonstrate the net impact of socio-economic aspects on the economic viability of a project (FAO and GIZ, 2018). It highlights how monetisable indicators compared with non-monetisable indicators can be jointly visualised and evaluated in a cost-benefit analysis. In four of the six case studies, the economic benefits outweigh the economic costs, and in two of the case studies the economic benefits and costs are similar, with roughly zero net impact. In addition, there is wide variation of impact among indicators, highlighting the uniqueness of each specific project.

Figure 7 Net impact of monetised and non-monetised socio-economic indicators of benefits and costs across six renewable energy case studies



Source: FAO and GIZ, 2018.

Adapting the INVESTA cost-benefit analysis methodology to geothermal energy applications includes the identification of a set of socio-economic indicators that are specific to geothermal direct-use agri-food value chains (see Table 10). These indicators can then be assessed following the methodology adapted from the INVESTA cost-benefit analysis (Figure 8).

A step-by-step application of the adapted INVESTA cost-benefit analysis methodology to assess the socio-economic benefits of geothermal agri-food interventions is presented in Table 9. At the centre of the methodology are financial and economic analyses, which are carried out in five steps. Both analyses follow the same steps; however, the economic analysis considers the social impacts of transfer payments and externalities (socio-economic indicators) in addition to the financial impacts of the project. Whereas the financial analysis focuses on the attractiveness of the investment from the enterprise's perspective, the economic analysis focuses on the attractiveness of the investment from the point of view of society.

Figure 8 Application of INVESTA cost-benefit analysis (CBA) to geothermal technologies in the agri-food sector

Feasibility analysis →	Financial CBA →	Economic CBA →	Sensitivity analysis
• Brief project description including institutional, economic, technological and social aspects • Description of the geothermal direct-use application and technology	• Benchmark & geothermal scenarios • ***Financial*** costs and monetised benefits for both scenarios • Discounted costs & benefits • ***Financial*** incremented net flows • ***Financial*** profitability indicators: NPV, IRR, B/C, PBT.	• Benchmark & geothermal scenarios • ***Economic*** costs and monetised benefits for both scenarios • Socio-economic indicators (monetise when possible) • Transfer payments (taxes, subsidies, value added along the value chain) • Discounted costs & benefits • ***Economic*** incremented net flows • ***Economic*** profitability indicators: NPV, IRR, B/C, PBT.	• Assess risks during all project phases

Adapted from FAO and GIZ 2018.

Table 9 A step-by-step methodology for carrying out financial and economic analysis

	Financial analysis	Economic analysis
Step 1	Identify fossil fuel benchmark scenario and geothermal energy scenario.	Identify fossil fuel benchmark scenario and geothermal energy scenario.
Step 2	Identify financial costs (*e.g.* initial capital investment, maintenance and operating costs) and the monetised benefits (*e.g.* income, tax reductions, subsidies and financial incentives) for both scenarios.	Identify economic costs and monetised benefits for both scenarios: • Identify externalities (socio-economic indicators) and determine positive or negative impact, monetising when possible: - Economic indicators - Social, health and well-being indicators - Environmental indicators • Identify transfer payments and determine positive or negative impact: - Subsidies - Taxes - Any additional value gained along the value chain.
Step 3	Choose a suitable rate to be used in the discounting of costs and benefits (net discounted benefits).	Choose a suitable rate to be used in the discounting of costs and benefits (net discounted benefits).
Step 4	Calculate financial incremental net flows from the discounted costs and benefits of the geothermal energy in relation to the benchmark scenario.	Calculate economic incremental net flows from the discounted costs and benefits of the geothermal energy in relation to the benchmark scenario.
Step 5	Calculate financial profitability indicators to support an investment decision using metrics such as NPV, IRR, BCR and PBT.	Calculate economic profitability indicators to support an investment decision using metrics such as NPV, IRR, BCR and PBT.

Adapted from FAO and GIZ, 2018.

Financial analysis

The financial analysis assesses the profitability and sustainability of an investment at the project level. The project viability is assessed from the perspective of the investor, entrepreneur, farmer or food processor. The objective of the financial analysis is to determine the financial returns to project stakeholders (FAO and GIZ, 2018). The five steps are outlined as follows.

Step 1: Identify the fossil fuel benchmark scenario (which would be used if geothermal energy was not available), and the geothermal energy scenario.

Step 2: Identify financial costs which include initial capital investment costs (CAPEX), maintenance and operating costs (OPEX), as well as monetised benefits (such as income, tax reductions, subsidies or financial incentives) for both scenarios. This step does not specify the source of capital for the investment, only assuming for simplicity that the capital is available.

Step 3: Choose a suitable rate to be used in the discounting of costs and benefits (discounted net benefits). The present value of future costs and benefits should be determined using the selected discount rate.

Step 4: Calculate financial incremental net flows over the lifetime of the project from the discounted costs and benefits of the geothermal energy scenario in relation to the benchmark scenario.

Step 5: Calculate financial profitability indicators to support an investment decision:

1. **Net present value (NPV):** the present value of all future net cash flows (*i.e.* benefits minus costs) over the project lifetime. NPV accounts for the time value of money with the application of a discount rate.

2. **Internal rate of return (IRR):** the growth that an investment is expected to generate on an annual basis. IRR is used to estimate the profitability of a probable business opportunity; the higher the IRR, the more attractive the investment.

3. **Benefit/cost ratio (BCR):** the overall relationship between the present value of benefits divided by the present value of costs over the project lifetime. If BCR is greater than 1, the benefits outweigh the costs, and there will be a positive NPV and an IRR above the discount rate. However, if BCR is less than 1, then the costs are greater than the returns and the project will not be profitable.

4. **Payback time (PBT):** the amount of the investment divided by the annual cash flow. The PBT indicates the time taken for the business to recover the amount invested, or the length of time needed to reach a break-even point. Shorter PBT indicates higher profitability.

These indicators are useful decision-making tools to indicate project viability and attractiveness as they compare the present value of the investment with its predicted future value.

Economic analysis

The economic analysis assesses the feasibility of a project from the perspective of a local, regional or national economy. The project is assessed in terms of its contribution to society. The economic analysis provides a means to identify and quantify the impacts of the project on the economy, society and environment. The five steps are outlined as follows.

Step 1: Identify the fossil fuel benchmark scenario and the geothermal energy scenario, following the same approach as in step 1 of the financial analysis.

Step 2: Identify economic costs and benefits for both scenarios. Externalities and transfer payments must be monetised when possible and evaluated to determine if they have positive impacts (and therefore represent economic benefits) or if they have negative impacts (and therefore represent economic costs). Non-monetised indicators can be represented graphically alongside monetised indicators to assess overall net impact.

1. **Externalities** (socio-economic indicators) are positive or negative effects of the project on society without a corresponding monetary gain or loss to the project (FAO and GIZ, 2018). Socio-economic indicators can be classified as economic; social, health and well-being; and environmental indicators. If the indicator has a positive impact, it is considered a benefit for society, whereas if it has a negative impact, it is considered a cost for society. Socio-economic indicators that can be quantified and monetised (*e.g.* job creation, income generation, greenhouse gas reductions) should be quantitatively included in the economic analysis. Socio-economic indicators that cannot be monetised (*e.g.* the majority of social, health and well-being indicators) should be qualitatively ranked as positive (benefit), negative (cost) or uncertain impact.

2. **Transfer payments** (payment for which no goods or services are exchanged), such as taxes, subsidies, fiscal incentives and value-added along the value chain, may have either positive or negative impacts. Government subsidies and fiscal incentives are considered a cost to society as they are publicly financed, whereas taxes are considered benefits as they generate revenue for government.

Step 3: Select an appropriate discount rate (*e.g.* social discount rate[3]) to compare discounted costs and discounted benefits (discounted net benefits), following the same approach as in step 3 of the financial analysis.

Step 4: Calculate economic incremental net flows from the discounted costs and benefits of the geothermal energy scenario in relation to the benchmark scenario, following the same approach as in step 4 of the financial analysis.

Step 5: Calculate economic profitability indicators to support an investment decision that considers for net societal impacts, following the same approach as in step 5 of the financial analysis.

Identification of socio-economic indicators and transfer payments for the cost-benefit analysis

This section presents a non-exhaustive list of indicators and transfer payments for assessing the socio-economic impacts of geothermal direct-use applications in agricultural production, post-harvest preservation and processing. The section draws on indicators identified in other renewable energy technologies (IRENA, 2016b; FAO and GIZ, 2019) and on examples from case studies presented throughout the guidebook. The indicators are divided into three categories: economic; social, health and well-being; and environmental. The indicators´ classification and descriptions are shown in Table 10.

[3] *The rate at which society discounts future net economic benefits relative to those of the present. Typical discount rates used are those determined by the Ramsey formula (proportional to the real per capita income growth) or interest rates on long-term government bonds.*

Table 10 Classification and description of socio-economic indicators

Indicator	Description
Economic indicators	**Income generation** • **Revenue:** Producers earn income due to an increase in the quantity and quality of their agricultural produce. • **Revenue:** Producers and processors earn income due to the branding of produce (sustainably grown and processed with "green" energy) to command a higher value in the market. • **Revenue:** Producers earn income from the sale of extra food resulting from the reduction in post-harvest food loss and waste, which is mainly attributed to improved post-harvest handling including proper drying, cooling and processing of agricultural produce using geothermal energy. • **Household income:** As a result of direct and indirect employment due to geothermal interventions in the agri-food sector, income levels in homes improve. **Diversification** • **Diversification:** New marketable products as a result of value addition generate additional income for processors. • **Diversification:** Geothermal developers earn extra revenue streams from the sale of heat to agri-food enterprises, in addition to the sale of electricity. **Savings** • **Savings:** Limited use of pesticides and fungicides in greenhouses due to geothermal heating reduces the cost of production. • **Savings:** In some cases, geothermal energy used in agri-food applications could be a cheaper option than alternative fuels, resulting in financial savings to agri-food enterprises. **Costs** • **Wages and salaries:** Costs are incurred by agri-food enterprises as a result of direct and indirect employment of the workforce. • **Retrofitting:** Enterprises must pay the costs of modification of their premises to allow for the connection to geothermal energy. **Employment opportunities:** Net jobs are created along the agri-food value chain, including temporary or permanent positions, skilled or unskilled expertise, and part-time or full-time positions. **Water and food security:** Generation of water for irrigation from geothermal sources, as well as use of geothermal heat in the agri-food value chains, enhances food security for local communities and contributes to a reduction in malnutrition, as follows: • Water for irrigation: With adequate supply of water, more food can be grown throughout the year. • Efficiency: Efficiency in agricultural productivity is improved without a corresponding increase in the land requirement. More can be produced within the same piece of land due to the application of geothermal energy. • Productivity: The use of geothermal energy in food production results in early maturity and higher yields of crops and aquatic life in comparison to the state where no energy is used due to the provision of an optimal environment for growth leading to more productivity. In addition, crops can be produced when they would otherwise have been off-season (*e.g.* production during winter). • Food preservation: Geothermal drying and cooling / cold storage preserves the quality of the produce and reduces post-harvest losses. **Time saving:** Drying using geothermal energy is less time consuming and requires less human power, therefore freeing time to engage in other productive activities. **Market access:** Establishment of industries that use geothermal energy to process agri-food produce creates new businesses that serve as markets to local farmers for selling their raw materials to agro-industries, hence assurance of income. **Food import reduction:** Increased local production of food due to the use of geothermal energy reduces the food import bill, resulting in savings due to reduced imports. **Energy security:** Energy security in food systems is enhanced due to the use of locally available renewable resources (geothermal). **Fossil fuel reduction:** Offset in fossil fuel consumption by enterprises due to the use of geothermal heating reduces the import bill in favour of balance of payment.

Indicator	Description
Social, health and well-being indicators	• **Education:** Higher education is promoted in relevant fields such as food, agriculture, engineering and finance. • **Health:** Geothermal heat is a clean source of energy that – with the proper application of best operation practices – has little to no emissions compared to fossil fuel alternatives. This results in decreased incidences of pollution-related health complications. • **Inclusivity and gender equality:** Women and youth participating in geothermal projects and agri-food ventures have increased opportunities for advancement. • **Standard of living and quality of life:** Stimulation of local economy due to geothermal use in agri-food enables people to afford various goods and services. This may improve their general well-being and happiness.
Environmental indicators	• **Greenhouse gas emissions reductions:** Greenhouse gas emissions are reduced with geothermal applications compared to fossil fuel use.

Each project has its own unique combination of economic; social, health and well-being; and environmental benefits and costs to all project stakeholders: investors, developers, farmers, local authorities, local communities, households and individuals. The following sub-sections describe these benefits and costs across the indicators.

Economic indicators

Income generation: Revenue from sales can be generated by a variety of mechanisms throughout the agri-food value chain. In upstream activities, revenue for food producers increases as a result of enhanced production quantity and/or quality of product yield owing to reduced production time. Furthermore, the use of geothermal in greenhouse horticulture in snowy winter climates, *e.g.* eastern Türkiye or southern Chile, ensures food production year-round. In downstream activities, branding of products as "geothermal" grown and processed, such as tomatoes, dried fruit, beer, cheese and spirulina, can command a higher market price. Branding of produce can be quantified as the price difference between a geothermal energy-related food product compared to a conventional product. A reduction in post-harvest losses due to timely and adequate drying, storage and processing creates surplus produce that can be sold to generate extra income for farmers and businesses.

At the household level, income is generated from the high-quality jobs created from using geothermal energy in the agri-food sector. These jobs translate to higher salaries for employees. Therefore, on average, the disposable income available to households is expected to increase as a result of the increase in the number of enterprises using geothermal energy in the agri-food sector.

Diversification: Applying geothermal direct-use technology to the agri-food sector can result in new income generation business opportunities along the value chain and additional revenue streams from diversification of businesses. In New Zealand, the Miraka milk processor uses the nearby geothermal resource not only to process milk but also to generate a second product, milk powder. The production of milk powder leverages the existence of high-temperature steam from the geothermal resource. For the geothermal developer, selling thermal energy to cascaded direct-use applications provides additional revenue streams, in addition to the revenue generated from the sale of electricity.

Savings: Cost savings resulting from using geothermal energy – a cheaper energy source compared to fossil fuel alternatives – saves money in the production, processing and storage of produce. As a result of production of food in a controlled environment, the produce is less susceptible to diseases. For example, the heating of greenhouses prevents the condensation of water vapour on the leaves of plants, which minimises the development of fungal diseases. Consequently, farmers reduce their usage of fungicides and other chemicals, which could be a significant part of the production cost. In food processing, cost savings can be realised if cheaper geothermal energy is used to offset fossil fuel consumption. Fossil fuel consumption is measured in tonnes or litres. All geothermal direct-use applications have the potential to offset or entirely replace non-renewable energy sources that are typically used in conventional agri-food heating applications. Geothermal can reduce costs associated with buying and using more expensive diesel/oil sources.

Costs: The use of geothermal energy in existing businesses could result in businesses incurring an extra cost to retrofit their energy supply systems and connection to the geothermal resource. This may include the cost of replacing fuel-powered boilers and installing additional heat exchangers and pipes to deliver hot water / steam from the geothermal systems. The jobs created in the local economy also represent a cost to the businesses in terms of wages and salaries. The wage and salaries are measured as an hourly wage or as a monthly or annual salary.

Employment opportunities

Employment opportunities are defined as net jobs for skilled or unskilled labour in temporary/seasonal positions or on a permanent, part-time or full-time basis. The employment opportunities indicator can be quantified as the net number of jobs created and replaced along the agri-food value chain due to the application of geothermal energy. The majority of new geothermal direct-use projects create employment opportunities for local communities. For example, the Miraka milk processing factory in New Zealand has 120 employees and 20 to 30 contracting staff who contribute to local economic growth (Richter, 2017) (see Box 2); the geothermal food drying company Deshidratador Geotermico de Alimentos de Nayarit at the Domo de San Pedro geothermal field in Mexico generates up to 50 local direct jobs and around 60 indirect jobs in the region; and the geothermal greenhouse facility owned by Caldiran Geothermal in Türkiye has created jobs for 40 people in the local community (Richter, 2019b). However, it could be possible that manual jobs could be replaced by the introduction of more efficient innovative technology.

Water and food security

Geothermal agri-food applications improve food and water security at the local and national levels. Increased food production from the use of geothermal energy to increase yields and reduce food spoilage provides improved food security and reduces malnutrition. For example, the GEOFOOD project in Europe has the objective to uncover the potential of low-temperature geothermal fields for food production and processing. It focuses on the advantages of circular food production, such as optimisation of energy and nutrient use, water treatment and waste recovery processes when geothermal heat infrastructures are implemented in agribusiness (Thorarinsdottir *et al.*, 2020).

In Tunisia, geothermal water is used for irrigation, converting arid desert environments into arable agricultural areas. Water from geothermal wells is cooled in atmospheric cooling towers prior to using it to irrigate desert oases (Ben Mohamed, 2015). Generation of drinking water from geothermal sources or using geothermal technology can provide a source of potable water for rural communities. In Kenya, potable water is generated from numerous fumaroles at the Eburru and Suswa area, which lack a reliable source of clean drinking water. Local communities harness the steam coming out of the ground by condensing and cooling it into water that can be used domestically (Ndetei, 2020). In Mexico, the iiDEA Group is developing a modular desalination unit powered by geothermal energy. This unit provides an alternative solution to the scarcity of potable water in desert regions of northeast Mexico. Geothermal energy for heat-intensive thermal desalination processes represents a cost-competitive, sustainable and environmentally friendly option (Gude, 2016).

Time saving

The use of modern sources of energy such as geothermal would result in more efficient operations such as drying of crops, leading to time savings as fewer people will be required to dry the same quantity of food in comparison to traditional sun drying.

Market access

The establishment of a geothermal agricultural processor such as a crop drying centre or milk pasteurisation creates a new market for local farmers to sell their raw materials to agro-industries. Perishable products such as fish, grains, fruits, and vegetables, once processed using geothermal energy, can be transported to new markets while still fresh as a result of improved shelf life.

Food import reduction

The increase in food yield from the use of geothermal energy in food production ensures that there is adequate food in the locality. In addition, reduction in post-harvest losses increases the availability of food in the local market. The increased availability of food reduces reliance on imported food, resulting in savings on food imports.

Energy security

Geothermal is a locally available energy resource that may be generated and utilised on-site without transport. This means that its availability is not subjected to supply chain constraints, unlike fossil fuels that require transport in most cases and may be affected by disruptions in global trade. As a result, agri-food enterprises using geothermal energy are assured of a stable supply of energy at a predictable price.

Fossil fuel reduction

Importation of fossil fuels could entail a significant share of a country's expenditure. In the agri-food sector, this expense could be avoided by using geothermal energy in agri-food value chains. This would save the countries considerable amounts in foreign exchange spending, considering that around 30% of global energy usage is in the agri-food sector.

Social, health and well-being indicators

The social, health and well-being indicators encompass education, health, inclusivity and gender equality, and standard of living and quality of life. These non-economic indicators are affected in varying ways by different projects and are more difficult to quantifiably measure. Therefore, they are usually treated as non-monetisable indicators in the cost-benefit analysis.

Education

On a professional level, geothermal direct-use projects require skilled workers and experts to design, finance, install, operate and maintain the project. This promotes skills development and higher education in relevant fields such as food, agriculture, engineering and finance to fulfil job needs in the geothermal agri-food industry. Companies may encourage professional development of employees through participation in international, regional and national training centres or programmes. For unskilled workers, on-the-job professional development and education about geothermal energy are often provided in direct-use agri-food projects.

Health

According to the World Health Organization, around 7 million people worldwide died in 2016 as a result of complications caused by air pollution, originating mainly from the use of fossil fuels. This not only causes suffering to families but also robs the world of a productive workforce and costs economies large amounts of money in the treatment of pollution-related complications. The use of clean energy solutions in the agri-food sector can reduce energy-related pollution such as emissions from particulate matter, carbon, nitrogen and sulphur oxides, which have a detrimental impact on human health and biodiversity.

Inclusivity and gender equality

Inclusivity and gender equality include the advancement of women and youth participation in geothermal projects and agri-food systems. Direct-use geothermal projects can create jobs and livelihood opportunities for women, as well as provide training and professional advancement. For example, the geothermal food drying company DGA de Nayarit at the Domo de San Pedro geothermal field in Mexico employs 90% women. Women are provided vocational training as well as education about geothermal energy. In Türkiye, a geothermal greenhouse facility owned by Caldiran Geothermal Inc. in eastern Türkiye employs 75% women, creating job opportunities for women where participation in Türkiye's geothermal sector is not common. In El Salvador, the by-products from geothermal power plants operated by LaGeo are used for productive uses and employment for women in neighbouring rural communities. Women grow and sell plants using geothermal steam condensates, use geothermal waste heat for fruit dehydration, and participate in cocoa and coffee reforestation programmes (ESMAP, 2019). On a corporate level, LaGeo has fostered an inclusive workplace culture, employing 35% women, as well as considering women in recruitment and training (ESMAP, 2019).

Standard of living and quality of life

Standard of living is the ability of certain socio-economic classes or geographic areas to procure comfortable lives through the acquisition and use of material means, whereas quality of life refers to fulfilment in life that cannot be measured using material means (*e.g.* happiness). Geothermal direct-use projects can have the potential to improve the standard of living and quality of life of employees, farmers, the local community and other stakeholders in several ways. Stimulation of the local economy from direct employment and income generation along the value chain results in success of local businesses and improved purchasing power of individuals. The local population has increased income to spend on better housing, better health care, quality education for their children, and leisure activities, among others.

Environmental indicators

Greenhouse gas emissions reductions

Greenhouse gas emissions reductions refer to the decrease in the total mass of greenhouse gases (kilograms of CO_2 equivalent) emitted due to the use of geothermal energy, or the relative mass of greenhouse gases emitted per unit of product (kilograms of CO_2 equivalent per kilogram of product) along the agri-food value chain compared to displaced fossil fuels. Geothermal energy is a renewable technology solution replacing fossil fuels in the production, storage and processing stages of the value chain, thereby decreasing greenhouse gases and reducing pollution and creating a positive impact on this environmental indicator. Approaches and methodologies to calculate greenhouse gas emissions in agriculture and food processing are well established, with several tools available (Camargo *et al.*, 2013; FAO, 2012).

Greenhouse gas reductions have potentially large impacts in applications that are energy intensive, such as geothermal micro-breweries, distilleries or dairy processors. The average global warming potential (GWP) for conventional breweries is 0.7 kilograms of CO_2 equivalent per litre, compared with 0.1 kilogram of CO_2 equivalent per litre for geothermal breweries in Italy (Guglielmetti, 2021; Peerdeman, 2017). San Martino farm in Tuscany, Italy produces pecorino cheese using 180°C geothermal fluid transported in a 500-metre insulated pipeline from a nearby power plant for geothermal heating and cooling in cheese production, maturing and storage (Eni, 2016). Geothermal heat use in the dairy farm reduces energy consumption costs by 8-9% of the total production costs and avoids the emissions of 138 tonnes of CO_2 per year (Guglielmetti, 2021). Other energy-intensive industries with potentially large greenhouse gas reductions are those that avoid food loss, for example agricultural dryers that avoid post-harvest loss or refrigerated food storage applications. Mechanical food dryers are often oil/diesel operated, and geothermal dryers have significant potential to reduce carbon footprints (Kinyanjui, 2013).

Transfer payments

Taxes and subsidies

New revenue is generated for local authorities from taxes, business permits and licence fees for agro-industries and related businesses. Taxes can represent positive revenue for authorities and therefore can be considered a benefit for society. However, taxes can also be considered a cost for society, for example if they are misallocated. Taxes may represent both costs and benefits for society, so the net economic effects must be evaluated on a case-by-case basis.

An energy subsidy is a deliberate and specifically targeted policy action by the government that results in a reduction of the net cost of energy purchased, a reduction of the cost of energy produced and/or an increase in revenue by energy suppliers (Kojima, 2017). Subsidies can vary widely and may include, but are not limited to, government-sponsored financial support for geothermal energy. Similar to the situation with taxes, energy subsidies can represent both costs and benefits for society. Government subsidies and incentives can be considered a cost for society in that they represent a loss to the economy through the missed income for the government and use of public resources to support business. However, subsidies may also be considered a benefit to society as subsidised energy tariffs can provide new livelihood opportunities, generating more economic welfare than their economic opportunity cost. Taxes, subsidies and other financial incentives are measured in hard or local currencies.

The applicable government taxes and subsidies in geothermal direct-use applications vary among countries, often depending on the relative support of national and local policies for geothermal as a renewable energy solution. Some governments, such as the Netherlands and Türkiye, have provided significant government incentives, *i.e.* grants, subsidies, tax reductions, and geothermal risk mitigation, enabling agro-industry development that would otherwise be cost-prohibitive (IRENA, 2019).

The government of Türkiye offers a wide variety of investment incentives for renewable energy technologies, including geothermal energy, to minimise the upfront cost and accelerate investment returns. Pursuant to the General Investment Incentive Regime, Council of Ministers' Decision No. 2012/3305, general investment incentives include VAT exemption on the purchase or import of equipment, and customs duty exemption on imported equipment. Corporate tax reductions, social security support, land allocation, favourable interest rates, and income tax withholding support comprise a suite of regional and strategic investment incentives, as well as those available for priority investment areas, which include greenhouse automation (Presidency of the Republic of Türkiye Investment Office, 2020).

Since 2019, renewable energy systems in Türkiye that generate up to 5 MW of energy may operate without a licence subject to fulfilling a set of conditions (Presidency of the Republic of Türkiye Investment Office, 2019). The Renewable Energy Resources Support Mechanism (YEKDEM) of 2021 ensures continued incentives for geothermal electricity generation, such as a feed-in tariff and support for domestic equipment. Within the framework of the support mechanism of local equipment, the Geothermal Power Plant Investors Association (JESDER) is advocating for the inclusion within YEKDEM of equipment for geothermal greenhouses, district heating, and fruit and vegetable drying facilities.

In another example, the government of Kenya has designated the area surrounding the Olkaria geothermal field as a Special Economic Zone (SEZ). An SEZ, established by the Special Economic Zones Act of 2015, is a designated geographical area where public, private or public-private partnership businesses benefit from tax shields and other business-enabling policies. The businesses operating within the SEZ near Olkaria are expected to benefit from preferential terms, including lower power tariffs and tax incentives, among others (Kenyan Tribune, 2020). Businesses in an SEZ are legally entitled to a number of tax benefits, including tax exemption or preferential rates on all products and services provided within the SEZ, exemption from customs duty, VAT and stamp duty, and exemption from acquiring certain business licences. Additionally, businesses in an SEZ can leverage international technical expertise as they are permitted to hire up to 20% foreigners as full-time employees.

Quantitative and qualitative assessment of socio-economic indicators

Socio-economic indicators must be quantified, wherever possible, to be included in numerical terms in the economic analysis. To do so, the indicators must be monetised when possible as costs (negative effect) or benefits (positive impact) with a defined unit of measurement. Economic indicators tend to be more easily monetisable in comparison to social, health and well-being indicators, which are more difficult or impossible to monetise. If the indicator cannot be monetised, it must be evaluated qualitatively (for example, binary impact: positive or negative, or a relative scale: high-medium-low). Another non-monetary way of assessing the indicator is determining if it meets the Sustainable Development Goals (Table 11).

If socio-economic indicators have positive impacts, they are considered benefits. In contrast, if they have negative impacts, they are considered costs. Most indicators have positive impacts and are therefore considered benefits; however, some indicators can have either positive or negative impacts, such as new projects creating employment opportunities or jobs being replaced by new technology or taxes representing positive revenue for authorities but negative revenue for developers. Some benefits, such as employment opportunities and income generation from wages, are universal to most projects and straight-forward to measure (*e.g.* the number of new jobs created), whereas other benefits, especially the social, health and well-being indicators, are project-specific and more challenging to quantify the impact of (*e.g.* quality of life or standard of living).

Table 11 Evaluation of socio-economic indicators

Indicators	Description	Monetisable (Yes/No)	Unit of measurement	Meets SDG
	Revenue: Productivity increase	Yes	Price of a kilogram or litre of food or agricultural product	
	Revenue: "Green" branding of produce	Yes	Price difference between a "green" product and its market alternative	
	Revenue: Prevention of post-harvest losses	Yes	Price of a kilogram or litre of food saved	SDG 1: End Poverty
	Household income	Yes	Average change in income of employees	SDG 2: End Hunger
	Diversification: New marketable products	Yes	Price of a kilogram or litre of product	SDG 8: Sustainable Economic Growth
	Diversification: Sale of thermal energy	Yes	Price of a unit of thermal energy	SDG 7: Affordable and Clean Energy
	Savings: Reduced use of pesticides and fungicides in food production	Yes	Hard or local currency	
	Savings: Potentially lower energy cost than fossil fuel	Yes	Difference in cost of geothermal heat and cost of fossil fuel	
	Costs: Wages and salaries	Yes	Hourly wage, or monthly or annual salary	
Economic indicators	Costs: Retrofitting	Yes	Hard or local currency	
	Employment opportunities	Yes	Number of jobs created	
	Water and food security: Water for irrigation	Yes	Volume of water generated	
	Water and food security: Increased efficiency of food production	Yes	Additional kilograms of food produced per area per year	SDG 1: End Poverty
	Water and food security: Increased productivity	Yes	Additional kilograms of food produced	SDG 2: End Hunger
	Water and food security: Reduced food spoilage	Yes	Kilograms of food saved from spoilage	SDG 7: Affordable and Clean Energy
	Time saving	Yes	Human hours	
	New businesses and expanded market access	Yes	Monetary value generated	SDG 8: Sustainable Economic Growth
	Reduced import bill for food	Yes	Hard or local currency	
	Energy security	No	Non-monetisable	
	Reduced import bill for fossil fuels	Yes	Hard or local currency	
	Education	No	Non-monetisable	SDG 4: Quality Education
Social, health and well-being indicators	Health	No	Non-monetisable	SDG 3: Health and Well-Being
	Inclusivity and gender equality	No	Non-monetisable	SDG 5: Gender Equality
	Standard of living and quality of life	No	Non-monetisable	SDG 3: Health and Well-Being
Environmental indicators	Greenhouse gas emissions reductions	Yes	Kilograms of CO_2 equivalent or kilograms of CO_2 equivalent per kilogram of product	SDG 13: Climate Action

4.2 Developing geothermal heat tariffs

Geothermal energy tariffs

Developing geothermal resources requires high upfront investments but relatively low operating costs. The use of geothermal heat in the agri-food sector means that customers need to pay for the use of this energy in the form of a heat tariff. Given the nascent nature of geothermal applications in the agri-food sector, proper pricing mechanisms for geothermal heat should result in a tariff that encourages investment in this technology. The development of tariffs for geothermal energy usually results in different pricing regimes that vary depending on the jurisdiction. Contrary to conventional sources of energy (*i.e.* fossil fuels) – which are traded in global commodities markets and their prevailing market price directly affects the ultimate energy tariff – the pricing of renewable energy (particularly from geothermal sources) varies widely around the world.

This diverse pricing stems from numerous factors that are site specific, including the success rate of drilling, energy output per well (*e.g.* temperature and flow rate), the chemical composition of the geothermal fluids (and the need for treatment during utilisation), the cost of capital (particularly risk capital), the status of field development (*e.g.* greenfield or brownfield), and available incentives from the government, among others. For example, high-temperature geothermal resources in brownfields may translate to lower capital expenditure (CAPEX) and operating expenses (OPEX), resulting in lower tariffs. On the other hand, development of greenfield projects with lower-temperature resources may result in higher investment costs and thus higher tariffs. These factors affect the tariffs both for electricity and for heat.

Key factors in establishing a heat tariff for geothermal energy

Below are some of the key factors to consider when applying a heat tariff to geothermal energy:

- Cost recovery for the energy supplier through the heat tariff should be achieved within a reasonable time frame. Development of the geothermal resource for use entails a significant share of the energy supplier's cost, and this varies widely depending on site-specific conditions. The operating cost, although minimal, could also vary greatly from location to location depending on the properties of the geothermal fluid as well as the geological conditions. Despite these cost variations, the heat tariff should remain affordable to users.

- Compared to geothermal electricity use, the product from geothermal direct use is hot water or steam, which can be used in a variety of applications. The temperature and flow rate of the fluid determine the amount of energy delivered per unit of time, which influences the heat tariffs.

- The value of thermal energy supplied by geothermal resources is higher for the developer if the application is adjacent to the resource. Nevertheless, under certain resource and market conditions, having the resource at distance from the application may not be detrimental. While there are some examples from Iceland and elsewhere where hot water or steam is transported over long distances, in general, it is much more expensive for thermal energy to travel long distances (especially compared to the delivery of power); hence, the thermal value may decline as the distance to the application location increases, if sufficient insulation is not done. The tariff for heating could be set based on the amount of energy (kilowatt hours) consumed, which requires the use of energy meters to determine consumption. Alternatively, the tariff could be based on the volume of hot water (cubic metres) delivered, which is measured using flow meters. In cascaded systems and systems that integrate direct use and electricity generation, new agri-food applications may be added to the system over time. This means that in the early years of operation, the demand for heating may be low, but could grow with time as more customers are added. As a result, the early years of operation experience higher operating costs per unit of energy consumed or hot water delivered.

- Certain agri-food produce such as coffee and fruit are produced on a seasonal basis, hence the agro-industries that process this produce operate at full capacity only at certain times of the year, whereas the processing of other produce such as vegetables may take place throughout the year. The seasonal nature of produce would influence the capacity factor of geothermal heating, resulting in idle time when little or no energy is delivered to customers.

Methods to determine the cost of thermal energy for direct-use applications

There are two key pricing approaches: cost-plus and market-based. A cost-plus pricing strategy considers the costs incurred to generate heat during a given period of time plus a mark-up. The market-based approach sets the price on the basis of a benchmark price. This benchmark is usually the price of an alternative energy source that will be displaced by geothermal energy.

In determining the tariff for geothermal heat to a specific direct-use application, the energy will be delivered in the form of hot water or steam. Hence, the amount of thermal energy available from such resources will be based mainly on the flow rate of the geothermal fluids and the temperature difference of this flow rate (inlet minus outlet temperatures).

Cost-plus approach

To deliver thermal energy from a geothermal resource to a customer in a financially viable manner, the developer has to include all the cost items in the heat tariff and make a reasonable profit. Two main cost items associated with developing a geothermal resource are capital costs (CAPEX), which are incurred one time, and operating costs (OPEX), which are recurring.

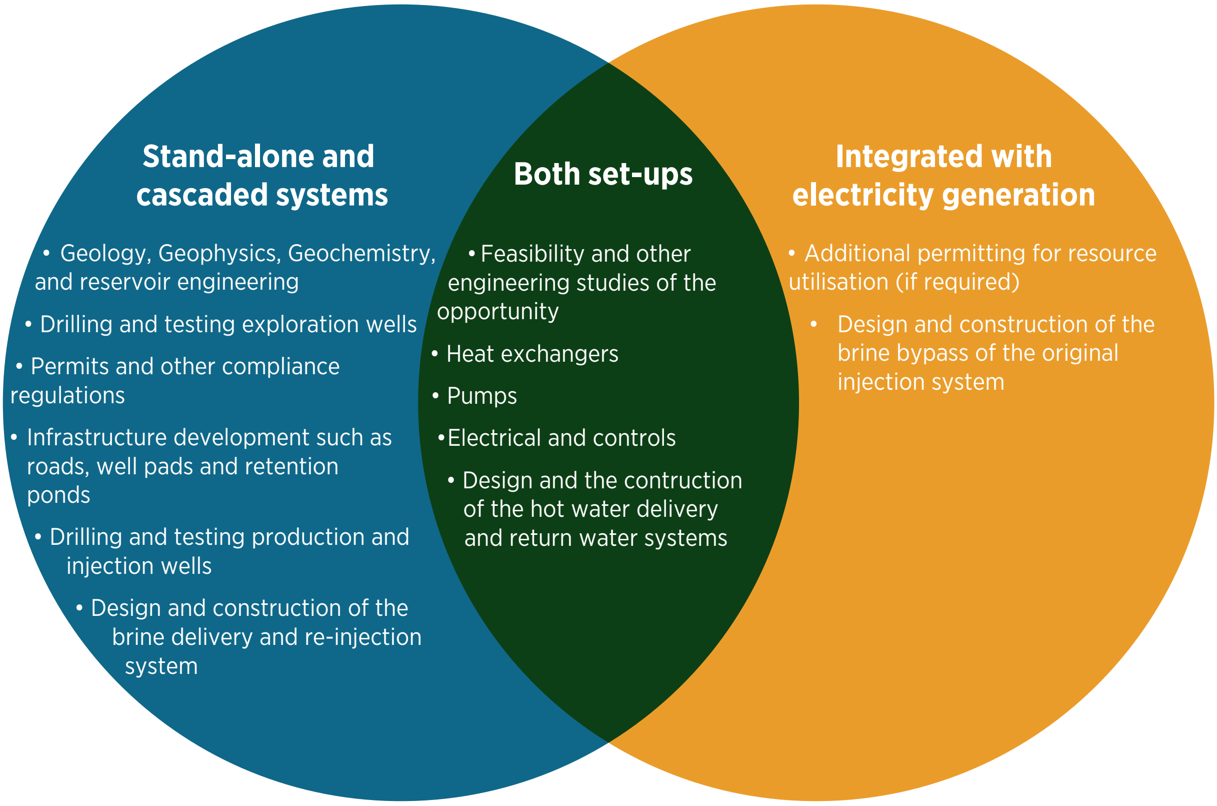
The main capital costs are incurred in undertaking the following activities: exploration studies such as geological, geochemical, geophysical and heat flow measurements; feasibility studies; obtaining permits and other statutory requirements; drilling and testing of exploration, production and re-injection wells (where required); development of energy delivery systems (pipelines, heat exchangers, pumps, connection to the customer, etc.); and development of infrastructure such as roads and well pads.

The main operating costs include the following: payment of salaries and wages for staff; electricity used to run water pumps; drilling of make-up wells; maintenance of equipment; interest and bank fees; and depreciation of assets (non-cash expense).

Geothermal heat can be supplied to the agri-food applications in a stand-alone, cascaded system, or through a system that integrates direct-use with electricity generation. As described in section 3.4, the stand-alone and cascaded systems may incur costs related to exploration studies and drilling, while the systems that are integrated with electricity generation do not. Figure 9 illustrates the key elements of the CAPEX, which are unique to each set-up and those that overlap among them. Notably, in the case of stand-alone and cascaded systems, the CAPEX elements could be similar to those for the integrated system if they use an existing well that was drilled for other purposes.

> "A sustainable heating tariff should account for all the costs incurred in generating the heat during a given period, in addition to a markup to pay back the investment cost within a reasonable period."

Figure 9 CAPEX elements for different geothermal direct-use set-up options



In determining the heating tariff, it is first necessary to estimate the amount of energy that should be delivered to the direct-use application during the period under consideration. The estimate can be based on the demand for energy from the direct-use application for an ongoing operation, or it can be estimated from demand based on alternative fuels. Since it is assumed that thermal energy will be supplied as hot water or steam, the delivered energy may be represented as the total volume of hot water/steam to be supplied to customers at a given temperature (*i.e.* cubic metres). Alternatively, the extractable thermal energy in the hot water could be represented in kilowatt-hours.

The second step is to approximate the cost expected to be incurred in supplying thermal energy to direct-use applications over a given period. This involves amortising the capital costs over the lifetime of the project and then allocating a proportionate cost to the period under consideration. The expected operating costs for the same period should also be determined.

Thirdly, the revenue expected to be generated from the project over the same period is approximated. This involves establishing a reasonable rate of return or profit margin, while striking a balance between affordability of energy to the customer and cost-sustainability to the supplier. The summation of the expected profit and the expected costs provides the estimated revenue from the project over the period under consideration.

Finally, the tariff can be determined by dividing the expected revenue by the estimated amount of energy to be generated and delivered to customers over the period under consideration.

A unique case with this approach may arise when dealing with systems that integrate direct use and electricity generation. In this case, most of the infrastructure as well as the exploration and drilling costs were paid for by the power plant owner/operator. Hence, only the CAPEX elements highlighted in Figure 9 as "integrated with electricity generation" and "both set-ups" needs to be incurred for the direct use operation. Similarly, during operation, some of the OPEX are paid for by the power plant. In this instance, the concept of cost sharing is introduced, whereby all of the CAPEX and OPEX for the combined facility (power generation and the direct-use application) are shared between the power generation activity and the thermal energy production. Hence, the portion of the shared cost assigned to the direct-use operation should be reflected in the heat tariff.

Potential issues may arise from a split operation when the geothermal resource and the direct-use facility are not owned and operated by one entity, as the interests of the parties may differ. Whereas the direct-use facility owner is interested in paying the least for the thermal energy from the geothermal resource, the resource owner is more concerned with the long-term viability of the resource and may also want to secure a high price for the thermal energy sold. To avoid such conflicts, it is important that the two parties agree in advance on the terms and conditions to apply through the term of the heat purchase agreement (HPA) (see discussion below: Key elements of a heat purchase agreement).

Market-based approach

This approach is based on the cost of energy supply from alternative sources. In the case of existing facilities, natural gas, firewood (with the added negative impact on the environment) or diesel oil are typically the fuels of choice for most agri-food applications in developing countries (see Table 6). In this case, the amount of thermal energy required over a given period should be calculated based on the fuel consumption, and the cost of supplying that energy established. The amount of thermal energy from a geothermal resource required to replace the alternative fuel is then established. If the temperature of the geothermal resource meets the minimum/maximum inlet temperature for the customer, the flow rate required to satisfy the thermal needs of the customer is then determined.

In cases where there is no existing facility, but there is potential to use local geothermal resources for agri-food applications, it makes sense to conduct feasibility studies to evaluate future demand for geothermal heat.

The cost of supplying thermal energy to agri-food facilities using fuels is then used as the benchmark for calculating the tariff for geothermal heat. In order for geothermal energy to be competitive against the alternative fuels, the geothermal heating cost should not exceed that of the alternative fuels. Therefore, to ensure sustainability of the market-based tariff and to ensure that the project meets all its costs of operation and maintenance, the methodologies related to the cost-based tariff may be useful to establish the minimum (floor) price. In case the floor price so determined is higher than the market-based price, it may be necessary to consider introducing subsidies to cover the difference between the two prices.

A full feasibility study is highly recommended before any investment decisions are made.

Key elements of a heat purchase agreement

As the direct-use geothermal industry in agri-food systems is still in its nascent stages, and most of the existing facilities today are stand-alone projects or integrated with electricity generation – usually by the owner of the power plant – a heat purchase agreement (HPA) is not a common contract. However, as multiple customers get connected to the geothermal resource for their process heating needs, an HPA to regulate the operation may become a necessity. Key elements of a typical HPA include:

- **Parties and duration:** Who are the parties to the HPA and how long will the contract be effective? It is preferable to enter into longer-term agreements to recover the investment costs, which are usually high.

- **Price for a unit of energy and how to measure it:** Customers could be billed based on energy consumed (kilowatt-hours) or volume of hot water supplied (cubic metres). Irrespective of the billing basis adopted, higher temperature supply is considered more valuable (since it is easier and cheaper to extract heat from higher-temperature resources), hence the tariff could be tied to the inlet temperature to the customers' premises.

- **Tariff structure:** The tariff paid by the customer could be calculated based on purely consumption; capacity and consumption; or other mechanisms. In a consumption-based structure, the customer pays only for the amount of energy / hot water utilised, whereas in the capacity-consumption structure, there is a fixed charge in addition to the cost of consumption.

- **Minimum and maximum temperatures and amounts:** Depending on the energy requirements of the customer, a minimum/maximum inlet temperature as well as an appropriate supply flow rate should be established between the customer and the energy supplier.

- **Obligations of the parties:** The HPA describes what each party is committed to – for example, the resource/power plant owner is committed to providing the energy at the agreed-upon quantity and quality; the recipient of the energy is committed to paying for it.

- Mechanism to deal with **underperformance** on one hand and non-payment on the other hand.

- **Dispute resolution mechanisms** – for example, arbitration or court as well as the jurisdiction and governing laws.

- **Other terms and conditions** that need to be considered including legal/commercial aspects of the operation such as warranties and securities, among others.

The market-based approach is by nature a moving target. When the cost of the alternative fuels increases considerably, there is potential for the supplier to make higher returns. On the other hand, when the demand and prices for alternative fuels subsides, this will result in geothermal heat prices dropping, and the energy supplier may incur losses. In the case of a cost-based tariff, the cost of energy varies mainly with the costs associated with developing and operating the energy supply system.

A key benefit for developing the heat tariff is that the supplier can establish long-term contracts for heat supply with customers and use them as a basis for obtaining financing.

REFERENCES

Alfaro, A.L. (2021), "Beyond (agro) industrial solutions: Approaching direct use of geothermal energy with a social and economic perspective", *World Geothermal Congress 2020, 1 March – October 2021*, *https://pangea.stanford.edu/ERE/db/WGC/Abstract.php?PaperID=5271*.

Ben Mohamed, M. (2015), "Geothermal energy development: The Tunisian experience", *Proceedings of the World Geothermal Congress 2015, Melbourne, Australia, 19-25 April*, *https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/28008.pdf*.

Blair, A. *et al.* (2018), "Beyond baseload: The future of geothermal", *Proceedings of the 40th New Zealand Geothermal Workshop, Taupo, New Zealand, 14-16 November*, *www.researchgate.net/publication/340267288_BEYOND_BASELOAD_THE_FUTURE_OF_GEOTHERMAL*.

Boda, K. (2016), *Fostering geothermal development in Hungary: Opportunities and bottlenecks*, United Nations University Geothermal Training Programme, *https://orkustofnun.is/gogn/unu-gtp-report/UNU-GTP-2016-12.pdf*.

Boissavy, C. (2020), *Report reviewing existing insurance schemes for geothermal*, Georisk, Brussels, *www.georisk-project.eu/wp-content/uploads/2020/02/D3.1_Report-reviewing-geothermal-risk-mitigation-schemes-v2.pdf*.

Boyd, L., Sifford, A. and Lund, J. (2015), "The United States of America country update 2015", *Proceedings of the World Geothermal Congress 2015, Melbourne, Australia, 19-25 April*, *www.geothermal-energy.org/pdf/IGAstandard/WGC/2015/01009.pdf*.

Camargo, G. *et al.* (2013), "Energy use and greenhouse gas emissions from crop production using the farm energy analysis tool", *BioScience*, Vol. 63/4, Oxford University Press, pp. 263-273, *http://dx.doi.org/10.1525/bio.2013.63.4.6*.

Casimiro, E. and Pastrana, E. (1996), "Wood and fruit drying in the Los Azufres Geothermal Field, Mexico", *Geothermal Resources Council Transactions*, Vol. 20, Geothermal Resources Council, Mount Laurel, pp. 563-566.

CCER (2021), "About us", Renewable Energy Food Community of Tuscany, *www.ccer-toscana.it/en/community* (accessed 16 December 2021).

China-NDC (2021), *China's achievements, new goals and new measures for Nationally Determined Contributions*, United Nations Framework Convention on Climate Change, Bonn, *https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/China%20First/China%E2%80%99s%20Achievements,%20New%20Goals%20and%20New%20Measures%20for%20Nationally%20Determined%20Contributions.pdf*.

CIP (2021), *IRENA for the Climate Investment Platform: Unlocking renewable energy investments through project facilitation*, International Renewable Energy Agency, Abu Dhabi.

Climo, M. (2015), *Geothermal direct use in New Zealand: Industrial heat park opportunities*, GNS Science, Taupo, *www.gns.cri.nz/content/download/11036/59104/file/Geothermal%20direct%20use%20in%20NZ%20-%20Industrial%20Heat%20Park%20Opportunities.pdf*.

Climo, M. and Carey, B. (2011), *Low temperature geothermal energy roadmap: fostering increased use of New Zealand's abundant geothermal resources*, GNS Science, Taupo, *www.gns.cri.nz/content/download/7569/41292/file/Low%20Temperature%20Geothermal%20Energy%20Roadmap%202011.pdf*.

CTCN (2020), *Development of a national roadmap for the use of low-temperature geothermal energy for thermal conditioning in the residential, industrial and commercial services sectors in Uruguay*, Climate Technology Centre & Network, *www.ctc-n.org/system/files/dossier/3b/ENGLISH_E2.1%20-%20Mapping%20of%20stakeholders.pdf*.

Daysh, S. *et al.* (2020), "2015-2020 New Zealand Country Update", *Proceedings of the World Geothermal Congress 2020, Reykjavik, 26 April – 2 May*, *www.researchgate.net/publication/341220788_2020_New_Zealand_Country_Update*.

Dickson, M.H. and Fanelli, M. (2004), "What is geothermal energy", *International Geothermal Association*, Bochum.

Drijver, B., Bakema, G. and Oerlemans, P. (2019), "State of the art of HT-ATES in The Netherlands", *Proceedings of the European Geothermal Congress 2019, The Hague, 11-14 June*, *https://europeangeothermalcongress.eu/wp-content/uploads/2019/07/289.pdf*.

Eni (2016), "Geothermal stories: What can we do with the hot water?" *Eni School Energy & Environment*, *www.eniscuola.net/en/2016/12/22/geothermal-stories-what-can-we-do-with-the-hot-water* (accessed 2 March 2022).

Ephraim, J. (2020), "New Zealand and the OECS to collaborate on direct uses of geothermal energy", Organization of Eastern Caribbean States, *https://pressroom.oecs.org/new-zealand-and-the-oecs-to-collaborate-on-direct-uses-of-geothermal-energy* (accessed 2 March 2022).

ESMAP (2019), *Gender equality in the geothermal energy sector: Road to sustainability*, World Bank Energy Sector Management Assistance Program, Washington, DC, *https://openknowledge.worldbank.org/bitstream/handle/10986/31607/Gender-Equality-in-The-Geothermal-Energy-Sector-Road-to-Sustainability.pdf*.

ETAF (2021), "About ETAF", Energy Transition Accelerator Financing Platform, *https://etafplatform.org/About* (accessed 17 December 2021).

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

FAO (2018), *Investing in sustainable energy technologies in the agri-food sector*, Food and Agriculture Organization of the United Nations, Rome, *www.fao.org/3/i9077en/I9077EN.pdf*.

FAO (2015), *Uses of geothermal energy in food and agriculture: Opportunities for developing countries*, Food and Agriculture Organization of the United Nations, Rome, *www.fao.org/3/i4233e/I4233E.pdf*.

FAO (2012), *Review of GHG calculators in agriculture and forestry sectors: A guideline for appropriate choice and use of landscape-based tools*, Food and Agriculture Organization of the United Nations, Rome, *www.fao.org/fileadmin/templates/ex_act/pdf/ADEME/Review_existingGHGtool_VF_UK4.pdf*.

FAO and GIZ (2019), *Measuring impacts and enabling investments in energy-smart agrifood chains*, Food and Agriculture Organization of the United Nations and Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH, Rome and Eschborn, *www.fao.org/3/ca4064en/ca4064en.pdf*.

FAO and GIZ (2018), *Costs and benefits of clean energy technologies in the milk, vegetable and rice value chains*, Food and Agriculture Organization of the United Nations and Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH, Rome and Eschborn, *www.fao.org/3/I8017EN/i8017en.pdf*.

Fraser, S. (2013), *Report presenting proposals for improving the regulatory framework for geothermal electricity: Annex 1 overview of national rules for licensing for geothermal*, Geoelec, Brussels, *www.geoelec.eu/wp-content/uploads/2011/09/D4.1-A.1-Overview-of-National-Rules-of-Licencing.pdf*.

GEA (2010), *Green jobs through geothermal energy*, Geothermal Energy Association, Washington, DC, *www.geothermal.org/sites/default/files/2021-02/Green_Jobs_Through_Geothermal_Energy.pdf*.

GIZ (2020a), *EEstudio de Mercado: Bombas de Calor Geotermicas y Aerotermicas en Chile (Market Study: Geothermal and Aerothermal Heat Pumps in Chile)*, Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH, Bonn, *www.energia.gob.cl/sites/default/files/estudio_de_mercado.pdf*.

GIZ (2020b), "Making direct use of geothermal energy in Central America", Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH, *www.giz.de/en/worldwide/78071.html* (accessed 2 March 2022).

GIZ (2020c), *Informe de Cierre 2016-2020: Resultados Alcanzados por el Proyecto: Fomento de la Geotermia en Centroamérica (Closing Report 2016-2020: Results Achieved by The Project: Promotion of Geothermal Energy in Central America)*, Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH, Bonn and Eschborn.

GIZ and SICA (2020c), *Geothermal direct use for a crop drying centre in Guatemala*, Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH and Sistema de la Integración Centroamericana, Bonn, *www.sica.int/download/?124297*.

GNS Science (2021), "Geothermal Use Map", *New Zealand Geothermal Use Database*, *http://data.gns.cri.nz/geothermal/wms.html* (accessed 15 December 2021).

González, A. *et al.* (2019), *Advancing gender in the environment: Gender-responsive geothermal generation – powering energy and social benefits in El Salvador*, IUCN Global Gender Office and US Agency for International Development, Washington, DC, *www.usaid.gov/sites/default/files/documents/1865/IUCN-USAID_LaGeo_Gender-Responsive_Geothermal_Generation_0.pdf*.

Gude, V.G. (2016), "Geothermal source potential for water desalination: Current status and future perspective", *Renewable and Sustainable Energy Reviews*, Vol. 57, Elsevier, Amsterdam, pp. 1038-1065, *https://doi.org/10.1016/j.rser.2015.12.186*.

Guglielmetti, L. (2021), "Boosting the sustainability of the agri-food sector by the integration of geothermal energy: Benefits and gaps", Webinar on Scaling-up Geothermal Direct Use for Industrial Applications in Latin America, International Renewable Energy Agency and Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH.

Guglielmetti L. *et al.* (2020), "Map of Geothermal food – an overview of applications of geothermal energy for food production", *Proceedings of the World Geothermal Congress 2020+1, Reykjavik, 24-27 October*.

Hachicha, M. and Ben Aissa, I. (2014), "Managing salinity in Tunisian Oases", *Journal of Life Sciences*, Vol. 8, No. 9, Elsevier, Amsterdam, pp. 775-782, *http://dx.doi.org/10.17265/1934-7391/2014.09.007*.

Haehnlein S., Bayer, P. and Blum, P. (2010), "International legal status of the use of shallow geothermal energy", *Renewable and Sustainable Energy Reviews*, Vol. 14, No. 9, Elsevier, Amsterdam, pp. 2611-2625, *https://doi.org/10.1016/j.rser.2010.07.069*.

Haustak Dried Fish Products (2021), "Dried fish products: Haustak", *https://www.haustak.is/index.php/general-for-haustak/3-afurdir* (accessed 15 December 2021).

Hawker-Green, K., Blair, A. and McCaw, M. (2020), "Geothermal is the solution: How a small town in New Zealand (Taupō) is growing the prosperity of its people using its geothermal resources", *Proceedings of the World Geothermal Congress 2020+1, Reykjavik, 26 April – 2 May*.

Hein, T. (2012), "100 percent renewably powered Alaskan greenhouse", Greenhouse Canada, *www.greenhousecanada.com/100-per-cent-renewably-powered-geothermal-alaskan-greenhouse-again-showcased-at-energy-fair-20227* (accessed 2 March 2022).

Hickson, C.J. *et al.* (2016), *Direct-use of geothermal resources in British Columbia*, Geoscience BC, Vancouver, *www.geosciencebc.com/projects/2015-022*.

Huttrer, G.W. (2020), "Geothermal power generation in the world 2015-2020 update report", *Proceedings of the World Geothermal Congress 2020, Reykjavik, 26 April – 2 May*, *www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01017.pdf*.

Iceland Chamber of Commerce (2020), *The Icelandic economy 2020, Reykjavik*, *www.government.is/library/09-Embassies/New-York-Consulate/ICEEcon2020-210920-Web_Final.pdf*.

IRENA (2021a), *World energy transitions outlook: 1.5°C pathway*, International Renewable Energy Agency, Abu Dhabi, *www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_World_Energy_Transitions_Outlook_2021.pdf*.

IRENA (2021b), *Integrating low-temperature renewables in district energy systems: Guidelines for policymakers*, International Renewable Energy Agency and Aalborg University, Abu Dhabi and Copenhagen, *www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/March/IRENA_District_Energy_Systems_2021.pdf*.

IRENA (2020), *Geothermal development in Eastern Africa*, International Renewable Energy Agency, Abu Dhabi, *www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Geothermal_Eastern_Africa_2020.pdf*.

IRENA (2019), *Accelerating geothermal heat adoption in the agri-food sector: Key lessons and recommendations*, International Renewable Energy Agency, Abu Dhabi, *www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Jan/IRENA_Geothermal_agri-food_2019.pdf*.

IRENA (2018), *Global energy transformation: A roadmap to 2050*, International Renewable Energy Agency, Abu Dhabi, *www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Apr/IRENA_Report_GET_2018.pdf*.

IRENA (2016a), *Solar pumping for irrigation: Improving livelihoods and sustainability*, International Renewable Energy Agency, Abu Dhabi, *www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Solar_Pumping_for_Irrigation_2016.pdf.*

IRENA (2016b), *Renewable energy benefits: Decentralised solutions in the agri-food chain*, International Renewable Energy Agency, Abu Dhabi, *www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Decentralised_solutions_for_agrifood_chain_2016.pdf*.

IRENA (2015), *Renewable energy in the water, energy and food nexus*, International Renewable Energy Agency, Abu Dhabi, *www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/IRENA_Water_Energy_Food_Nexus_2015.pdf*.

IRENA and FAO (2021), *Renewable energy for agri-food systems – towards the Sustainable Development Goals and the Paris Agreement*, International Renewable Energy Agency and Food and Agriculture Organization of the United Nations, Abu Dhabi and Rome, *www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Nov/IRENA_FAO_Renewables_Agrifood_2021.pdf*.

IRENA and ILO (2021), *Renewable energy and jobs – annual review 2021*, International Renewable Energy Agency and International Labour Organization, Abu Dhabi and Geneva, *www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Oct/IRENA_RE_Jobs_2021.pdf*.

IRENA, IEA and REN21 (2020), *Renewable energy policies in a time of transition: Heating and cooling*, International Renewable Energy Agency, International Energy Agency and Renewable Energy Policy Network for the 21st Century, Abu Dhabi and Paris, *www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_IEA_REN21_Policies_Heating_Cooling_2020.pdf*.

Kenya Geothermal Development Company (2020), "GDC, Nakuru Country sign Collaboration Framework Agreement", *www.gdc.co.ke/blog/gdc-nakuru-county-sign-collaboration-framework-agreement* (accessed 23 April 2021).

Kenyan Tribune (2020), "KenGen's Olkaria Geothermal Power Plant lower evacuation costs causes competitor to lower electricity tariff", *www.kenyantribune.com/kengens-olkaria-geothermal-plant-lower-evacuation-costs-causes-competitor-to-lower-electricity-tariff* (accessed 23 April 2021).

Kerecis (2021), "Fish skin technology", *www.kerecis.com* (accessed 15 December 2021).

Kinyanjui, S. (2013), *Direct use of geothermal energy in Menengai, Kenya: Proposed geothermal spa and crop drying*, United Nations University Geothermal Training Programme, *https://rafhladan.is/bitstream/handle/10802/7392/UNU-GTP-2013-09.pdf*.

Kojima, M. (2017), *Energy subsidies: Identifying and quantifying energy subsidies*, World Bank, Washington, DC, *https://openknowledge.worldbank.org/handle/10986/28926*.

Limberger, J. *et al.* (2018), "Geothermal energy in deep aquifers: A global assessment of the resource base for direct heat utilization", *Renewable and Sustainable Energy Reviews*, Vol. 82, No. 1, Elsevier, Amsterdam, pp. 965-981, *https://doi.org/10.1016/j.rser.2017.09.084*.

Lund, J. (1997), "Milk pasteurization with geothermal energy", *Geo-Heat Center Quarterly Bulletin*, Vol. 18, Oregon Institute of Technology, Klamath Falls, *https://oregontechsfstatic.azureedge.net/sitefinity-production/docs/default-source/geoheat-center-documents/quarterly-bulletin/vol-18/art44e96ee4362a663989f6fff0000ea57bb.pdf*.

Lund, J. and Toth, A. (2020), "Direct utilization of geothermal energy 2020 worldwide review", *Proceedings of the World Geothermal Congress 2020*, Reykjavik, 26 April – 2 May, *www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01018.pdf*.

Mannvit (2020), "Algaennovation: Vaxa Impact Nutrition", *www.mannvit.com/projects/algaennovation* (accessed 7 December 2022).

Masum, M. and Akbar, A. (2020), "The Pacific Ring of Fire is working as a home country of geothermal resources in the world", *IOP Conference Series Earth and Environmental Science*, Vol. 249, No. 1, IOP Publishing, Bristol, p. 012020, *http://dx.doi.org/10.1088/1755-1315/249/1/012020*.

McDonagh, V. (2019), "Iceland's largest aquaculture centre opens", *Fish Farmer*, *www.fishfarmermagazine.com/news/icelands-largest-aquaculture-centre-opens* (accessed 23 April 2021).

Merida, L. (1999), "Curing blocks and drying fruit in Guatemala", *Geo-Heat Center Quarterly Bulletin*, December, Oregon Institute of Technology, Klamath Falls, *https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.535.3232&rep=rep1&type=pdf*.

Ndetei, C. (2020), *Environmental & social impact assessment report for the proposed Energy Research & Development Centre and corporate archive building in Murang'a South Sub-county, Murang'a County*, Kenya Electricity Generating Company, PLC, Nairobi, *www.nema.go.ke/images/Docs/EIA_1820-1829/ESIA_1825%20R%20%20D%20Lab%20and%20Corporate%20Archive%20-%20Tana_SR%202073-min.pdf*.

Ndetei, C. (2016), "Opportunities for direct utilization of geothermal energy in Eburru Area, Nakuru County in Kenya", *Proceedings of the 6th African Rift Geothermal Conference Addis Ababa, November*, *http://theargeo.org/fullpapers/OPPORTUNITIES%20FOR%20DIRECT%20UTILIZATION%20OF%20GEOTHERMAL%20%20ENERGY%20IN%20EBURRU%20AREA.pdf.*

NREL (2014), *US Department of Energy Geothermal Technologies Program: Direct Use*, National Renewable Energy Laboratory, US Department of Energy, Washington, DC, *www.nrel.gov/docs/fy04osti/36316.pdf*.

NZGA (2017), *Geoheat strategy for Aotearoa New Zealand: 2017-2030*, New Zealand Geothermal Association, *www.nzgeothermal.org.nz/geothermal-in-nz/geoheat*.

Paiz, C. (2021), "Proyecto Geotermico San Michkael, Guatemala", Webinar on Scaling-up Geothermal Direct Use for Industrial Applications in Latin America, International Renewable Energy Agency and Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH.

Peerdeman, C. (2017), *An environmental and economical case study of local beer production in Tuscany – a scenario approach*, Master of Science Thesis, Universidad de Zaragoza, Spain.

Presidency of the Republic of Turkey Investment Office (2020), *Guide to state incentives for investments in Turkey*, Ankara, *investturkey.or.jp/wp-content/uploads/2021/01/guide-to-state-incentives-for-investments-in-turkey.pdf*.

Presidency of the Republic of Turkey Investment Office (2019), *Guide to investing in the Turkish renewable energy sector*, Ankara, *https://www.invest.gov.tr/en/library/publications/lists/investpublications/guide-to-investing-in-turkish-renewables-energy-sector.pdf*.

Ramsak, P. (2020), "Geothermal energy in the Netherlands", Webinar Energy Solutions for Cities of the Future, International Renewable Energy Agency, 14 May, *https://irena.org/-/media/Files/IRENA/Agency/Events/2020/May/Developing-enabling-frameworks-for-geothermal-heating---The-case-of-The-Netherlands.pdf*.

Rangel, M.E. (1998), "Mushroom growing project at the Los Humeros, Mexico Geothermal Field", *Geo-Heat Center Quarterly Bulletin*, Vol. 19, No. 4, Oregon Institute of Technology, Klamath Falls, *https://oregontechsfcdn.azureedge.net/oregontech/docs/default-source/geoheat-center-documents/quarterly-bulletin/vol-19/art4.pdf*.

Richter, A. (2020a), "ThinkGeoEnergy Global Geothermal Power Plant Map", *ThinkGeoEnergy*, *www.thinkgeoenergy.com/map* (accessed 23 April 2021).

Richter, A. (2020b), "Geothermal allowing growth of tomatoes in greenhouses in coldest part of Turkey", *ThinkGeoEnergy*, *www.thinkgeoenergy.com/geothermal-allowing-growth-of-tomatoes-in-greenhouses-in-coldest-part-of-turkey* (accessed 23 April 2021).

Richter, A. (2019a), "Geothermal heat key element of new aquaculture facilities in the West Fjords of Iceland", *ThinkGeoEnergy*, *www.thinkgeoenergy.com/geothermal-heat-key-element-of-new-aquaculture-facilities-in-the-west-fjords-of-iceland* (accessed 7 December 2021).

Richter, A. (2019b), "New loan product announced for greenhouse development in Turkey", ThinkGeoEnergy, *www.thinkgeoenergy.com/new-loan-product-announced-for-greenhouse-development-in-turkey* (accessed 23 April 2021).

Richter, A. (2017), "Successful Maori-owned dairy operations utilising geothermal, New Zealand", ThinkGeoEnergy, *www.thinkgeoenergy.com/successful-maori-owned-dairy-operations-utilising-geothermal-new-zealand* (accessed 7 December 2021).

Rodríguez, J.A. and Herrera, A. (2005), "El Salvador country update", *Proceedings World Geothermal Congress 2005 Antalya, Turkey, 24-29 April 2005*, pp. 24-29, *www.geothermal-energy.org/pdf/IGAstandard/WGC/2005/0108.pdf*.

Royal Society of Chemistry (2018), "New protein from geothermal microorganism could aid fight against antimicrobial resistance", *www.rsc.org/news-events/journals-highlights/2018/sep/geothermal-antimicrobial-protein* (accessed 7 December 2021).

SENER and CeMIE-Geo (2018), *Mapa de Ruta Tecnológica: Usos Directos del Calor Geotérmico (Technology Roadmap: Direct Uses of Geothermal Heat),*, Secretaria de Energía and Centro Mexicano de Innovación en Energía Geotérmica, Mexico City, *www.gob.mx/cms/uploads/attachment/file/416191/MRT_UDCG_Final.pdf*.

Shirley, R. *et al*. (2021), "Identifying high-priority impact areas for electricity service to farmlands in Uganda through geospatial mapping", *Journal of Agriculture and Food Research*, Vol. 5, Elsevier, Amsterdam, p. 100172 *https://doi.org/10.1016/j.jafr.2021.100172*.

Sims, R., Flammini, M., Puri, M. and Bracco, S. (2015), *Opportunities for agri-food chains to become energy-smart*, Food and Agriculture Organization of the United Nations and Powering Agriculture: An Energy Grand Challenge for Development (PAEGC), Rome.

Sommaruga, A., Eichenberger, U. and Marillier, F. (2012), *Seismic atlas of the Swiss Molasse Basin*, edited by the Swiss Geophysical Commission, Matér. Géol. Suisse, *Géophys*, Vol. 44, *www.geologieportal.ch/en/themes/fundamentals-of-geology/geophysics/seismic-atlas.html*.

SSEK (2020, December 2), "Indonesia's Omnibus Law puts focus on direct use of geothermal resources", Soewito Suhardiman Eddymurthy Kardono, *www.conventuslaw.com/report/indonesias-omnibus-law-puts-focus-on-direct-use-of*.

Stichting Platform Geothermie (2018), *Master plan geothermal energy in the Netherlands: A broad foundation for sustainable heat supply*, Government of the Netherlands, Ministry of Economic Affairs and Climate Policy, Amsterdam, *https://geothermie.nl/images/bestanden/Masterplan_Aardwarmte_in_Nederland_ENG.pdf*.

Surana, T. *et al*. (2010), "Development of geothermal energy direct use in Indonesia", *Proceedings of the World Geothermal Congress 2010, Bali, 25-29 April*, *www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/2824.pdf*.

Thorarinsdottir, R. *et al*. (2020), "Geothermal energy for circular food production – GEOFOOD", *Forschung and Entwicklung*, *https://geofoodproject.eu/wp-content/uploads/2020/09/Geothermal-energy-for-circular-food-production---GEOFOOD.pdf*.

UN DESA (2021), *World social report 2021: Reconsidering rural development*, United Nations Department of Economic and Social Affairs, New York, *www.un.org/development/desa/dspd/wp-content/uploads/sites/22/2021/05/World-Social-Report-2021_web_FINAL.pdf*.

USAID and GDC (2014), *Direct-use guidebook – a case study from Kenya*, US Agency for International Development and Kenya Geothermal Development Company, Washington, DC and Nairobi.

Uwera, J. *et al*. (2015), "Design of a cooling system using geothermal energy for storage of agricultural products with emphasis on Irish potatoes in Rwanda, Africa", *Geothermal Resources Council Transactions*, Vol. 39, Geothermal Resources Council, Mount Laurel, *https://publications.mygeoenergynow.org/grc/1032145.pdf*.

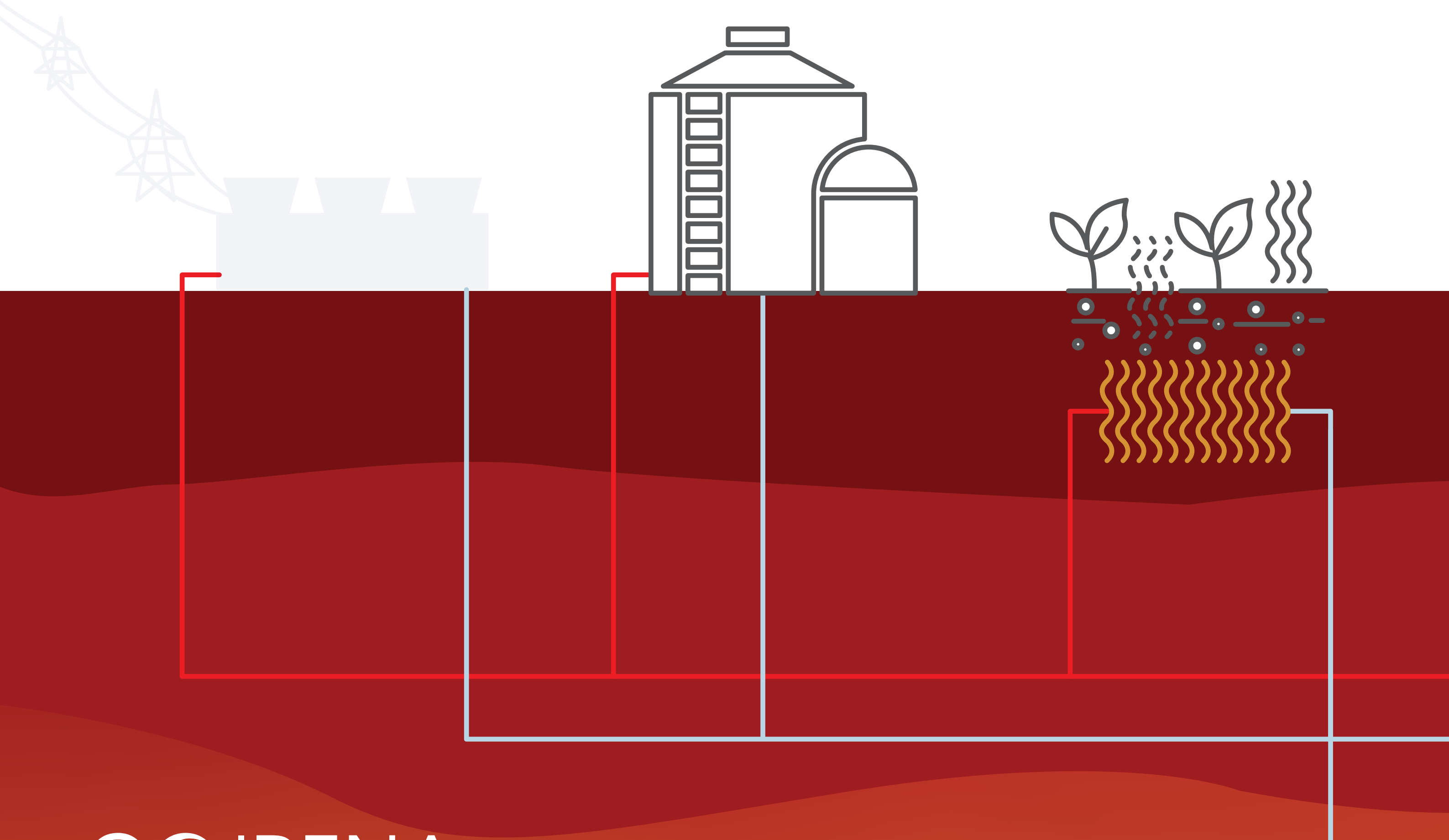
Vrijlandt, M. *et al*. (2019), "ThermoGIS update: A renewed view on geothermal potential in the Netherlands", *Proceedings of the European Geothermal Congress 2019, The Hague, 11-14 June*, *www.thermogis.nl/sites/default/files/2019-09/Vrijlandt_etal_ThermoGIS_Paper-EGC-2019.pdf*.

Wairakei Research Centre (2020), *Renewable geothermal energy used in milk processing*, Wairakei, *www.gns.cri.nz/gns/content/download/12757/67970/file/Milk-Processing%20-Miraka.pdf*.

Williams, C.F., Reed, M.J. and Anderson, A.F. (2011), "Updating the classification of geothermal systems", *Proceedings of the Thirty-Sixth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, 31 January – 2 February*, *https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2011/williams.pdf*.

World Bank (2021), "CL Technical Assistance for Geothermal Development in Chile", World Bank Project ID P152820, *https://projects.worldbank.org/en/projects-operations/project-detail/P152820* (accessed 2 March 2022).

World Bank (2018), *Opportunities and challenges for scaling up geothermal development in Latin America and the Caribbean*, Washington, DC, *https://openknowledge.worldbank.org/handle/10986/30895* License: CC BY 3.0 IGO.



IRENA
International Renewable Energy Agency

P.O. Box 236
Abu Dhabi, United Arab Emirates
Tel: +971 2 4179000
www.irena.org