IGA

IRENA
International Renewable Energy Agency

GLOBAL GEOTHERMAL
MARKET AND TECHNOLOGY ASSESSMENT

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About IRENA

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

About IGA

The International Geothermal Association (IGA), is the leading global platform on geothermal energy, serving as a hub for networking opportunities aimed at promoting and supporting global geothermal development. With industry partners, the IGA sets standards, matures the technology agenda and nurtures entrepreneurs engaged in clean technology. With its four pillars; Visibility, Sustainability, Partnerships and Authority, the IGA is committed to push geothermal as a gamechanger for achieving Sustainable Development Goal #7: providing affordable, clean, baseload energy for all.

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Abbreviations

AGS	advanced geothermal system
DDU	deep direct use
EGEC	European Geothermal Energy Council
EGS	enhanced geothermal system
EJ	exajoule
ESMAP	Energy Sector Management Assistance Programme
EU	European Union
FiT	feed-in tariff
GDH	geothermal district heating
GEORISK	Geothermal Risk project
GHP	geothermal heat pump
GIZ	German Agency for International Cooperation
GRMF	Geothermal Risk Mitigation Facility
GW	gigawatt
GW_e	gigawatt electric
GW_{th}	gigawatt thermal
IDB	Inter-American Development Bank
IEA	International Energy Agency
IGA	International Geothermal Association
IRENA	International Renewable Energy Agency
JPY	Japanese yen
km	kilometre
KW_e	kilowatt electric
kWh	kilowatt hour
LCOE	levelised cost of electricity
mg/L	milligrammes per litre
MiRiG	Geothermal Risk Management Programme (Chile)
MW_e	megawatt electric

MW_{th}	megawatt thermal
NREL	National Renewable Energy Laboratory
ORC	organic Rankine cycle
PPA	power purchase agreement
PV	photovoltaic
REN21	Renewable Energy Policy Network for the 21st Century
RHC	Renewable Heating and Cooling
RSM	risk sharing mechanism
SDE	Stimulering Duurzame Energieproductie (Dutch subsidy for renewable energy)
SICA	Central American Integration System
TJ	terajoule
USD	United States dollar
US DoE	United States Department of Energy
UTES	Underground Thermal Energy Storage
YEKDEM	Yenilenebilir Enerji Kaynakları Destekleme Mekanizması (Turkish Renewable Energy Sources Support Mechanism)

Executive summary

The global use of renewable energy has grown substantially over the past decade, driven by increasing awareness of the effects of climate change and the urgency of cutting emissions of greenhouse gas by minimising the use of fossil fuels. Geothermal energy – a clean and reliable source of heat and electricity – will play a critical role in the sustainable and clean energy transition alongside other renewable energy sources.

This global assessment provides an overview of developments in the geothermal sector and the factors that are likely to shape the market in the near future. It provides recommendations to guide policy makers, governments, potential investors, development partners and other stakeholders on how to promote growth of the geothermal market, exploit the potential of geothermal energy and further expand geothermal's integration within global energy systems.

The report also reviews the status of geothermal technologies, with reference to new technological approaches and developments that have the potential to scale up the use of geothermal energy. Various markets were analysed to establish the place of geothermal in the global energy mix. The assessment revolves around the following questions:

- What major changes have occurred in the geothermal industry in recent years?
- What are the key trends in the geothermal sector?
- Which areas of geothermal development are expected to drive growth in the coming years?
- How is the global energy sector affecting the geothermal industry?
- How have global and regional events and changes affected the geothermal industry?
- How can geothermal stakeholders stimulate and support further development of geothermal energy, building on existing and emerging market and technology trends?

Growth in the use of geothermal energy worldwide is driven by multiple factors. Energy demand is increasing as a result of economic growth. At the same time, to counteract climate change and to move towards a green economy, there is a global effort to transition to renewable energy sources. The demand for sustainable heat is also increasing, leading to a growing trend towards the use of geothermal resources for heating and cooling applications where technically and economically feasible.

Geothermal energy can and should play a greater role in meeting global energy needs – for both electricity and heating and cooling. Geothermal resources are widely available in areas with volcanic activity and in sedimentary basins. These attributes make geothermal a cost-effective and weather-independent source of renewable energy. With the recent accelerated deployment of variable power from wind and solar photovoltaic (solar PV), geothermal can contribute to the stabilisation of electricity grids.

In addition, geothermal energy technology has evolved beyond its focus on the electricity market to encompass a broader range of applications within the energy sector, including for sustainable heating and cooling.

So far, geothermal energy in electricity generation has grown at a modest rate of around 3.5% annually, reaching a total installed capacity of approximately 15.96 gigawatts electric (GW_e) in 2021. As a result, geothermal still accounts for a mere 0.5% of renewables-based installed capacity for electricity generation, and heating and cooling, globally.

But geothermal energy holds a unique place in the renewable energy ecosystem. In contrast to other renewable energy sources, it can provide both electricity and heat, as well as value-added mineral extraction. As an electricity source, it provides reliable generation with high plant efficiency, low greenhouse gas emissions and a small ecological footprint; it is a long-lasting sustainable source when properly managed. As a heat source, geothermal is scalable, has low operating costs, offers increased efficiency (by supplying heat directly) and reduces electricity consumption for heating and cooling. Here, too, it can provide a long-lasting source of sustainable heat.

Despite all these advantages, geothermal energy development faces challenges that have limited its development, even in regions endowed with easily accessible resources. Compared with other energy technologies, geothermal projects have longer project-development timelines, require higher upfront capital expenditures and face high risk during the early phases of exploration. Other challenges are related to financing, policy and regulatory frameworks, institutional and technical expertise, and technological advancement; these affect both electricity generation and heating.

However, there are many opportunities to overcome these challenges to market growth. Examples include expanding and interconnecting regional electricity grids to export geothermal electricity from countries with high potential; leveraging oil and gas expertise and technology to scale up geothermal development; recovering minerals from geothermal brines; increasing synergies with green hydrogen production; improving the efficiency of electricity production from medium-temperature geothermal resources; advancing research and development in enhanced geothermal systems, advanced geothermal systems, and supercritical resources; and promoting the use of geothermal resources for heating and cooling through accelerating the use of geothermal heat pumps, applying advanced district heating technology and expanding the use of geothermal heat in agriculture, food processing and industry.

The current situation – characterised by highly volatile oil and gas prices – provides renewed opportunities for geothermal energy to further develop as a strategic alternative in electricity generation, heating and cooling worldwide. However, national policies and regulations are key to the successful development of geothermal projects, and these strongly vary around the world.

Over the last several decades, the geothermal industry has developed in different ways around the world. Each region has distinct geography, geologic conditions, electricity and heat market conditions, policies and regulatory frameworks, development ambitions and implementation capacity. These factors have combined to produce different patterns in the development and use of geothermal resources.

Keeping these different patterns in mind, this report provides recommendations for addressing barriers to the development and utilisation of geothermal resources. These recommendations are summarised below and illustrated in Figure 1.

Promote widespread development and use of all available sources of geothermal energy. The significant potential of low- and medium-temperature resources, which are more widely available than high-temperature resources, remains largely untapped. These resources can be unlocked through exploration and development in volcanic zones and sedimentary basins, and through expanded utilisation of abandoned mines, oil and gas wells, shallow geothermal energy, energy storage (using underground thermal energy storage) and geothermal heat pumps.

Position geothermal energy as a key contributor to the achievement of sustainable development goals and climate action. Geothermal resources have many competitive advantages that are often overlooked. Industry players can devise appropriate messaging to highlight the multiple opportunities to use geothermal resources in sustainable, climate-friendly ways, including clean electricity generation, clean heating and cooling in the end-use sectors and extraction of minerals such as lithium for battery manufacture, as well as the other benefits of geothermal energy development, such as low greenhouse gas emissions over the project life cycle and low resource-utilisation footprints (*e.g.* low land and water requirements per unit of energy produced). At the same time, efforts to promote awareness could focus on increasing acceptance of geothermal energy among the general public and policy makers.

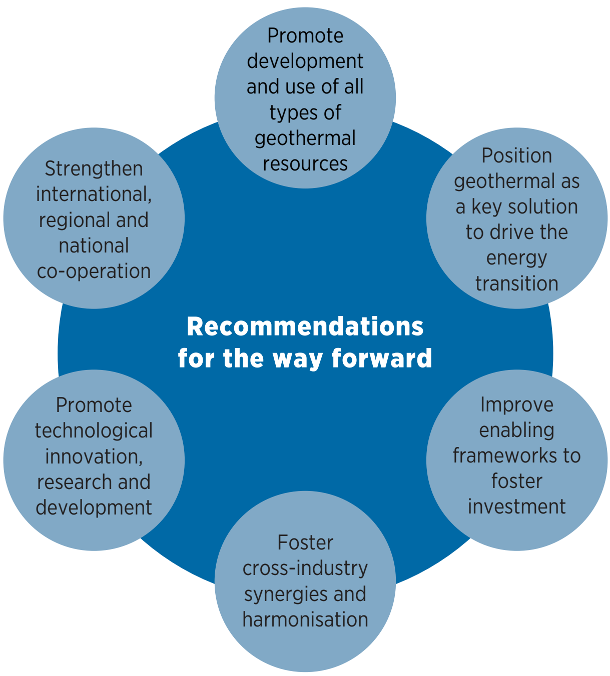
Improve enabling frameworks to foster investments in geothermal energy. Geothermal projects have high upfront costs and high resource risks, particularly in the early stages of development. These attributes constitute a major barrier to investment. Establishing new tailor-made risk mitigation schemes and enhancing existing ones will help developers mitigate the sub-surface geological risks of geothermal exploration. Furthermore, harmonising and simplifying licensing and permitting procedures for geothermal energy projects will facilitate project development in jurisdictions where they are presently viewed as too lengthy and complex. In addition, policy instruments and energy procurement procedures which take into consideration the intrinsic characteristics of geothermal resources will promote the integration of geothermal in energy systems.

Foster cross-industry synergies and harmonisation between geothermal and other sectors. The development and use of geothermal energy are entwined with a variety of other sectors – notably other renewable energies, carbon capture and storage, green hydrogen production, the extractives sector and end-use sectors including housing, industry and agri-food. Promoting synergy between geothermal and other sectors requires cross-sectoral collaboration in the form of sharing data, repurposing mining or oil and gas assets for geothermal energy production, building hybrid power plants and harmonising policies and regulations across those sectors, *e.g.* rights to access and extract co-located geothermal energy and minerals (such as lithium) recoverable from brines.

Promote technological innovation, research and development to scale up geothermal development. Various innovations and research and development initiatives are ongoing in different countries, with a focus on extraction of geothermal energy from hot dry rock (through an enhanced or engineered geothermal system), large-scale closed-loop systems (which are a type of advanced geothermal system), green hydrogen production, development of supercritical resources and mineral extraction from geothermal brines. Funding these initiatives through grants or equity is expected to enable the development of geothermal globally; improve the efficiency of geothermal electricity generation from low- and medium-temperature resources; reduce resource risks; improve the financial viability of new technologies; and enable the economical extraction of minerals from geothermal brines. Implementing pilot projects will demonstrate technical project viability, as well as boost the confidence of communities, policy makers and other stakeholders.

Strengthen international, regional and national co-operation among partners. Adopting a regional or national approach to address common issues that hinder geothermal development will promote the integration of geothermal in energy systems. This will require building in-house technical and institutional capacity by leveraging the resources and expertise of bilateral, international and multilateral partners willing to provide technical assistance and share their experience and best practices.

Figure 1 **Recommendations for accelerating the development and use of geothermal energy**



1. INTRODUCTION

The transition to clean energy is critical for achieving the Paris Agreement, which aims to limit the increase in global average temperatures to less than 1.5°C above pre-industrial levels. One of the pillars of the sustainable energy transition is the widespread adoption of renewable energy solutions to lower and eventually eliminate the emission of greenhouse gases from global energy systems. Accelerated deployment of renewable energy solutions such as solar, wind, hydropower, geothermal, bioenergy and ocean energy can put the Paris climate goals within reach. To this end, all renewable energy sources will be needed to create an optimal mix matched to local resource availability and energy market conditions.

Renewable energy sources, especially solar and wind technologies, are gradually becoming more competitive, even without subsidies. They have started to benefit from coupling with energy storage solutions that help modulate their variable output. New applications for renewable energy, such as green hydrogen production, have also emerged in recent years. The focus of geothermal energy has broadened beyond baseload electricity generation to flexible operation in support of electricity grid stability and sustainable heating and cooling. As technology, policies and regulatory frameworks, and financing evolve, it is increasingly important to make sure that the added value of geothermal energy to sustainably meet global energy needs is fully exploited and that this source of energy becomes competitive in more markets.

This report is based on published reports on geothermal energy and the wider renewable energy markets as well as interviews with geothermal stakeholders in various regions of the world. A practitioners' group of geothermal experts established by the International Renewable Energy Agency (IRENA) supported the development of the report through a consultative process of review and feedback.

The report is structured as follows:

Chapter 1 discusses the aims of the assessment and introduces the key elements of geothermal energy, such as resource types and their use for electricity production as well as heating and cooling. It also describes the competitiveness of geothermal energy solutions compared with other renewable energy sources and discusses cross-industry synergies (with other renewables, and with the oil and gas industry).

Chapter 2 provides a global overview of the geothermal industry. It describes the global context and market drivers of geothermal in the energy transition, emphasising the decarbonisation and diversification of the energy mix, changing energy demand and different climate change policies. This chapter also examines the effects of global events on energy markets and on financial and economic incentives for geothermal development. It describes the current status of and key trends in worldwide geothermal electricity generation and heating and cooling, as well as challenges and opportunities for market growth. It also describes financing mechanisms and risk mitigation schemes to incentivise investment and reduce risks. It examines financing instruments and risk mitigation schemes and compares their application and outcomes. The chapter also describes international and multilateral collaborations, that affect the growth of the geothermal sector.

Chapter 3 looks at regional highlights, challenges and opportunities in five geothermal regions: Asia and Oceania, Africa and the Middle East, Latin America and the Caribbean, North America and Eurasia.

Chapter 4 provides recommendations for accelerating the development and utilisation of geothermal resources. The recommendations focus on proposed solutions to address existing barriers to geothermal electricity and heat generation in the global market context.

1.1 AIMS OF THE ASSESSMENT

Global geothermal market and technology assessment takes stock of the geothermal sector and provides insights into the elements that are likely to drive geothermal development in the coming years. It analyses the current status of geothermal deployment and the trajectory of its development in recent years; reviews the status of geothermal technologies, particularly technologies with the potential to scale up geothermal development and utilisation; and assesses various geothermal markets in order to establish the current and expected future place of geothermal in the global energy mix.

The analysis examines trends in different markets; technological developments for geothermal electricity; the heating and cooling applications and added value of mineral recovery from geothermal brines; and the implications of public policies, regulatory regimes, environmental and social constraints, financing, capacity building, cross-industry collaborations, geopolitical changes, global events, and changes affecting the energy market, climate change policies and politics.

The assessment seeks to answer the following questions:

- What significant changes have occurred in the geothermal industry in recent years?
- What trends have affected the geothermal sector?
- Which geothermal development areas are expected to drive growth?
- What is the impact of the global energy sector on the geothermal industry?
- How have global and regional events and changes affected the geothermal industry?
- How can geothermal stakeholders, from both the public and private sectors, stimulate and support the further development of geothermal energy solutions, building on existing and emerging markets and technology dynamics?

It provides insights and actionable recommendations to guide policy makers, potential investors and development partners on how to support geothermal development, demonstrate the potential of geothermal energy and further expand its integration within global energy systems.

1.2 INTRODUCTION TO GEOTHERMAL ENERGY

1.2.1 Geothermal resources

Geothermal energy is heat stored in the Earth's crust. This energy is extracted mainly by drilling into the ground and then transported to the surface using fluids. At the surface, the energy is extracted and converted to electricity or used directly as heat.

Geothermal energy can be found at various depths and temperatures. The most widely developed resources are those found in hydrothermal systems, which consist of hot water circulating in deep-seated permeable rocks.

The mode of utilisation of geothermal energy depends largely on the resource temperature. Temperatures are usually divided into three groups: high (greater than 150°C), medium (90-150°C) and low (less than 90°C). Electricity production is more favourable from geothermal resources of medium to high temperatures. For commercial-scale electricity generation, a minimum resource temperature of about 150-180°C is necessary (depending on the technology used), although existing technologies can produce electricity from temperatures as low as 70°C in small-scale applications (ThinkGeoEnergy, 2021a). Medium-temperature geothermal resources are used for various applications, such as space heating and cooling, industrial processes and agri-food applications. The use of combined heat and power, for heating and cooling applications as well as electricity generation, is also possible. A geothermal heat pump (GHP) can be used to increase the heat content of low-temperature resources to meet the energy requirements for various applications. In order to maximise the use of geothermal resources, cascaded utilisation (*i.e.* sequential applications powered from the same stream of energy source, where the outlet stream from the first application, for instance the hot water collected after electricity generation), is used for a second lower-temperature applications, such as district heating, followed by other successively lower-temperature uses.

Most high-temperature geothermal resources are found around volcanoes in areas that are tectonically and volcanically active, such as the Pacific Ring of Fire, the mid-Atlantic ridge, parts of Europe and the East African Rift. Depending on the local sub-surface temperature gradient, these resources can be found at depths of a few hundred metres (m) and several kilometres (km).

Low - and medium-temperature resources are more widely distributed geographically, with significant resources along faults and fractures in tectonically active areas as well as deep in sedimentary basins. As sedimentary basins usually have lower temperature gradients than volcanic areas, deeper drilling (to several kilometres) is usually necessary to reach sufficient reservoir temperatures.

The stable, low-temperature (near-ambient temperature) conditions in the shallow sub-surface are also widely used through GHPs to provide efficient space heating and cooling.

Novel technologies that allow for the production of geothermal energy from deep-seated resources beyond those mentioned above are being developed through research and demonstration projects and tests of commercial feasibility. Although not yet commercially available, these technologies are at varying levels of maturity and readiness. They include the following:

- **Enhanced or engineered geothermal systems** (EGSs) improve the permeability of geothermal systems through hydraulic, chemical and thermal stimulation. This stimulation can be done in some geological settings that have high sub-surface temperatures but where fluid volumes and/or rock permeability are not sufficient to permit economic extraction using current techniques. In such cases, permeability can be enhanced by stimulating the reservoir through pumping of water (or other fluids, such as carbon dioxide [CO_2]) to fracture the rock, thereby creating an artificial reservoir.
- **Advanced geothermal systems** (AGSs) are deep, large, artificial closed-loop circuits in which a working fluid is circulated and heated by sub-surface rocks through conductive heat transfer. As AGSs do not require a water-bearing reservoir with good permeability, they have the potential to be applicable in almost any location worldwide. However, substantially longer well bores are required to increase the surface area for heat transfer, which may result in higher drilling costs.
- **Supercritical geothermal systems** are characterised by very high temperatures and a natural reservoir containing fluid in the supercritical state. For pure water, this means a temperature of at least 374°C and a pressure of at least 221 bar (Reinsch *et al.*, 2017). Such supercritical fluids can be found deep in volcanic hydrothermal systems in Iceland, Japan, Kenya, Mexico and New Zealand, among other locations. The productivity of such supercritical systems could be much greater than conventional high-temperature geothermal systems, because of the higher energy content of the fluid (Friðleifsson, Elders and Albertsson, 2014). Their utilisation implies several technological challenges, such as corrosive fluids, that have been investigated in recent years.

"Advancements in emerging sub-surface technologies have the potential to scale-up geothermal development worldwide."

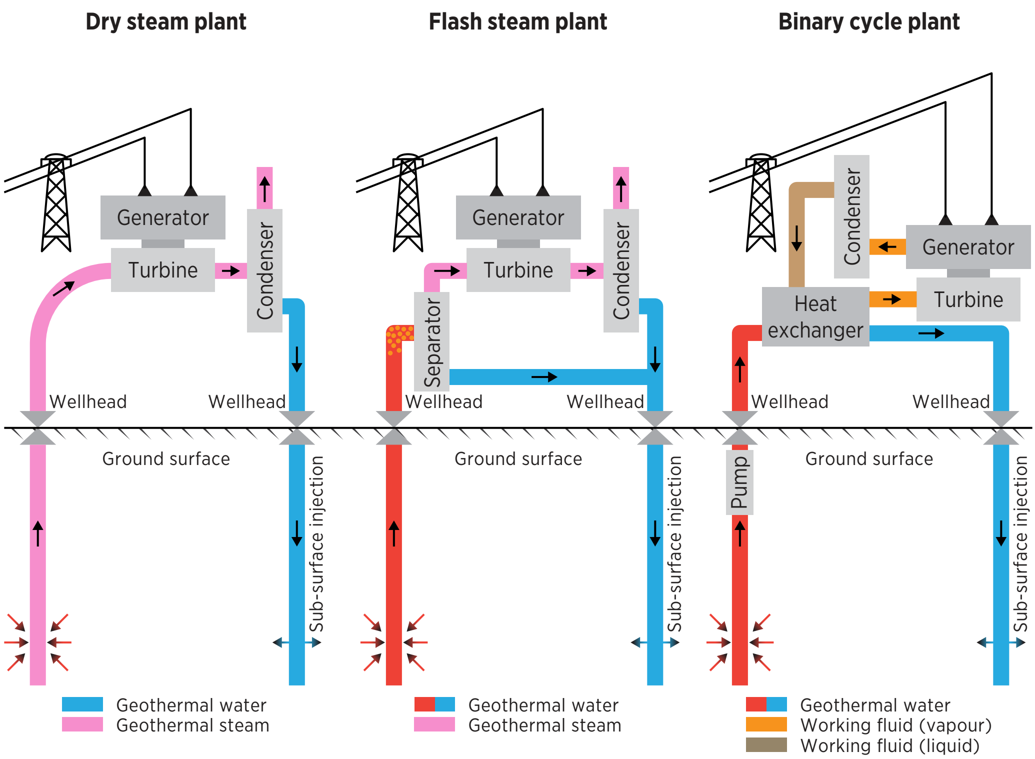
1.2.2 Geothermal electricity generation

Dry steam, back pressure and flash plants

Three primary power plant technologies are used to convert the energy in geothermal resources to electricity: dry steam, flash steam and the binary cycle (Figure 2). Most geothermal plants in operation for electricity generation are dry steam or flash plants that harness geothermal resources at temperatures of more than 150°C. However, lower-temperature resources are increasingly being developed for electricity generation or combined heat and electricity using binary cycle technology.

Dry steam technology is applicable when dry steam is produced directly from the geothermal reservoir. With this technology, saturated or superheated geothermal steam at high pressure is obtained directly from the geothermal well and directed to a steam turbine coupled with a generator to produce electricity (DiPippo, 2012; Anderson and Rezaie, 2019). The steam exhaust from the turbine is discharged into a condenser at low pressure or partial vacuum to optimise the efficiency of electricity generation. In small modular units, backpressure plants that discharge the exhaust steam directly into the atmosphere provide a technologically simpler and cheaper solution for early electricity generation in developing fields.

Figure 2 Geothermal power plant technologies



Based on: USGS (2003).

Globally, flash steam is the most common technology used in existing geothermal plants (Anderson and Rezaie, 2019). This technology utilises two-phase geothermal fluids under high pressure and high temperature to generate electricity by first vaporising the two-phase geothermal fluid at a lower pressure through a process known as “flashing”. The steam component of the geothermal fluid generated during this process is separated from the liquid component. The steam is then expanded through a turbine that is coupled to a generator to produce electricity (single flash). Similar to the dry steam process, the steam exhaust from the turbine is discharged into a condenser at low pressure or released directly into the atmosphere in backpressure plant solutions. The separated liquid component of the geothermal fluid may be flashed further to generate more steam for additional electricity generation (double/triple flash) and eventually returned to the reservoir source through reinjection wells.

Binary cycle plants

Binary plants work by transferring heat from the geothermal fluid to a secondary working fluid with a lower boiling point than water, contained in a closed loop. The secondary working fluid vaporises and generates enough pressure to drive a turbine. Binary power plants usually use geothermal fluids with lower temperatures than required for flash and dry steam. Advances in binary cycle technology have allowed electricity to be generated from geothermal resources with temperatures as low as 70-80°C, albeit at a small scale. Binary plants can operate on an organic Rankine cycle (ORC) or a Kalina cycle, depending on the type of secondary fluid used (butane or pentane in an ORC and a mixture of ammonia and water in a Kalina cycle) (DiPippo, 2012; RHC, 2014; Anderson and Rezaie, 2019). Binary plants can work in a completely closed cycle, in which 100% of the geothermal fluid extracted is returned to the reservoir source by reinjection, allowing for an emission-free operation and maximising the sustainability of resource utilisation.

Wellhead generators

Wellhead generators are modular units of less than 10 megawatts electric (MW_e), usually with a standard design that produces electricity from a single well. Wellhead generators have become an attractive solution because they can enable early generation of revenue during the development phase of a geothermal field, reducing the time before return on investment. Wellhead generators have several advantages: they make use of wells waiting to be connected to larger-scale electric power plants, require shorter pipelines, have shorter installation periods, facilitate early acquisition of data on the reservoir behaviour before start-up of larger electric power plants and serve as a training opportunity for field operations personnel (IRENA, 2020).

1.2.3 Geothermal heating and cooling

Direct utilisation of geothermal heat covers a wide range of resource types and sub-surface characteristics – geological setting, depth and temperature – as well as end-user heating and cooling applications. Geothermal resources, which are suitable for heating and cooling, are widespread globally, in the form of shallow geothermal resources, or deep-seated aquifers hosted in permeable formations in sedimentary basins, and volcanically and tectonically active zones.

Geothermal energy for heating and cooling can be obtained at varying depths. Geothermal fluids can be extracted from shallow wells that are a few hundred metres deep using GHPs or from deep wells of several kilometres in depth.

With heat exchange, heat (or cold) can also be artificially stored in the shallow sub-surface using heat pumps to create underground thermal energy storage (UTES) systems and then used later for heating or cooling applications.

The major categories of geothermal heating and cooling applications are space heating and cooling; agriculture and food processing; industrial process heat; and health, recreation and tourism.

Space heating and cooling applications

Geothermal heat can be used to heat or cool buildings at a variety of scales. At the individual building level, GHPs are commonly used, though direct heating using geothermal fluids is also practiced. District heating networks supply hot water to residential and commercial buildings for space heating and domestic hot water on a larger scale to multiple buildings.

District energy networks enable the utilisation of a combination of renewable energy sources located in different parts of a city for the provision of domestic hot water and space heating and cooling needs of buildings and industries. District heating systems have traditionally supplied energy at 80°C or more, but technological advances in district energy networks have enabled the utilisation of low-temperature energy sources (less than 50°C) from low-temperature geothermal resources or UTESs to supply heat to buildings, including with the support of large heat pumps. Doing so requires the development of 4th generation district energy systems (*i.e.* systems that provide heat supply to low-energy buildings with low grid losses by using low-temperature heat sources) and buildings that are well insulated, to increase energy performance.

Agriculture and food-processing applications

Geothermal energy is used across a range of temperatures in various agri-food applications, including food production, through greenhouse heating for horticulture, aquaculture for fish farming and algae production, and soil warming (Van Nguyen *et al.*, 2015). Greenhouse geothermal heating requires temperatures of 40-100°C. In aquaculture, geothermal heat is used to heat water, generally to 20-30°C, to ensure optimal growth conditions for fish and algae. Geothermal soil heating is done through a network of buried hot water pipelines in open-field agriculture to extend the growing season and increase crop yields. In food processing and storage, processes such as crop drying, pasteurisation, peeling, blanching, cold storage, refrigeration and sterilisation require temperatures of 60- >140°C.

Industrial process heat applications

Industrial processes that can benefit from geothermal energy include thermal processes such as evaporation, distillation, extraction, washing and dying. The food-processing industry represents the most common industrial application of geothermal heat, because of its low and moderate energy requirements. Other industrial processes include laundry operations, pulp and paper processing, textile washing and dying, leather and fur treatment, salt processing, concrete curing and desalination (Jóhannesson and Chatenay, 2014).

Health, recreation and tourism

Naturally occurring geothermal hot springs have historically been used for bathing, swimming and medicinal purposes. Japan's *onsens* (hot spring resorts) are a world-class example of the use of geothermal resources for recreation purposes. Swimming pools, steam baths, saunas and baths supplied by artesian or pumped geothermal wells are also used for recreation and therapeutic purposes in many countries.

1.2.4 Geothermal energy in the renewable energy ecosystem

The recent development of the geothermal industry reflects local geology and market conditions, technologies, policy and regulatory frameworks, and development ambitions and implementation speed. Chapter 2 describes the status and outlook for the industry on a global level; Chapter 3 examines regional opportunities.

Although it has been in commercial use for more than a century, geothermal energy has long been a niche market. With the exception of shallow GHP systems, its use has been limited to deployment of hydrothermal resources found in particular locales. Because only a tiny fraction of hydrothermal resources has been tapped, there is ample room for market growth, even using existing technologies. In many countries, however, the more accessible high-temperature hydrothermal resources have already been developed. Expansion may face technical, logistic, environmental and social barriers, such as the need for more complex and higher-risk exploration of deeper or concealed geothermal reservoirs; the need to explore locations in remote mountainous areas or environmentally protected zones; and social opposition, particularly in urban areas and on indigenous lands.

Growing concern over climate change has intensified public and private efforts to develop EGSs, AGSs and GHP technologies, which permit geothermal energy to be tapped practically anywhere. EGSs and AGSs have greatly expanded the potential for scaling up geothermal solutions for generating electricity and for heating and cooling. These developments have altered the perspective of the entire geothermal market. As a result, geothermal is gradually gaining recognition as a valuable contributor to energy diversity and a major player in addressing the climate crisis. As the geothermal industry demonstrates scalability, it is drawing attention from stronger energy sector players, particularly in the oil and gas industry, which is looking to diversify its investments into clean energy while adapting its huge and highly specialised infrastructure to the energy transition.

Because of the strong technological similarities between the geothermal and oil and gas industries, many new developments in EGS and AGS investigation and testing have emerged from the application of advanced technologies originally developed in oil and gas.

Many countries have set targets for geothermal energy development. In the United States, for instance, the GeoVision analysis conducted by the United States Department of Energy's Geothermal Technologies Office (US DoE 2019) evaluated future geothermal deployment opportunities. It concluded that the use of geothermal energy could be significantly increased through wider access to geothermal resources, improvements in project economics, and enhanced education and outreach. With technological improvements, geothermal electricity generation in the United States could rise to 60 gigawatts electric (GW_e) of installed capacity by 2050, and the potential for geothermal heating and cooling is significant. The GeoVision report considers deep EGSs to have the greatest potential to drive growth.

In 2017, China adopted its "13th Five-Year Plan for Geothermal Energy Development and Utilisation", which promoted the development of geothermal to reduce air pollution and supply continuous base-load electricity and heat (Jianchao, Mengchao and Liu, 2018). The 14th five-year plan for renewable energy calls for the development and use of geothermal energy (Nextrends Asia, 2021), focusing on optimising geothermal heating and cooling deployment.

In Europe, the International Energy Agency (IEA) and the French Environment and Energy Management Agency (ADEME) have identified geothermal as the most cost-effective solution for heating (EU Reporter, 2022). The European Geothermal Energy Council (EGEC) is pushing to unlock Europe's geothermal energy resources as a permanent source of renewable heating, cooling and electricity, as well as for the extraction of lithium and other critical minerals. It has called on the European Commission to devise a strategy for developing geothermal energy and extracting sustainable raw materials from geothermal fluids by 2023 (Renewables Now, 2022).

In Africa, Kenya plans to almost double its geothermal electricity capacity, to 1.6 GW_e, by 2030 (Burkardt and Herbling, 2021).

Many countries (including Indonesia, Kenya, New Zealand and Türkiye) have seen significant increases in geothermal installed electricity capacity over the last ten years. Some countries (including China and Türkiye) have significantly developed geothermal heating and cooling. Geothermal development is currently uneven, taking place only in some countries and regions, but prospects for significant expansion are promising, as climate change goals, volatile oil prices and ongoing technological developments increase the scalability and competitiveness of the geothermal solutions.

In countries with deregulated electricity markets, different electricity sources compete for access to the grid. In the last decade, renewable electricity sources have become very competitive, as declining technology costs have lowered the levelised cost of electricity (LCOE). With an average LCOE of USD 0.068 per kilowatt hour (kWh) in 2021, the cost of generating electricity from geothermal energy is within the lower band of the cost of electricity generated from fossil fuels. However, geothermal's actual LCOE depends on site-specific conditions for the power plant, such as the depth and number of wells drilled and their average electricity output, the technology deployed for electricity generation, and whether the field is green or brown, among others. The LCOE for geothermal remained largely within the range of USD 0.05-0.07/kWh over the last decade. In contrast, the LCOEs for utility-scale solar photovoltaic (PV), onshore wind, concentrated solar power and offshore wind declined by 88%, 68%, 67% and 60%, respectively. As a result, around 225 GW_e of wind and solar was deployed in 2021, representing around 88% of the total new capacity of renewable electricity projects. In contrast, only around 370 MW_e of geothermal was deployed (IRENA, 2022c). The relatively low level of deployment could be attributed to factors such as higher upfront capital costs and longer project development timelines to locate and develop geothermal resources.

The potential exists to lower the LCOE of geothermal projects, and maintain the competitiveness of energy prices from geothermal projects, particularly on drilling costs, which accounts for a significant share of geothermal project costs. Project developers in Indonesia and elsewhere are implementing measures to reduce the costs associated with developing new and makeup geothermal wells through the application of best practices, including (1) foreseeing and circumventing potential drilling problems to reduce the duration of drilling; (2) using advanced sub-surface modelling techniques to target permeable structures, in order to drill highly productive wells; and (3) managing the geothermal reservoir properly to slow the decline in well production and thus reduce the need for makeup wells (Star Energy Geothermal, 2022).

Geothermal energy offers several advantages beyond its LCOE that contribute to its competitiveness (Box 1). It can provide both electricity and heat, as well as value-added mineral extraction. As an electricity source, it offers continuous, reliable generation, with high plant efficiency, low greenhouse gas emissions and a small ecological footprint. Its continuous supply distinguishes it from variable sources, which require sophisticated processes and equipment to ensure efficient, economical and reliable integration with the grid. Geothermal is also a long-lasting source when properly managed. As a heat source, it is scalable, has low operating costs, increases efficiency by using heat directly, reduces electricity consumption and can provide a long-lasting source of sustainable heat. Geothermal can contribute to improved energy access and security, improved air quality, sustainable food systems and the decarbonisation of the world's cities (Vargas, Caracciolo and Ball, 2022).

The investment profile of geothermal projects – which includes high upfront capital requirements and risks – commonly necessitates a long-term power purchase agreement (PPA), typically in the 15-25-year range, with an electric utility or other off-taker to secure financing for the development stage. Though this condition may not be challenging in countries where geothermal development is framed within strong supportive policies, the PPA process itself still may delay the commencement of projects. The situation becomes more complex in countries with less developed policies, where signing long-term PPAs may be limited by electricity market conditions, such as deregulated electricity markets. When PPAs are assigned through technology-neutral auctions essentially structured on a price basis, geothermal cannot compete against lower-cost alternatives provided by solar PV and wind projects. Under such circumstances, geothermal projects face increased financial risks associated with clauses and deadlines for project completion, commissioning and delivery of power to the grid. Failure to meet these requirements may subject the developer to strict non-compliance fines. Some countries (such as Chile) have partly addressed this issue by introducing special conditions that take into account the characteristics and risks of the geothermal resource projects that persist through their development stages (uncertainties about resource capacity and the exact development timeframe, depending on drilling results).

Box 1 **Competitive advantages of geothermal energy**

The technical potential of hydrothermal geothermal resources is estimated at around 200 GW_e and over 5 000 gigawatts thermal (GW_{th}). The Intergovernmental Panel on Climate Change projects that geothermal energy can supply about 18% of the world's electricity demand and meet the electricity needs of 17% of the world's population.

Geothermal is a sustainable energy resource that is widespread in different geological and geographical settings. It occurs over a wide range of temperatures that enables it to be utilised as a renewable and clean energy for electricity generation and heat and cooling applications. In addition, critical minerals such as lithium can be extracted from geothermal brines.

Geothermal energy is considered environmentally benign. The life-cycle emissions of geothermal binary electricity plants with 100% reinjection are estimated to be as low as 11.3 grammes of CO_2 per kWh, and the water consumption of a similar plant is estimated to be 0.66 litres/kWh. The land requirement of a geothermal power plant is around 7.5 square kilometres/terawatt hour.

With proper reservoir management, geothermal power plants can provide stable and reliable electricity and heat with a capacity factor of more than 80%. At the same time, binary technology can allow geothermal power plants to be operated in flexible mode, which is ideal for grids with a diverse energy mix that includes variable renewable sources.

Geothermal energy competitively generated electricity at a LCOE of USD 0.068/kWh for new plants commissioned in 2021. Given its high availability, it is estimated that integrating geothermal electricity into grids in the United States will save the system around USD 41/kWh, mainly through avoidance of installing ancillary services to stabilise the grid.

Source: IRENA (2021, 2022c).

1.2.5 Cross-industry synergies

Cross-industry projects allow the geothermal industry to exploit synergies with other industries, including other renewables, oil and gas, green hydrogen, mineral recovery, energy storage in mines, and carbon capture and storage (CCS).

Hybrid generation with other renewables

Cross-industry synergies have given rise to hybrid power plants that combine geothermal electricity with other renewable sources, such as concentrated solar power, solar PV and biomass (Wendt *et al.*, 2018). In geothermal-solar hybrids, the two types of energy complement each other. Geothermal typically provides a constant electricity output, but technological advancements in modern power plants support flexibility in operation, allowing generation to be ramped up or down in response to variable generation from solar PV. In addition, concentrated solar power plants can be used to increase the temperature of geothermal fluids before they are used in electricity generation, thereby increasing the electric output from geothermal plants. Biomass is also being used to increase working fluid temperatures in geothermal plants. Alternatively, geothermal heat can be used to pre-heat the working fluid in biomass plants, thereby increasing the efficiency of the power cycles.

Synergies with the oil and gas industry

Since the 1970s, oil and gas companies have contributed to the advancement of geothermal energy as project operators and sponsors of innovative research. Successive oil crises (in the 1970s, 1980s and 2010s) have encouraged data sharing, human capital development, technology development and investment in alternative energy sources, including geothermal.

The oil and gas industry has extensive datasets and knowledge of sub-surface hydrocarbon reserves, especially in sedimentary basins that also host low- to medium-temperature geothermal resources suitable for heating and cooling applications and electricity generation. In these areas, the use of geologic data collected during oil and gas drilling can reduce exploration costs and mitigate sub-surface risk. Oil and gas industry professionals have skills that can be applied to geothermal exploration, development and operation. Technologies developed for deep hydrocarbon drilling can be adapted to geothermal reservoir conditions and may accelerate technological developments in the geothermal industry.

Oil and gas wells also present an opportunity to produce geothermal energy. Geothermal energy can be co-produced from active oil and gas wells that contain sufficient volumes of higher-temperature water. Abandoned and non-producing wells can be repurposed to produce geothermal energy for electricity and heating applications (Caulk and Tomac, 2017). However, oil and gas wells often have casings of smaller diameter and relatively low temperature gradients and are generally not designed to produce the high fluid volumes needed in a geothermal project, posing a challenge to repurposing oil and gas wells for geothermal energy production. Even with these constraints, however, there is potential for low-temperature binary electricity generation, heat generation from closed-loop borehole heat exchangers and open-loop systems, the last of which can be combined with EGSs (Santos *et al.* 2022).

Green hydrogen production using geothermal electricity

Generation of hydrogen is an energy-intensive process. Renewable sources, including geothermal, are increasingly being promoted as a way to reduce the carbon footprint of hydrogen generation. For example, geothermal electricity can be used to power the electrolyser in the hydrogen generation process. This option is especially attractive for geothermal sites that have a resource potential that far exceeds domestic market demand, such as sites on small islands. Using geothermal to power hydrogen production would present an opportunity to export geothermal energy. Production of green hydrogen from geothermal energy is beginning to be commercialised worldwide, with a commercial project in Iceland and a pilot project in operation in New Zealand since 2021 (see Box 5 in section 2.2.2).

Mineral recovery from geothermal brines and other synergies with the mining industry

Minerals such as lithium, silica, zinc, manganese, several rare earth elements and potentially many other elements can be recovered from geothermal brines and sold commercially. Extraction of lithium from geothermal brine, for example, could be of value for the production of batteries in a more environmentally sustainable manner compared to traditional lithium production from dry salt lakes or hard-rock mining. Removing some minerals from geothermal brine also holds potential advantages for geothermal resource management (Bloomquist, 2006). Silica removal, as practiced at Ohaaki in New Zealand and Hellisheiði in Iceland, can reduce scaling issues in geothermal injection wells, pipelines and surface facilities (see Box 4 in section 2.2.2).

Several projects in Canada and Europe use abandoned and flooded coal mine shafts to extract geothermal energy and store thermal energy. In Europe, examples of such systems are found in the Netherlands (Mijnwater, 2022); Spain (Lara *et al.*, 2017); and the United Kingdom (Coal Authority, 2021), In Papua New Guinea, the extraction of geothermal fluids contemporaneously with mining operations provides electricity for operations at the Lihir gold mine while also providing electricity for nearby communities.

Carbon capture and storage

Carbon capture and storage technologies exploit the geological conditions of areas that harbour geothermal resources, using them to store CO_2 that otherwise would be released into the atmosphere. CO_2 emitted from geothermal electric plants can be injected back into the geothermal reservoir for permanent storage through natural mineralisation, as it is in the Carbfix initiative in Iceland. CO_2 emissions from other sources, including direct extraction from the atmosphere, can also be injected into geothermal reservoirs in this manner. Bioenergy emissions in New Zealand and direct CO_2 removal from the air in Iceland are examples. Hot sedimentary geothermal reservoirs have large volumetric storage capacity for carbon storage in gaseous form; but volcanically hosted reservoirs are preferred for permanent storage through natural mineralisation in volcanic rocks.

2. OVERVIEW OF THE GLOBAL GEOTHERMAL INDUSTRY

2.1 CONTEXT AND MARKET DRIVERS

Population growth and economic development are increasing global energy demand, intensifying the problem of climate change. To mitigate climate change and move towards a "green" economy, global efforts are seeking to transition towards renewable energy sources.

Geothermal contributes to stabilising the electricity grids in systems with large shares of renewables. Climate change politics and policies, such as the development and implementation of nationally determined contributions, are needed to facilitate the energy transition and the development of renewable energy projects. Sustainable heating and cooling solutions are increasingly being sought, especially in Europe, increasing demand for geothermal resources in tectonically active areas and deep sedimentary basins where development and utilisation is technically and economically feasible.

Global events, such as the COVID-19 pandemic and the uncertainty of energy supply in 2022, have greatly affected global energy markets. The quest for energy security and independence has resulted in increased interest in accelerating development of geothermal resources as a strategic energy source (EGEC, 2022a). An array of fiscal and economic incentives facilitates project financing and reduces project risk.

2.1.1 Decarbonisation and the global energy transition

The transition to net-zero carbon emissions is a complex process in which fossil fuels are phased out over time and replaced with renewable and sustainable energy sources in combination with other measures, such as energy efficiency. Fossil fuel power plants, which are large emitters of greenhouse gases, are being decommissioned for environmental reasons. In 2020 and 2021, an average of 62 GW_e of fossil fuels were decommissioned annually (Energy Matters, 2021). Significant renewable capacity will be required to replace these plants. Variable hydropower, solar and wind solutions cannot (yet) fully replace these plants. Geothermal energy, with its constant and high plant capacity factor, is therefore a valuable element in the global energy transition.

Since 2015, renewable sources have led global growth in new electricity capacity. Renewable capacity grew by 257 GW_e in 2021 to reach a total of 3 064 GW_e of installed capacity, an increase of 9% over the previous year (IRENA, 2022b). Renewables represented about 80% of the new installed capacity in 2021, with almost 90% coming from solar and wind. Geothermal electricity grew at just around 3% between 2000 and 2020, but that pace is set to accelerate, as the new technologies profiled in section 1.2.1 mature and gain broader use. Hydropower remains the largest renewable source of electricity, representing 40.1% of the installed renewable electricity capacity. Solar energy comes next (27.7%), closely followed by wind (26.9%). Bioenergy (4.7%), geothermal (0.5%) and marine (0.02%) command smaller shares (Table 1).

Table 1 Total installed renewable electricity capacity, 2021

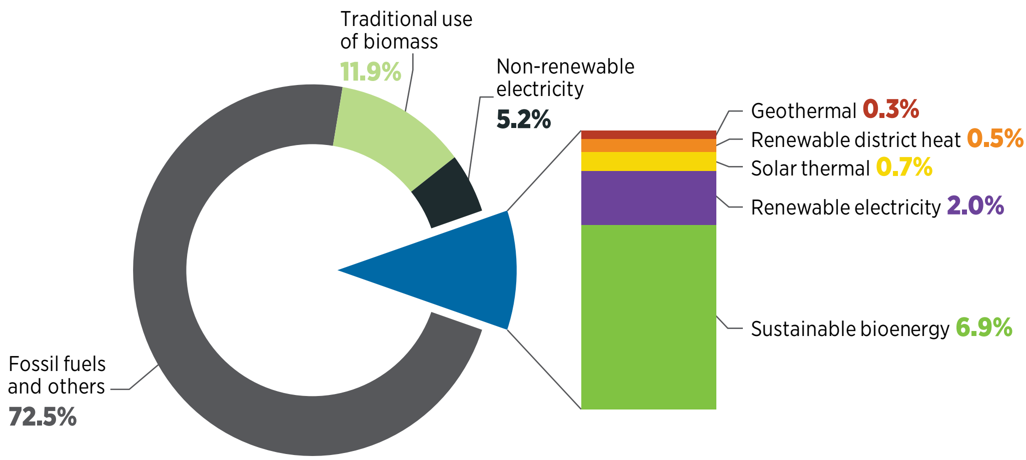
Type of power	Installed capacity (GW_e)	Share of total installed renewable electricity capacity (%)
Hydropower	1 230.0	40.1
Solar energy	849.5	27.7
Wind energy	824.9	26.9
Bioenergy	143.4	4.7
Geothermal energy	16.0	0.5
Marine energy	0.5	0.02

Source: IRENA (2022b).

Heating and cooling represent almost half of total energy use globally, most of it derived from burning fossil fuels. Heating and cooling produce around 40% of greenhouse gas emissions in the energy sector (IRENA, IEA and REN21, 2020). As of 2019, renewable energy provided only 10.4% of total global energy consumption for heating and cooling, including 0.3% from geothermal heat (Figure 3). Given the adverse climate effects of using fossil fuels for heating and cooling, it is expected that bioenergy, solar thermal and geothermal will gradually expand their roles in providing heat for industrial processes, cooking, space heating and cooling, and domestic hot water supply (IRENA, IEA and REN21, 2020).

Because transporting heat over long distances while preserving the minimum required temperatures and avoiding loss of energy is economically challenging (Kavvadias and Quoilin, 2018), the transition of the heating sector from fossil fuels to renewable sources depends strongly on local characteristics affecting heat production, distribution, utilisation and storage. In the building sector, using geothermal heat in local district heating systems is becoming increasingly common, especially across Europe and parts of China.

Figure 3 Shares of energy sources in final energy consumption for heating and cooling, 2019



Based on: IRENA, IEA and REN21 (2020).

2.1.2 Diversification of the electricity mix

To achieve the energy transition, every country needs an optimal combination of renewable sources. As countries increasingly deploy wind and solar energy, geothermal can play an important role by compensating for their variable operation.

Over-reliance on a single source of energy can result in insecurity and unreliable supply. Along the East African Rift, for example, hydroelectric power is the main source of electricity. Changing precipitation patterns – as a result of climate change, land use and the effects of geopolitics on cross-border water resources, including the Nile River – have created uncertainty over the supply of electricity from hydropower plants (Sridharan *et al.*, 2019). Utilisation of the geothermal resources in the region would diversify the electricity supply. In Kenya, the share of electricity generated from geothermal increased from 15% in 2010 to more than 40% in 2021. As a result, hydropower's share of electricity generation fell from 46% to around 30%. The increased generation of electricity from geothermal resources allowed Kenya to reduce the frequency of electricity outages.

2.1.3 Climate change politics and policies

Sustainable Development Goal (SDG) 7 of the United Nations 2030 Agenda aims to ensure access to affordable, reliable and modern energy for all, and energy has been identified as a key enabler of the other SDGs. Renewable energy technologies, including geothermal, and energy efficiency will be central to achieving sustainability in the production and utilisation of energy. They will contribute to the reduction in energy-related greenhouse gas emissions and achievement of the goals of climate action.

Growing awareness about climate change has contributed to a change in global politics and policies concerning climate action in recent years. The Paris Agreement resulted in countries making a political commitment to scale down their emissions, and setting targets for emission reduction through Nationally Determined Contributions (NDCs).

Guided by the Inter-Governmental Panel on Climate Change, climate models indicate the need to cut emissions to net zero by 2050 to maintain the average temperature within 1.5°C above the pre-industrial level. The urgent need to mitigate climate change provides an opportunity to position geothermal energy as a suitable option for reducing and eventually replacing fossil fuels as energy sources. The benefits of geothermal energy must be disseminated to educate policy makers, stakeholders and the public, so that they can leverage geothermal energy to meet their climate objectives under the Paris Agreement. Dominica, for instance, has identified the harnessing of geothermal energy as a major driver for reducing emissions in the energy sector. It targets transitioning to 100% renewable by 2030 using geothermal energy, envisaging a reduction of emissions by over 98% compared with 2014. Beyond education and focused energy policies, investment in research and development (R&D) is key to integrating geothermal into the energy systems of the future.

2.1.4 Sustainable energy for heating and cooling

The application of geothermal heating and cooling solutions has grown substantially in recent years, to reach close to 110 GW_{th} in 2022, an increase of over 50% since 2015. Europe in particular has seen a progressive shift in the political framework for heating and cooling, associated with higher requirements for sustainable building practices, greater demand for housing (because of the increase in the urban population) and other factors that have made geothermal energy a part of many strategies for implementing decarbonisation while pushing fossil energy technologies out of the market (EGEC, 2021). The major heating and cooling applications of geothermal energy – bathing, heating and cooling of buildings, and supply of process heat for industrial and agri-food sectors – have focused attention on the use of low- and medium-temperature sources, which are widely available in most countries.

2.1.5 Global events affecting energy markets

Recent global shocks since 2020 disrupted many sectors of the economy, including the energy sector. The COVID-19 pandemic led to lockdowns, which disrupted the movement of people and transport of commodities and supressed demand for energy. Energy markets experienced disruptions as global energy supply chains were put under pressure following the conflict in Ukraine. The resulting price volatility of traded energy commodities put additional pressure on economies (Benton *et al.*, 2022).

In response to disruptions in global energy markets, many countries are exploring ways to develop local and strategic alternative energy sources, in order to reduce their dependence on international energy markets and achieve energy security. The disrupting impact of these global events has boosted opportunities for locally available alternative energy sources, including geothermal energy, an autochthonous energy resource that can provide energy security.

2.1.6 Financial and economic incentives

If the cost of geothermal energy exceeds alternatives or high upfront development costs and risks create barriers to development of geothermal projects, the market will be limited. Several policy tools and instruments can incentivise the development of geothermal projects (see sections 2.2.1 and 2.3.1).

Tax incentives

Tax incentives can help make geothermal energy competitive with alternative sources of energy. They can be applied to capital expenditure for equipment and costs such as duties and value added tax to lower the cost of renewable energy technologies. Tax incentives can also be applied to the operating expenditure of energy projects, through measures such as income tax holidays and the waiving of royalty fees.

Feed-in tariffs

Feed-in tariffs (FiTs) have been used in Japan, Kenya, Türkiye and other countries to promote the accelerated deployment of geothermal energy by offering preferential prices and long-term contracts to project developers for the supply of electricity to the national grid from geothermal sources. The preferential price enables the developer to bridge the gap between the costs of geothermal electricity and the cost of alternatives sources. FiTs allow geothermal to compete with fossil sources and other renewable energy sources (see Box 2).

Direct subsidies

Direct subsidies to market-ready technology or individual projects can help develop geothermal projects when they are not yet competitive with other energy sources, especially when scale advantage has not been reached. The US Department of Energy funds various grant programmes to support investigation and feasibility studies for enhanced or engineered geothermal system (EGS) projects, geothermal deep direct use and geothermal co-production in oilfields (See section 3.4).

Subsidies for R&D and innovation

Research programmes develop innovative technologies relevant to geothermal energy and adapt them to the local context. A research and innovation ecosystem that increasingly focusses on scalability, maturity and cost-effectiveness at higher technology readiness level allows for market adoption of innovative technologies.

Grants, convertible loans-to-grants and loans

Governments and multilateral banks can support geothermal projects with grants and loans for exploration and drilling campaigns to incentivise geothermal energy development by sharing this part of the upfront costs and risks. Loans may be convertible to grants upon receiving unsuccessful drilling results.

Risk mitigation, guarantee and insurance schemes

Risk mitigation schemes can be used to cover sub-surface risks, especially during exploration drilling, when the resource risks are typically highest. Other risk mitigation schemes may address declining well productivity during operation of a power plant as well as energy off-take risks.

Construction of infrastructure and to match demand

Incentives for the modernisation and extension of the local and national energy infrastructure (including electricity and heating grids) can support the development of geothermal projects. Extending electricity grids to remote areas with geothermal potential could facilitate the development of those resources. In the heating and cooling sector, construction of new district heating networks, extension or modernisation of existing networks and energy-efficiency improvements in buildings could support the integration of more geothermal energy.

Carbon revenue

Geothermal projects can obtain additional benefits through the carbon market and carbon trading. Selling carbon credits can increase revenues and improve the economic feasibility of geothermal electricity as well as heating and cooling projects.

2.2 GENERATION OF GEOTHERMAL ELECTRICITY

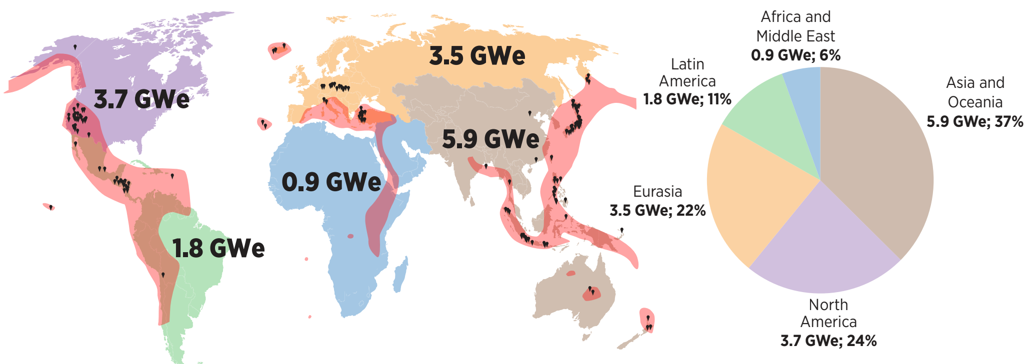
2.2.1 Current status and key trends

Installed capacity and energy use

Geothermal energy provides electricity generation in more than 30 countries. Installed capacity per country ranges from less than 1 MW_e to 3.7 GW_e. The main technologies employed in electricity generation include dry steam, flash steam and binary power plants. (see section 1.2.2). In some countries – notably countries belonging to the geothermal "1 GW_e club" (Indonesia, New Zealand, Philippines, Türkiye and the United States) – geothermal plants have been operating for decades. Others (including Belgium, Chile, Colombia, Croatia, Honduras and Hungary) only recently began generating geothermal electricity and are at earlier stages of development. The global installed capacity for geothermal generation of electricity was 15.96 GW_e at the end of 2021, distributed across five main regions (Figure 4). The regions with the largest installed capacity are Asia and Oceania (5.9 GW_e), North America (3.7 GW_e) and Eurasia (3.5 GW_e). (Chapter 3 examines capacity in more detail.)

The use of geothermal energy for electricity generation is more advanced in some regions and countries than in others, in a manner that is not directly correlated with the presence of suitable geothermal resources. Even in very favourable volcanic settings (such as the Pacific Ring of Fire), geothermal development shows significant differences across regions and countries. For example, North America and Central America have more mature geothermal industries than South America and the Caribbean Islands. Recent successful developments of geothermal electricity have resulted from the use of lower-temperatures resources not associated with volcanically active sites, such as in Türkiye and certain European countries.

Figure 4 Installed geothermal electricity capacity, by region, 2021



Source: IRENA, 2022a; ThinkGeoEnergy, 2022 (b); Huttrer, 2021.

Note: The red zones on the map indicate high-temperature geothermal zones. The black symbols indicate geothermal electric plants, many of which are located in high-temperature zones. The geothermal regions used in this report were selected based only on the occurrence and development of geothermal resources, not on political or socio-economic considerations.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

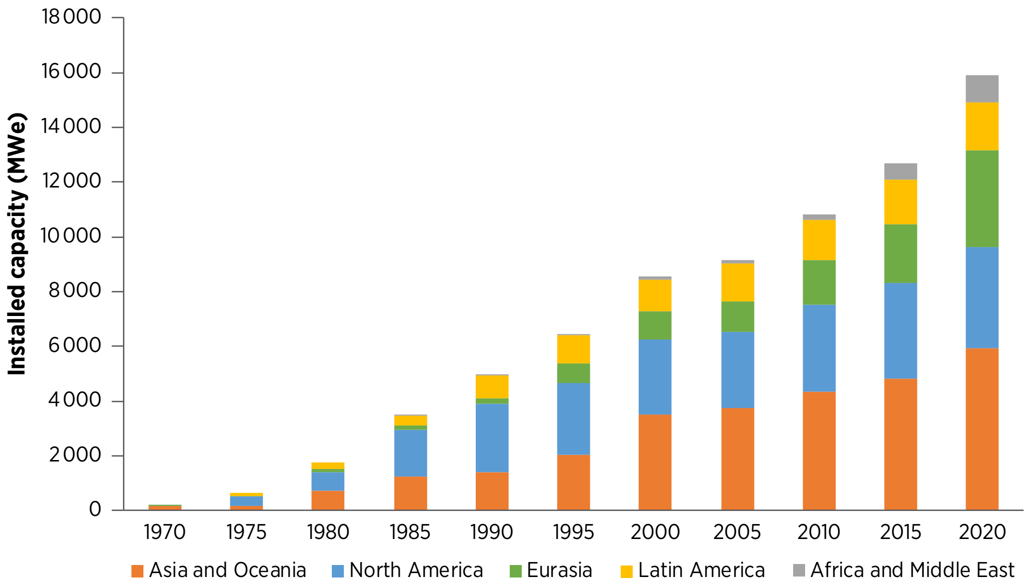
The success of geothermal development cannot be defined only in terms of installed capacity; other aspects, such as how geothermal contributes to national electricity output, also need to be taken into account. In some small countries with limited electricity markets, such as Iceland and countries in Central America, and islands such as the Azores archipelago (Portugal), installed geothermal capacities in the range of a few hundred MW_e contribute to satisfying national electricity demand. In El Salvador, for example, 204 MW_e of installed geothermal electricity capacity provided 24.9% of the annual demand of electricity in 2020.

The global electricity generation capacity of geothermal plants grew from 200 MW_e in the early 1950s to approximately 16 GW_e in 2020 (Figure 5). Geothermal capacity increased significantly in the 1970s and 1980s, thanks in part to the oil crises of 1973 and 1980/81. Sharp increases in oil prices led to R&D of many alternative electricity sources, including geothermal (Sanner, 2016). One of the driving forces for these developments was that geothermal energy, which is available locally, allowed countries to reduce their dependence on imported fossil fuels to generate electricity (Dickson and Fanelli, 2013).

Steady growth continued after the 1980s. Since 2000, installed geothermal electricity capacity increased at an average annual rate of about 3%, with significant contributions from Indonesia, Kenya, Türkiye and the United States. Despite this growth, geothermal represented only 0.5% of the global renewable electricity market in 2022 (see table 1) (IRENA, 2022b).

The global energy market context is similar to what it was during earlier energy crises. It provides new opportunities for geothermal electricity to further develop as a strategic alternative that can strengthen electricity generation systems in many countries.

Figure 5 **Growth of installed geothermal electricity capacity by region**



Source: ThinkGeoEnergy statistics, ThinkGeoEnergy (2022b), Huttrer (2021), Uihlein (2018), and Bertani (2015).

Enabling policies and regulations

National policies and regulations are key to developing the geothermal industry. Weak or complex policies and legal frameworks for geothermal development create market barriers, hindering the potential development of the sector, particularly through the participation of private developers.

Many countries have enacted specific geothermal laws and regulations; they include Chile, Colombia, Dominica, Indonesia, Kenya, Mexico, Nicaragua, Peru, Saint Kitts and Nevis, Saint Vincent and the Grenadines, Türkiye and the United States. In others – including Argentina, El Salvador, Grenada, Guatemala, Honduras, Iceland, New Zealand, Panama and Saint Lucia – the geothermal sector is regulated through diverse legislation, such as mining, environmental, water resources, electricity and renewable energy laws. In a few countries – including the Plurinational State of Bolivia, Costa Rica, Djibouti, Ecuador and the United Republic of Tanzania – geothermal resource exploitation is reserved for government institutions; regulation is therefore limited.

Policies range from strong promotional measures to a lack of specific support. In some countries, such as Germany, Japan and Türkiye, the geothermal industry has flourished when supported by favourable FiTs (Box 2). In most countries, geothermal projects must compete with other energy sources in deregulated electricity markets. In South American countries, including Chile, Colombia and Peru, the existence of very competitive and deregulated electricity markets has hindered the deployment of significant geothermal resource potentials, despite the availability of several geothermal electricity projects identified at the prefeasibility to feasibility stage. Access to the electricity market in these countries is controlled largely by technology-neutral auctions that either do not include geothermal energy or force it to compete under conditions that can be difficult to meet.

Many countries have implemented policy measures that foster the deployment of geothermal energy, with diverse results. In the United States, for example, a geothermal boom in which more than 2 000 MW_e were installed in a decade occurred throughout the 1980s and early 1990s, thanks to a combination of state policy decisions, a favourable tax climate, and direct government support through cost-shared drilling programmes and government loan guarantees (ESMAP, 2016). The reduction of government support, particularly the end of federal programmes and of the Public Utility Regulatory Policies Act (PURPA), resulted in slower and more irregular development.

Conducive policies and regulatory reforms have allowed Türkiye to scale up geothermal development, increasing its geothermal electricity capacity from 15 MW_e in 2008 to over 1.7 GW_e in 2022. It has also scaled up geothermal heating and cooling, positioning it among the world's geothermal leaders. These results are attributable largely to implementation of a strong national policy based mainly on tax regimes, market incentives and national content standards.

Box 2 Stimulating small-scale binary electricity generation projects through government incentives in Japan

Development of small-scale binary electricity plants has increased in Indonesia, Japan and the Philippines. The trend is especially notable in Japan, where developers have favoured small binary plants over larger conventional electricity plants, especially since 2010.

Government-supported incentives have been crucial to enabling the development of geothermal projects in Japan, where such projects are rarely developed without government support. During the 1980s and 1990s, government agencies' support for geothermal resulted in a large increase in electricity capacity. This support ended in the 2000s, and limited development took place over the next 20 years. With the exception of Matsuo-Hachimantai (7.5 MW_e), and Wasabizawa (46 MW_e), which were commissioned in 2019, no large-scale geothermal plants have been developed in Japan since the 1990s, because such projects take longer to enter into operations than smaller-scale projects (Yasukawa *et al.*, 2021).

The effects of the nuclear incident at Fukushima in 2011 induced the government to restart support for renewable energy through subsidies and FiTs. Japan introduced the FiT mechanism in July 2012. Under it, energy companies are required to procure certified renewable electricity (including from geothermal plants) at fixed prices over a 15-year period, as established by the Ministry of Economy, Trade and Industry. For geothermal plants, the current FiT is JPY 26/kWh (USD 0.23) for plants larger than 15 MW_e and JPY 40/kWh (USD 0.35) for plants smaller than 15 MW_e.

Development of small-scale geothermal electricity generation installations has increased since the government introduced the FiT. More than 60 geothermal plants of less than 2 MW_e each have been built across 45 geothermal fields (Imamura, Shiozaki, and Okumura, 2020). Beyond the FiT incentive, many small geothermal electric plants have been developed. They carry less risk than larger plants, require lower levels of investment and do not require extensive exploration to go into operation.

Photograph 1 Small-scale geothermal electric plant in Japan made feasible through FiT

Source: Nikkei Asia (2017).

Financing and risk mitigation

The development of geothermal resources carries various risks. Unlike other renewable energy sources, the geothermal industry has significant sub-surface resource risks, particularly in the early stages, when the uncertainty of the resource capacity and the upfront investment required for drilling to confirm the resource are high, as described in section 2.2.2. These risks make it challenging to obtain project financing. Country-specific factors can also undermine geothermal investments. They include (1) inadequate policies and weak regulatory frameworks, (2) investors' perceptions of country risk, (3) local market conditions, (4) unfavourable logistical conditions or specific social aspects of geothermal areas and (5) the limited availability of technical expertise.

Financing challenges – and the accompanying approaches to risk mitigation – have been the subject of careful analysis (ESMAP, 2012, 2016; Boissavy, 2020; GEORISK, 2021). Several risk mitigation facilities have started to operate. At the regional level, they include the Geothermal Development Facility in Latin America and the Geothermal Risk Mitigation Facility in the East African Rift. Similar facilities at the country level are found in Chile, several European countries, Indonesia, Mexico and Türkiye.

Risk mitigation schemes are now drawing on several years of experience to increase the effectiveness of existing schemes and introduce new ones. Regulatory frameworks for geothermal projects are being reviewed and updated in many countries where the lack of clear policies and regulations – as well as limited technical and institutional capacity – exacerbate other risks and barriers. Several multilateral organisations (including the World Bank, the Inter-American Development Bank, the Asian Development Bank and the Caribbean Development Bank) and international co-operation agencies (such as the Japan International Cooperation Agency) provide country-based risk mitigation solutions through technical assistance and financial support for geothermal project assessment and development, particularly in developing countries.

The risk mitigation instruments and technical assistance that are commonly used to tackle barriers in the exploration stage of geothermal projects may not be sufficient to spur geothermal development. Other actions need to be taken to enhance the overall investment climate and create attractive conditions for geothermal energy in national electricity markets.

A report by the Energy Sector Management Assistance Programme (ESMAP, 2016) reviews global experience managing risks associated with the geothermal resource. It classifies efforts into four groups:

- The government takes on all resource and other project risks by acting as the sole project developer, undertaking surface studies, conducting exploration drilling, and building and operating the project through state-owned enterprises or other government-backed entities.
- The government shares the cost of drilling with private developers, shifting some or all of the risk of drilling to develop the steam field to the public sector.
- Geothermal resource risk insurance pools exploration risks across a portfolio of development.

- Early-stage fiscal incentives (exemption from duties, tax credits, *etc*.) lower the financial exposure developers would face during exploration drilling.

These approaches have resulted in different outcomes, depending on each country's conditions and development goals. Certain risk mitigation schemes have been more effective than others in fostering geothermal development (ESMAP, 2016; Boissavy, 2020). All countries need to strike an appropriate balance between public and private efforts. State companies or government institutions have successfully led geothermal projects in Costa Rica, Djibouti, El Salvador, Kenya, Mexico and the Philippines. But building technical and operational capacity to undertake geothermal electricity projects is a long, complex process that requires political planning and determination. Lacking financial capacity and/or technical expertise, many governments engage with private companies to develop their geothermal resources, through various combinations of public-private participation and division of responsibilities. Such collaboration takes advantage of the stronger government capacity for mobilising risk capital needed to de-risk the early stages of project development (exploratory drilling particularly) and the usually stronger technical capacity and international experience of private companies to develop and operate geothermal fields.

International collaboration

International collaboration has advanced the dissemination of information on geothermal technologies and market development. Many international organisations are working collaboratively on geothermal energy development with a global, regional or national reach. Synergies among government institutions, private developers and investors, multilateral organisations, international aid agencies and academic institutions, among other stakeholders, can facilitate solutions that address industry challenges and accelerate the global development of geothermal energy.

Collaboration yields benefits in a variety of areas. Chief among them are (1) the sharing of international best practices and experiences in creating enabling frameworks for geothermal development; (2) the building of local capacity to plan and manage geothermal development; (3) environmental management and social outreach of geothermal projects; and (4) technological innovation.

Global organisations and regional and bilateral collaborations that are actively promoting geothermal energy include the following:

- The **International Geothermal Association**, the leading global organisation representing and supporting the geothermal sector in delivering the future of clean energy.
- The **Global Geothermal Alliance (GGA)**, established by IRENA as a platform for enhancing dialogue, co-operation and co-ordinated action among the geothermal industry, policy makers and other relevant stakeholders worldwide.
- The **IEA Geothermal Technical Cooperation Programme**, established to promote international co-operation, through activities ranging from the sharing of information on technologies and methodologies for geothermal development to the development of knowledge.

Selected regional collaborations featuring advocacy, policy support, training and research initiatives include the following:

- **Geothermica (Europe and the United States)** promotes research and innovation to make geothermal energy reliable, safe and cost competitive.
- The **Africa Rift Geothermal Project (ARGeo)**, managed by the United Nations Environment Programme (UNEP), supports the development of the vast geothermal resources of Eastern Africa, with a focus on de-risking the resources and building technical expertise.
- The **European Geothermal Energy Council (EGEC)** promotes the European geothermal industry and enables its development in Europe and worldwide by shaping policy, improving business conditions and promoting R&D.
- The **Geothermal Research Cluster (GEORG)** is a non-profit organisation that promotes R&D on geothermal resources in a sustainable way, in order to reduce the world's dependence on carbon-based energy sources.
- **Geo-energy Europe**, funded by the European Union, provides opportunities for networking and sharing opportunities in geothermal markets.

Selected bilateral collaborations include the following:

- The **German Agency for International Cooperation (GIZ) and the Central American Integration System (SICA)** are co-operating intensively on geothermal technology development and initiatives, particularly for heating and cooling uses.
- The **New Zealand–Africa Geothermal Facility** is providing responsive, flexible and timely geothermal technical assistance and capacity building to Eastern African countries and, as appropriate, assisting with funding applications to the existing Geothermal Risk Mitigation Facility (GRMF), to help develop regional geothermal energy resources.
- New Zealand's **Ministry of Foreign Affairs and Trade (MFAT)** and Indonesia Aid are partnering under the Joint Commitment for Development to increase access to affordable, reliable, clean energy by increasing workforce skills and capability in geothermal energy.
- The **Japan International Cooperation Agency (JICA)** is providing technical capacity building for geothermal steam supply and management, particularly in Africa and Latin America.

2.2.2 Challenges and opportunities for market growth of geothermal electricity

Challenges

Geothermal electricity development faces diverse challenges that hinder market growth and project deployment. Many of those challenges are encountered during the higher-risk early exploration phases, but also occur during more advanced stages of project development.

A significant challenge faced by many geothermal projects (which are common in other natural resources sectors) is public resistance. Several projects have met with opposition from local people and indigenous communities, as well as from other social levels and organisations. Reasons for opposition include differing perspectives and conflicting interests on land use, limited information on geothermal technology, concerns about the environmental and social impacts potentially generated by a geothermal development (including the use and contamination of shallow groundwaters and public health problems associated with gas emissions). Inappropriate initial approaches by some geothermal developers to community engagement created distrust and resistance that is difficult reverse. In some cases, working with communities allowed projects to move forward; in others, challenges remain. Overall, sensitivity to social issues has significantly increased in the geothermal industry in recent years.

Other global challenges include the following:

- **Financing:** Geothermal projects face difficulty mobilising or accessing capital for early exploration and project financing, because of project complexity, investment risk and other factors.
- **Policy:** Many projects are not profitable under prevailing market conditions and require public support through enabling policies and incentivising frameworks. The formulation of these frameworks needs to take into consideration the unique characteristics of geothermal energy development.
- **Regulatory:** Improvements to the geothermal regulatory framework are needed in several countries to attract investors. Complex permitting procedures may hinder the acquisition of development rights and permits needed to execute geothermal projects.
- **Market:** Energy-market-related issues such as uncompetitive electricity tariffs in deregulated electricity markets (*e.g.* in Chile) and/or delays in obtaining PPAs (*e.g.* in Ethiopia) have slowed the pace of geothermal industry growth. In countries with a less mature geothermal industry, policy making and technical and administrative capacity are still under development. As a result, technological innovation and market development are limited.
- **Institutional:** Many countries have limited institutional technical capacity to administer and manage geothermal development.
- **Technological:** Technological development and innovation are still needed to make geothermal a globally scalable energy solution. Research and demonstration projects are crucial to reduce resource risks, improve project economics and allow the more efficient and widespread use of geothermal resources.

Other challenges may be region or country specific. Countries in the Andes face difficult logistical conditions in remote mountainous areas. Remote island countries have small electricity markets. Many countries (including Costa Rica, Indonesia, Italy, Japan, New Zealand and the Philippines) face social opposition and environmental restrictions because geothermal resource areas overlap national parks, indigenous lands, tourist sites or areas of landscape value. Other countries face political instability and/or unstable electricity markets. In some countries in Latin America and Europe, the pandemic created logistical and global transport challenges during 2020 and 2021 that significantly slowed or stalled project advancement, especially for new projects.

Opportunities

There are many opportunities to overcome these challenges to achieve geothermal market growth, including expanding and interconnecting regional electricity grids, leveraging oil and gas expertise and technology in geothermal, recovering minerals from geothermal brines and increasing synergy with green hydrogen. As many of the world's easily accessible geothermal resources have already been developed for electricity generation and thermal utilisation, the geothermal industry is focusing on accessing previously uncommercial resources through technological optimisation and innovation. Opportunities can be exploited by improving the efficiency of above-ground heat exchange and energy conversion technology and below-ground technology to enable binary electricity production from lower-temperature geothermal reservoirs as well as oil and gas wells, EGSs, AGSs and supercritical resources. (Chapter 4 summaries these opportunities.)

Increasing electricity grid interconnectivity

Expansion and interconnection of regional electricity grids, could present opportunities for the development of renewable electricity, including geothermal, sources. In the Eastern African Power Pool, which includes most of the countries with significant geothermal resources in the region, bilateral exchange of electricity, generated mainly from hydropower, takes place. A similar situation occurs in Central America, where the interconnected grid Central American Electrical Interconnection System facilitates the exchange of electricity in the regional market. Connecting the eastern Caribbean Island countries with undersea cables could allow countries with geothermal resources to export geothermal electricity to neighbouring islands without adequate resources.

The integrated planning of geothermal electricity generation with connectivity to regional electricity grids could foster the development of geothermal projects in countries with significant potential by allowing exports of electricity to countries with low potential. However, several political and market issues constrain the integrated approach to planning electricity production at a regional level. In addition, in many cases, geothermal development is still limited by other challenges, such as inadequate financing and competitiveness of geothermal power.

Leveraging oil and gas expertise and technology

The hydrocarbon industry has started to recognise the opportunities inherent in the geothermal market to leverage oil and gas technologies, datasets, skills and financial resources in support of the clean energy transition. The oil and gas industries are increasingly looking for opportunities to develop geothermal projects, as demand for replacing fossil fuels by renewable clean energy sources grows. Their experience and technologies could significantly contribute to the development of geothermal resources in deep sedimentary basins.

Research on how to use geothermal fluids in sedimentary basins and geo-pressurised resources dates back to the 1980s in the United States. Several demonstration projects are currently underway globally, using a range of technologies to repurpose oil and gas wells or co-produce geothermal fluids. Recent studies conducted in oilfields in the United States concluded that co-production may be less viable than converting existing oil and gas wells into wells suited for sole geothermal production (Gosnold *et al.*, 2020) (see section 3.4). Box 3 highlights examples of these efforts in Canada, Colombia and Hungary. The International Geothermal Association is conducting surveys and interviews to research transitioning oil and gas companies; it has hosted forums, panels and webinars to raise awareness of this opportunity, including through online learning and industry-focused training (IGA, 2021).

Developing geothermal energy involves sub-surface geoscience exploration and deep drilling, which share some characteristics with sub-surface exploration for hydrocarbon resources. Oil and gas companies, drilling companies and upstream service companies offer advanced drilling and geophysical technologies developed in the hydrocarbon industry that can be applied to and adapted for geothermal applications.

The geothermal energy sector can benefit from data, such as seismic, well geology or heat flow data, previously acquired for oil and gas projects (Bradley *et al.*, 2019). Some reservoir properties that are typically determined for hydrocarbon exploitation, such as formation porosity and permeability, are also relevant to geothermal resources. In some countries, sub-surface data are made publicly available in a national repository after a set period and can thus be used in the geothermal sector. Interactive web-based data portals provide access to publicly available oil and gas data in Hungary (OGRe Geothermal Information Platform) and the Netherlands (ThermoGIS).

It is also possible to combine energy resources. Small-scale electricity generation using co-produced water in oil fields was recently demonstrated in the Las Maracas oil field, in Colombia (ThinkGeoEnergy, 2021b). Similar initiatives are ongoing elsewhere in Colombia and in the United States (ThinkGeoEnergy, 2022c).

The co-production of hydrocarbons and geothermal resources requires regulations to address overlapping resource rights and the potential impacts of extracting geothermal fluids on existing hydrocarbon operations and vice versa. In many countries, the regulatory framework needs to be reviewed to facilitate the development of geothermal resources in sedimentary basins. Steps in this direction are being taken in Australia, where regulators are investigating how to manage the potential implications of a proposed geothermal project on existing hydrocarbon permits in the North Perth basin.

Box 3 Using existing oil and gas wells to recover geothermal energy in Canada, Colombia and Hungary

Existing wells in oil and gas fields can be used or repurposed to recover geothermal energy at significantly reduced costs. Several pilot projects are being implemented.

Canada: Open-loop geothermal doublet

An open-loop geothermal doublet is being developed at the Tu Deh-kah project in British Columbia. One of the wells is a deepened gas well; the other is a newly drilled well (Tu Deh-Kah, 2022). The project is located in the Clarke Lake geothermal field. It is led by the Fort Nelson First Nation indigenous community, with funding from the Canadian government. Geothermal water (of around 120°C) is produced from highly porous carbonate rocks. The aim is to generate 7-15 MW_e of electricity. Opportunities for cascade utilisation of the waste heat are also being evaluated.

Colombia: Co-production of oil and hot geothermal water

In 2021, Colombia commissioned its first geothermal electricity generation project, at the Las Maracas field in Casanare, where oil has been produced for many years (ThinkGeoEnergy, 2021b). This geothermal system uses hot water, which is extracted as a co-product of oil production, at no extra costs. An ORC binary plant produces 0.1 MW_e, which is used to power the fossil fuel pumps and other oilfield facilities.

Hungary: Closed-loop borehole heat exchanger

In 2021, Hungary implemented its first closed-loop geothermal heating system in an abandoned oil well in Kiskunhalas, to generate small-scale thermal power using the Wells for Heat Exchanging Advanced Technology (WeHEAT) (ThinkGeoEnergy, 2021c; WeHEAT, 2022). A geothermal pilot plant produces around 0.5 MW_{th} of renewable heat for heating and cooling use. The project received support from the National Research, Development and Innovation Fund of Hungary. It is considered a showcase example that could be implemented throughout the country, as Hungary has over 8 000 deep out-of-use oil and gas wells, as well as scaled up globally.

Photograph 2 Geothermal site of the Tu Deh-Kah project, in Canada

Source: Nu Deh-Kah (2022).

Photograph 3 Geothermal site of the Las Maracas project in Colombia

Source: ThinkGeoEnergy (2021b).

Generating electricity from low- and medium-temperature resources

The generation of electricity from low- and medium-temperature geothermal resources using binary technology has expanded significantly in recent years. Before 2000, binary technology was used in only 5% of global installed capacity. This share increased steadily, to around 20% in 2000-2010, around 40% in 2000-2017 and 58% in 2015-2021 (Uihlein, 2018; Thinkgeoenergy Statistics). The recent technological development of small binary modules applicable to fluids with temperatures as low as 80-90°C has started to attract interest, with pilot applications on marginal geothermal wells and medium-temperature resources, such as hot springs, shallow hot aquifers, co-produced water in oilfields and mine water. The capacity of these lower-temperature applications is limited to a few hundred kilowatts. Other disadvantages are a high flow rate requirement of geothermal water, low conversion efficiency and difficult project economics, particularly when the thermal water is not readily available at the surface and must be pumped from wells, whose energy consumption may offset much of the electricity generated. Under favourable conditions, however, they can provide valuable and clean electricity solutions for remote off-grid communities, as is the case at the Chena hot spring in Alaska (see section 3.4) and in remote industrial operations, such as oilfields and mines.

Binary technology is also used in some high-temperature fields (*e.g.* Cerro Pabellon, Chile; Olkaria, Kenya; Ngatamariki, New Zealand). This technology provides 100% reinjection of geothermal fluids to meet environmental requirements and resiliency in hurricane-prone regions like the Philippines or the Caribbean. In bottoming applications, it recovers additional electricity generation from flashed residual brines.

Recovering minerals from geothermal brines

Investigations in mineral recovery from geothermal brines intensified in recent years. Successful demonstration projects in France, Germany, Iceland, New Zealand, the United Kingdom and the United States have shown that production of lithium and silica is technically feasible. Larger-scale commercial projects still depend on further development to make the process economically and environmentally sustainable (Stringfellow and Dobson, 2021).

Countries such as Argentina, Plurinational State of Bolivia, Chile and Italy have the potential to exploit geothermal mineral by-products. The Cesano area of Italy is of interest for geothermal lithium production; a licence was granted in 2022 (ThinkGeoEnergy, 2022e). The Andean region of Argentina, southern Bolivia and northern Chile is called the ”lithium triangle”, because concentrated lithium is present in salt lakes. The potential extraction of lithium from brines could enhance the business case for geothermal plants in this region.

Current projects for mineral recovery from geothermal brines include the following:

- **France and Germany:** Deep hot brines in the Upper Rhine Graben, from Strasbourg (France) to Mannheim (Germany), contain lithium concentrations of up to 200 milligrammes per litre (mg/L) (UnLimited, 2022). In 2021, lithium was extracted from a geothermal brine in a pilot project at the Rittershoffen geothermal plant in northern Alsace (France) (Eramet, 2021). Battery-grade lithium carbonate was extracted from a geothermal brine later in 2021 in Soultz-sous-Forêts (Bas-Rhin, France) (Eramet, 2022; BRGM, 2022) and in the German part of the Upper Rhine Graben in the Zero Carbon Lithium project, which targets commercial production by 2024 (ThinkGeoEnergy, 2021e).
- **Iceland:** In Iceland, geothermal operators are extracting silica from geothermal brine used for electricity generation at the Hellisheiði and Svartsengi geothermal fields to produce silica dietary supplements and natural skincare products respectively (ThinkGeoenergy, 2020).
- **New Zealand:** In 2021, the first commercial silica was recovered at the Ohaaki geothermal field (Geo40, 2022) (Box 4). Tests were performed to also extract lithium from the brine, and a pilot project is planned at this field. In 2022, the Government of New Zealand announced its plan to invest in scaling up geothermal lithium production (ThinkGeoEnergy, 2022d).
- **United Kingdom:** Lithium-enriched geothermal waters were discovered in mines in Cornwall in 1864. In 2021, tests demonstrated concentrations of more than 250 mg/L (ThinkGeoEnergy, 2021d, 2022d). Several projects are under development in this area to extract lithium from geothermal brines at different depths (Sanjuan *et al.*, 2022; ThinkGeoEnergy, 2022d; BBC News Mundo, 2020; Cornish Lithium, 2022a).
- **United States:** Lithium-rich geothermal brines are produced by geothermal wells in the Salton Sea area (southern California), with concentrations up to 440 mg/L (Neupane and Wendt, 2017; NREL, 2021). Planning of a new commercial geothermal plant that would both generate electricity and extract lithium is underway at the site.

"Generation of electricity from low- and medium-temperature geothermal resources using binary technology expanded significantly to reach around 58% of new capacity in 2015-2021."

Box 4 **Recovering silica and lithium from the Ohaaki geothermal field in New Zealand**

Located in the Taupo Volcanic Zone of New Zealand, the Ohaaki electric power station produces 110 MW_e from a high-temperature (around 300°C) geothermal reservoir.

In 2021, the world´s first sustainable large-scale commercial silica recovery plant from geothermal brine was commissioned, at Ohaaki (Geo40, 2022). It can produce 5 000 tonnes per year of colloidal silica. A smaller-scale demonstration plant in the same field is capable of producing 500 tonnes per year. Silica recovery before reinjection will provide an added benefit to Ohaaki's geothermal electricity production, as it prevents silica scaling in the pipes and wells, which can reduce electricity output over time.

In 2019, near-battery-grade geothermal lithium was extracted at the silica demonstration plant. Silica has to be recovered from the brine before lithium can be extracted. A pilot plant for lithium recovery is being developed at this field. In 2022, the New Zealand government announced an investment of NZD 2 million (USD 1.29 million) for upscaling geothermal lithium production (ThinkGeoEnergy, 2022d).

Photograph 4 **The Ohaaki silica and lithium extraction plant, New Zealand**

Source: New Zealand Herald (2022).

Note: The plant's cooling tower is visible in the background.

Increasing synergy with green hydrogen

The transition from grey to blue and green hydrogen production could spur implementation of green hydrogen systems. Until now, the renewable energy focus has been on solar, wind and hydropower as the favoured renewable energy sources powering green hydrogen. The use of geothermal energy for green hydrogen production has great potential, as geothermal provides stable electric and thermal power and enhanced efficiency (by increasing the input temperature of water into the electrolyser) (Hand, 2008). Green hydrogen production from existing geothermal plants could allow expansion of resource use by taking advantage of existing field facilities and improving projects' economies of scale. It could be especially beneficial in markets with limited growth and demand for electricity or market conditions, such as small island markets. Developing small-scale hydrogen production for use in the local market can be relatively easy; massive development of green hydrogen using geothermal electricity still faces challenges (including lack of technological development and the need to transport the hydrogen to global market facilities), which in certain countries or regions may require significant cross-industry co-ordination, planning and investment.

The world's first geothermal green hydrogen production facility was established in Iceland. Demonstration plants are in operation in New Zealand and under construction in Japan (Box 5). In the Oceania region, there is also potential for green hydrogen production in the Pacific, mainly in Fiji and Papua New Guinea, where linking geothermal energy to productive uses (combining hydrogen production, heating and cooling) may make it more economically attractive. Green hydrogen could be used to power new inter-island ferries or retrofit existing ferries. Interest in geothermal green hydrogen is also growing in Central and South America and the Caribbean Islands.

> ***"Green hydrogen production could enhance geothermal use - particularly in countries with small electricity markets - and would benefit from stable electric and thermal power from geothermal resources for improved efficiency."***

Box 5 **Producing green hydrogen with geothermal energy in Japan and New Zealand**

Japan and New Zealand are pioneering the production of green hydrogen using geothermal energy. International co-operation and partnerships between companies from both countries are leveraging state-of-the-art hydrogen technology, geothermal plant operations, environmental protection and a vision of sustainability. As a result, green hydrogen demonstration plants have been established in Kyushu, Japan and Taupo, New Zealand.

In New Zealand, a 1.25 MW_e geothermal green hydrogen pilot plant is operating at Mokai geothermal field near Taupo (www.halcyonpower.nz/). The pilot plant is owned by a joint venture between the owner of the Mokai geothermal plants, an indigenous land trust, and a leading Japanese construction and energy company (Halcyon Power, 2022). The project started in late 2017, and the plant went into operation in June 2021. The hydrogen plant is the latest addition to Mokai, where 112 MW_e electricity is generated and multiple cascade applications - including a milk-processing plant, a greenhouse complex and a plant nursery - make use of geothermal heat. The hydrogen plant has the capacity to produce 180 tonnes of hydrogen per year, which could fuel about 1 000 cars or 30 trucks or buses. The hydrogen is being used to power a fuel cell vehicle in order to demonstrate the potential of green hydrogen as a transport fuel.

The project developer aspires to supply the hydrogen market in Japan, New Zealand and other countries. In New Zealand, potential green hydrogen markets include the shipping industry, the long-distance transport industry and sailboat racing.

Following its success in New Zealand, the same developer has undertaken a geothermal green hydrogen demonstration plant in Kokoneo-cho, Kusu-gun, Oita Prefecture, Japan. The demonstration plant will combine a 125 kilowatts electric (KW_e) installed capacity binary geothermal power plant with a 50 Newtons per square metre (N/m^2) production capacity green hydrogen plant, where 50-60 KW_e electricity generation will be used to produce hydrogen. Construction of the demonstration plant started in 2020. The hydrogen produced will power fuel cell vehicles, supply a local hydrogen refuelling station, and be used for research purposes (FuelCellsWorks, 2021).

Photograph 5 **Demonstration plant for green hydrogen production powered by geothermal energy at the Mokai geothermal field, Taupo, New Zealand**

Source: Obayashi Corporation and Halcyon Power.

Photograph 6 **Demonstration plant for green hydrogen production powered by geothermal energy in Kyushu, Japan**

Source: Obayashi Corporation and Halcyon Power.

Developments in enhanced geothermal systems.

Since the 1970s, a variety of technologies have been used worldwide to improve the permeability of hot dry rock through hydraulic, chemical and thermal stimulation. Most EGS projects are located in Australia, Europe, Japan, the Philippines and the United States (Pollack, Horne and Mukerji, 2021).

The continued development of EGS technology would enable the economic use of lower-permeability reservoirs (Yu, Dempsey and Archer, 2022). However, many EGS projects encounter technical challenges, such as induced seismicity, drilling and plant operation issues or insufficient connectivity between injection and production wells (Pollack, Horne and Mukerji, 2021). EGS has yet to be demonstrated as a commercially viable technology ready for scaled-up deployment.

Developments in advanced geothermal closed-loop systems.

Closed-loop technology is still under development. More investigation and testing are needed to prove its commercial viability.

In 2019, a large-scale closed-loop prototype was built at a demonstration facility in Alberta (Canada). It demonstrated the technical feasibility of the innovative AGS technology, effectively unlocking a potential new source of geothermal energy for electricity or heat generation (Eavor Technologies, 2021). The next step is to demonstrate commercial feasibility. Closed-loop technology has the potential to be applied to geothermal reservoirs with sufficient temperatures but lacking permeability, such as the geothermal project in Saint Vincent and the Grenadines in the Eastern Caribbean.

AGSs have the potential to yield large societal and economic benefits, as they carry few externalities. The risk of inducing seismicity is low, because an AGS does not involve fracturing the rocks. The risk of negative environmental impacts through leaks into surrounding aquifers is also low, because the wellbores are sealed, and AGSs do not emit greenhouse gases, as open geothermal systems can. Declines in the cost of drilling, through technological advancement, are needed to make AGSs economical by reducing closed-loop development costs (Malek *et al.*, 2022). Other improvements, including the use of other working fluids (CO_2, ammonia and others), could eliminate the need for heat transfer to a secondary cycle, resulting in higher electric power outputs (Malek *et al.*, 2022).

Research on supercritical resources

Supercritical conditions, with temperatures in excess of 374°C under high pressure, are reported from many deep wells drilled in geothermal fields (Reinsch *et al.*, 2017) in Iceland, Italy, Japan, Kenya, Mexico and the United States. In Hawaii, Iceland and Kenya, magma has been unexpectedly encountered during drilling. Very high enthalpy fluids are often very corrosive. Most supercritical temperature wells have encountered challenges regarding low permeability, drilling and well completion.

Several research projects are assessing possibilities, challenges and innovative techniques for tapping and utilising supercritical geothermal fluids. They include the Iceland Deep Drilling Project, the DESCRAMBLE project in Italy and the Geothermal: Next Generation initiative in New Zealand. Innovation is very important to enable the use of supercritical fluids, from which much more energy can be produced than from conventional geothermal systems. Supercritical geothermal systems have the potential to greatly improve the economic feasibility of geothermal development.

2.3 GEOTHERMAL HEATING AND COOLING

2.3.1 Current status and key trends

Globally, interest is growing in the use of geothermal energy for applications requiring heating or cooling. Direct utilisation of geothermal energy increased by over 50% between 2015 and 2020 (Lund and Toth, 2021). This growth occurred despite many challenges, including the following:

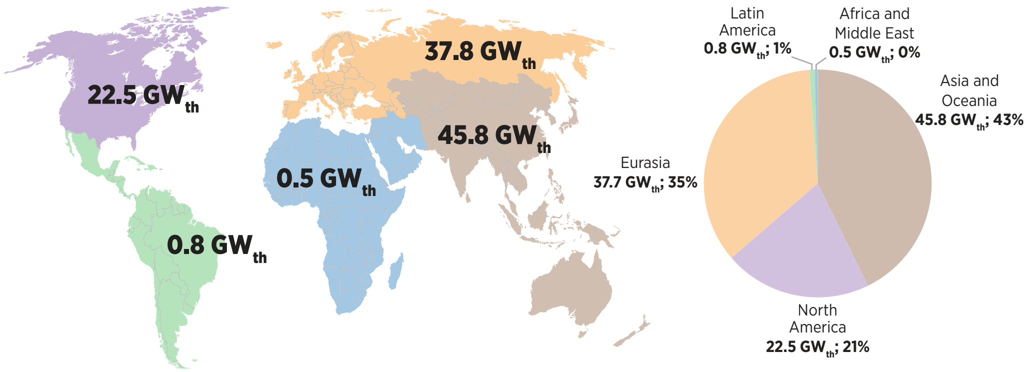
- Limited public awareness, of and familiarity with, heating and cooling applications and potential.
- Lack of sufficient data and tools to assess the geothermal resource and match it to demand for heating and cooling.
- Lack of certified technicians and personnel with the right technical skills.
- Limited local access to drilling services and equipment.
- Regulatory frameworks lacking specific legislation on heating and cooling.
- Inadequate technical and administrative institutional capacity.
- The low priority of promoting geothermal among other energy policies
- Difficulty accessing funding, particularly for smaller projects.

Initiatives have sought to overcome these challenges by improving the regulatory framework for geothermal heating and cooling, creating new risk mitigation mechanisms for heat generation, implementing technical assistance programmes funded by co-operation agencies and multilateral organisations, and piloting projects in many countries. This section analyses the global growth of geothermal heating and cooling. It covers installed capacity and utilisation, leading markets, enabling policies and regulations, financing and risk mitigation, public versus private sector involvement, and international collaboration. It is based on regional analysis of five major geothermal regions: Asia and Oceania, Africa and the Middle East, Latin America and the Caribbean, North America and Eurasia. (Chapter 3 provides detailed analysis at the national and project level.)

Global installed capacity and energy use

The global installed capacity for geothermal heating and cooling was 107.4 GW_{th} in 2020. Geothermal heat pumps constituted 72% of this capacity, with the remaining 28% coming from direct heating and cooling using geothermal fluids. Geothermal heating and cooling applications are concentrated in three regions. The Asia and Oceania region, with installed capacity of 45.8 GW_{th}, is the global leader, with a 43% share; it is followed by Eurasia (38%) and North America (21%) (Figure 6). Latin American and the Caribbean, Africa and the Middle East each contribute 1% or less.

Figure 6 Geothermal heating and cooling installed capacity, by region, 2020



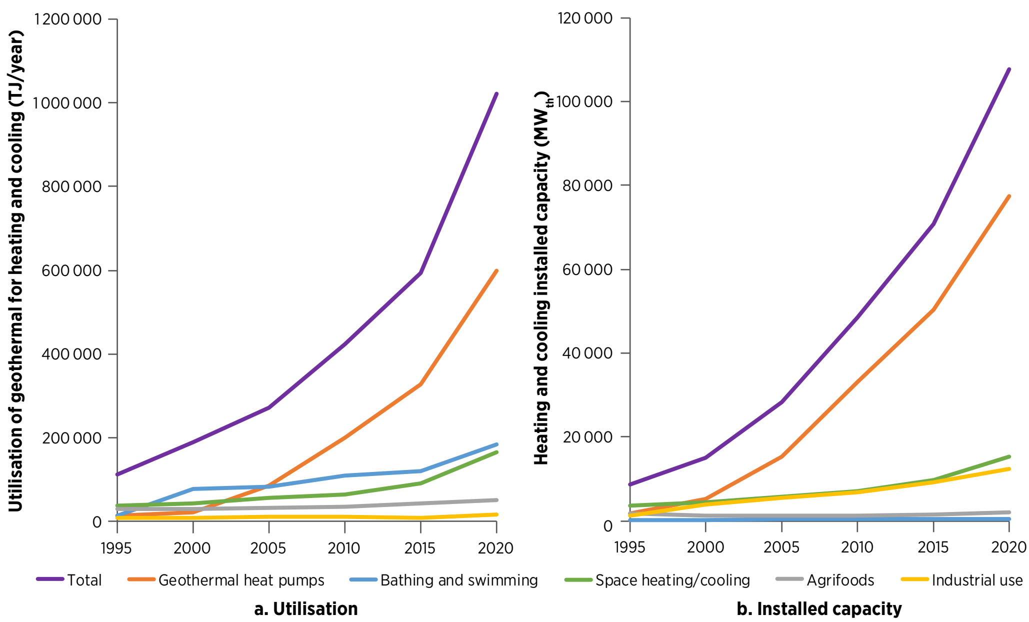
Adapted from: Lund and Toth (2021).

Note: The geothermal regions used in this report have been selected based only on the occurrence and development of geothermal resources and not political or socio-economic considerations.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

Heating and cooling growth accelerated between 2015 and 2020 across all end-use sectors, with the most significant growth in the GHP sector (Figure 7).

Figure 7 Utilisation and installed capacity for geothermal heating and cooling, 1995-2020



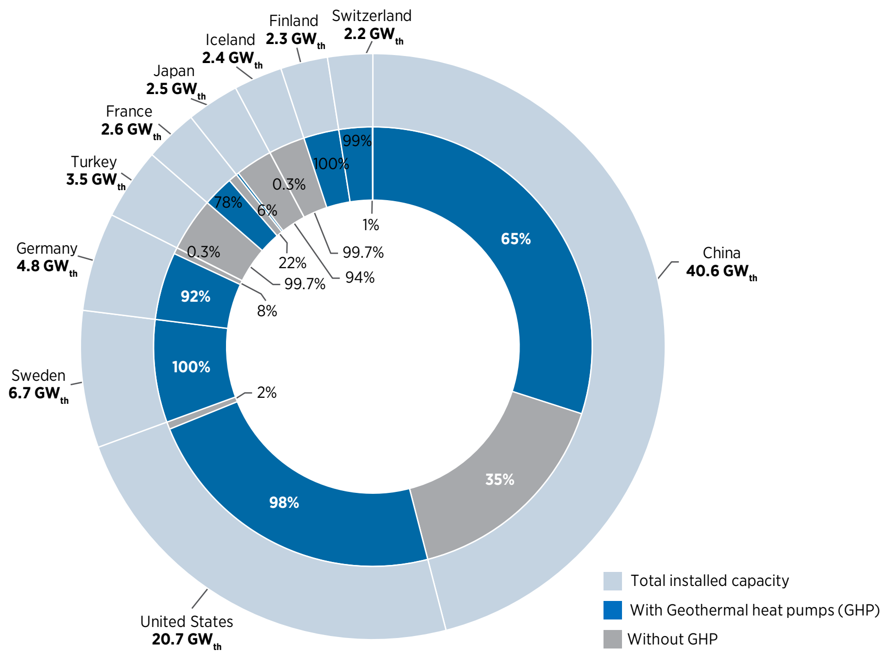
Source: Lund and Toth (2021).

The geothermal heating and cooling industry experienced a 52% growth in installed thermal capacity and a 74% growth in utilisation between 2015 and 2020. Over the same period, installed capacity in the GHP sector grew 54% and utilisation increased by 84%. The heating and cooling applications with the largest use worldwide are GHPs, space heating (both individual and district heating) and agri-food applications (Lund and Toth, 2021). In the last ten years, geothermal heating and cooling grew in various sectors, including fish farming, agricultural crop drying, food and beverage processing, industrial heat, space cooling and snow melting. Many countries, in both developing regions (*e.g.* Latin America and the East African Rift) and developed regions (*e.g.* Europe and New Zealand), are making strides to deploy more heating and cooling projects for agri-food and industrial applications.

Geothermal heating and cooling markets

More than 80 countries use geothermal energy for heating and cooling. Ten have at least 2 GW_{th} of installed capacity, including GHPs (Figure 8). China has the most installed capacity (40.6 GW_{th}), followed by the United States (20.7 GW_{th}), Germany (4.8 GW_{th}), Türkiye (3.5 GW_{th}), France (2.6 GW_{th}), Japan (2.5 GW_{th}), Iceland (2.4 GW_{th}), Finland (2.3 GW_{th}) and Switzerland (2.2 GW_{th}). GHPs account for a large share of heating and cooling installed capacity in many of these countries (100% in Finland and Sweden, 99% in Switzerland, 98% in the United States, 92% in Germany, 78% in France and 65% in China). Other significant heating and cooling applications in leading countries include district heating in China, Iceland and Türkiye; hot springs resorts (*onsens*) in Japan; and bathing in Türkiye.

Figure 8 **Top ten geothermal countries for heating and cooling, by installed thermal capacity in 2020**



Source: Lund and Toth (2021).

Enabling policies and regulations

A well-defined regulatory framework and appropriate government policies are essential for the advancement of the geothermal heating and cooling industry. Regulation must be clear and straightforward; it must also be periodically revised and adapted to new technologies, to ensure that it remains attractive to investors and protects the sustainability of the resource and the environment. Geothermal legislation is often spread across a variety of laws, regulations, standards, best practices and guidelines administered by multiple regulatory agencies (GEOELEC, 2013). Regulations may also vary across regions within a country, as is the case in Australia, where each territory has its own geothermal regulations.

In regions with mature geothermal heat markets, such as Europe, the regulatory and policy framework is more advanced, having been developed over the last 20 years (Box 6). Policies supporting the development of heating and cooling may include national and local planning of renewable energy sources, government-led exploration or R&D projects, standardised geothermal data collection and reporting, public sharing of sub-surface data, and education and training for policy makers.

In regions with nascent geothermal heating and cooling markets, such as Latin America and Africa, the enabling framework is being improved (*e.g.* Chile) or new regulations for both electricity generation and heating and cooling have recently been established (*e.g.* Ethiopia) to facilitate investments. Many countries with geothermal-enabling frameworks for electricity generation, however, lack policies, regulatory frameworks and financial incentives to foster development of geothermal heating and cooling. In Kenya, the New Energy Act of 2019 introduced progressive government policies and incentives that support private sector investment in electricity generation. However, geothermal heating and cooling are included as a co-development only as allowed by resource characteristics, and no licencing procedures are in place for these applications (IRENA, IEA and REN21, 2020). In Ethiopia, the geothermal law and associated regulations passed in 2016 through the Geothermal Proclamation provide for the licencing of electricity generation and heating and cooling projects separately (IRENA, IEA and REN21, 2020).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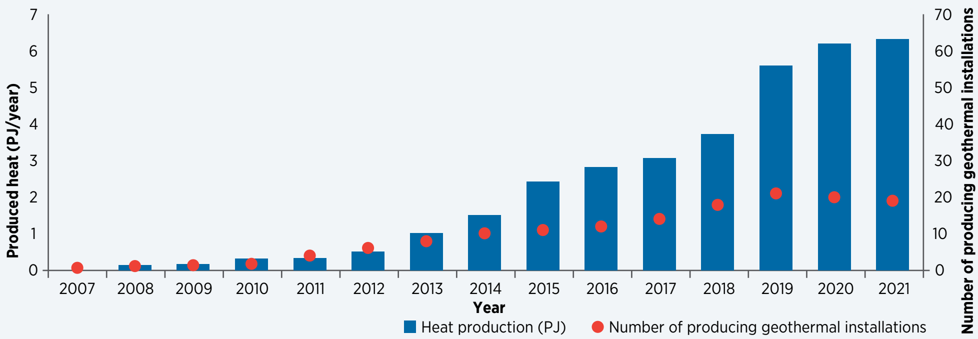
Commercial greenhouse powered by geothermal.

Box 6 Developing an enabling environment and incentives for geothermal heating and cooling in the Netherlands

Heating and cooling account for about half of total energy demand in the Netherlands. The government aims to reduce natural gas use and require residential areas to be "natural gas free". It hopes that by 2050, 25-30% of the demand for heat will be supplied by geothermal energy, which it views as a key source of renewable heat for greenhouses, district heating and other smaller-scale space heating.

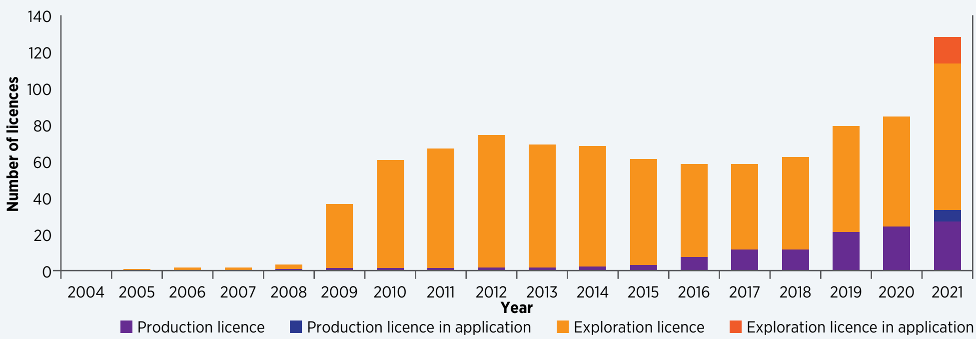
The first geothermal well in the Netherlands was drilled in 2007, for greenhouse heating. Since then, similar projects have steadily entered into operation (Figure 9), culminating in over 100 licensed exploration and production projects with total production capacity of 6 petajoules a year (PJ/year) in 2021 (Figure 10). District heating projects will soon come online in Delft, The Hague and Leeuwarden (Geothermie Nederland, 2022a). Projects backed by large energy, oil and gas, and utility and investment companies are planned to go into operation in the coming years (NLOG, 2022).

Figure 9 Geothermal heat produced and number of geothermal installations in the Netherlands, 2007-2021



Source: Ministerie van Economische Zaken en Klimaat (2022).

Figure 10 Number of production and exploration licences for geothermal greenhouse wells issued in the Netherlands, 2004-2021



Source: Ministerie van Economische Zaken en Klimaat (2022).

Box 6 Continued

Various incentives and risk mitigation mechanisms are available to stimulate growth of geothermal heat applications in the Netherlands. The government funded studies to estimate nationwide geological and the techno-economic potential for geothermal energy; they are publicly available on an online digital data portal (ThermoGIS). Sub-surface data, such as seismic data and petrophysics, are made public after five years on the Dutch oil and gas portal (NLOG), assisting developers of small-scale geothermal energy projects. The National Economic Affairs Subsidies Regulation (RNES) established the guarantee scheme for geothermal energy in 2009 to mitigate the risk of sub-surface geological uncertainty. Since 2012, geothermal projects are eligible for the SDE+/SDE++ scheme, which provides preferential FiTs for renewable heat projects. National funds are available for innovation and feasibility studies, and exploration of areas with little sub-surface data is funded through the Dutch Seismic Campaign for Geothermal Energy (SCAN) programme.

Despite the existence of diverse incentives, the financing and investment environment remain challenging. For instance, the RNES guarantee scheme is limited to guaranteeing single wells. Subsidy schemes, such as SDE++, typically impose strict project development and operation timelines, which is a limiting factor for geothermal projects that can carry significant project timeline uncertainty. Delays in permitting also mean that deadlines in subsidy schemes cannot easily be achieved. Geothermal energy had to compete for subsidies with other renewable heat technologies, without taking into consideration the unique characteristics of geothermal projects. Beginning in 2023, geothermal projects will compete only within their sector for subsidies. An update to the Dutch mining law that governs deep geothermal projects, currently pending legislative approval, will require the state-owned investment company EBN to participate in geothermal projects as a shareholder. Through direct participation in projects, the Dutch government hopes to accelerate development of geothermal energy, share risks and improve knowledge sharing in the sector.

These policy and regulation changes led to an increase in exploration licences awarded as well as exploration and production applications in 2021 (see Figure 10). With the upcoming amendment of the mining law, development is expected to accelerate again.

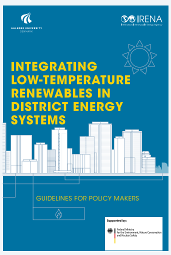
International organisations have been supporting countries in promoting the development of geothermal heating and cooling, including by improving national regulatory frameworks. The World Bank has been active in Chile, El Salvador, Dominica and Kazakhstan; the Inter-American Development Bank has worked in Colombia and other Latin American countries; and GIZ has promoted geothermal heating and cooling in Central America. ESMAP is promoting heating and cooling as a decarbonisation solution through knowledge generation, regional and country-specific studies and technical support, and capacity building.

IRENA, in the context of the Global Geothermal Alliance, has been supporting countries' efforts to create enabling frameworks for geothermal energy, particularly in heating and cooling, through dialogue and capacity building at the regional and national levels. It has developed guidebooks for policy makers that identify the priority actions countries can undertake to accelerate the deployment of geothermal heat in district energy systems (IRENA and Aalborg University, 2021) and agri-food value chains (IRENA, 2022a). These guidebooks assess various case studies to identify best practices that contributed to the success of the projects (Box 7). UNEP, through the ARGeo programme, is supporting African countries' efforts to develop a technical guidebook for heating and cooling using geothermal energy and to increase the awareness of policy makers about geothermal heat utilisation.

Box 7 IRENA guidebooks on geothermal heating and cooling

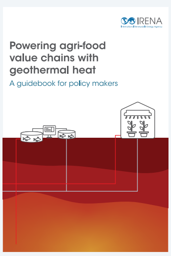
IRENA has produced two guides for policy makers on geothermal heating and cooling. Both were developed with the support of practitioners' groups of geothermal experts from the member states and partner organisations of the Global Geothermal Alliance and other organisations.

Integrating low-temperature renewables in district energy systems: Guidelines for policy makers



This guidebook presents examples of tools and resources policy makers can use to enhance the use of low-temperature renewable heat sources (including low-temperature geothermal) in new and existing district heating and cooling systems. It proposes solutions to key technical and market challenges that prevent the deployment of renewables in district energy systems. IRENA is using the recommendations of the guidebook to support countries' efforts to facilitate the deployment of geothermal energy in their district energy systems.

Powering agri-food value chains with geothermal heat: A guidebook for policy makers



This guidebook identifies challenges and proposes recommendations for accelerating the uptake of geothermal energy in agri-food industries and value chains. Challenges include insufficient data about geothermal resources and heating demand for agri-food applications, absent or insufficient enabling frameworks, lack of financing and limited awareness, among others. It highlights priority areas for accelerating the development of geothermal agri-food applications.

IRENA is using the findings of the guidebooks to stimulate dialogue at the country and regional level to advance the deployment of geothermal heating and cooling applications in the end-use sector in Belarus, China, Eastern Africa, Latin America, Mongolia and the Western Balkans.

Financing and risk mitigation

One of the main challenges to developing geothermal heating and cooling projects is financing. District heating and larger projects have access to a range of financing mechanisms, including public financing, cost-sharing risk mitigation schemes, fiscal incentives, grants, FiTS and subsidies. Smaller projects at the industrial or residential level do not have the same level of access.

A wide array of subsidies is available for research and early-stage exploration of geothermal heating and cooling projects, both locally and internationally. Subsidies are provided for both innovation and research to move innovative technologies to market and support the implementation of mature geothermal technologies. In Europe, geothermal energy is eligible for multiple subsidy programmes (EGEC, 2020).

Many European countries, including France, Germany, Iceland, the Netherlands and Switzerland have developed long-standing national public risk mitigation schemes historically devoted to heat generation (GEORISK, 2021). Hungary is the most recent European country to offer national geothermal heating risk insurance. In Türkiye, risk mitigation schemes are applicable for both electricity and heat production. Examples of cost-sharing risk insurance schemes for geothermal heating in Europe include the following:

- **SAF Environment (France):** Launched in 2008, this EUR 20 million (USD 21.8 million) fund provides grants and subscription fees for heat projects in deep aquifers. The fund has been a major catalyst for the development of geothermal district heating in the Parisian Basin.
- **GEODEEP (France):** Launched in 2015, this EUR 50 million (USD 54.4 million) fund is financed by the French Environment and Energy Management Agency – ADEME (a public institution managed by the Ministry of Environment, Energy and the Sea) and La Caisse des Dépôts (a public investment bank) to cover deep geothermal wells for electricity and/or heat generation in France.
- **NL RNES Geothermal Guarantee Scheme (the Netherlands):** Launched in 2007, this scheme provides grants and insurance of up to 85% of the cost of drilling and testing exploration wells. The fund has allowed for the drilling of 17 doublets for heating purposes, mainly in the greenhouse sector.
- **SWISS 2018 (Switzerland):** Launched in 2018, this fund provides grants that cover 60% of exploration costs (surface exploration, deep drilling) for development of a geothermal heating plant.
- **Risk Sharing Mechanism (RSM) for Geothermal Resource Validation (Türkiye):** Launched in 2017 by the Development and Investment Bank of Türkiye and the World Bank's Clean Technology Fund, this USD 355 million fund seeks to increase private sector investment in exploration drilling in Türkiye by providing partial coverage (40-60%) of exploration drilling costs for electricity generation or heating and cooling projects (Türkiye Jeotermal, 2020).

- **National Risk Insurance Programme (Hungary):** In 2021, the Hungarian Ministry of Innovation and Technology launched a HUF 6 billion (USD 15 million) national risk insurance programme for geothermal heat generation projects, offering 30-60% coverage for drilling and testing new wells, renovating old wells and constructing pipelines (Western Balkans Green Center, 2021).
- **The European GEORISK (Geothermal Risk) project:** This project was conducted between 2018 and 2021, with the aim of developing risk mitigation schemes designed to reduce resource risk through financial instruments (GEORISK, 2021). The project promoted the development of new national risk insurance schemes in several countries with untapped geothermal heat production potential (Greece, Hungary and Poland) and created a pan-European Geothermal Risk Insurance Fund.

Outside Europe, most heating and cooling projects were historically largely from multilateral and/or public financing of national risk mitigation mechanisms (*e.g.* MiRiG in Chile, the Mexican Geothermal Financing and Risk Transfer Facility) and regional risk mitigation mechanisms (*e.g.* GRMF, GDF). However, this is beginning to change. For example, since its inception in 2012, the GRMF limited eligibility to electricity generation projects. In May 2022, however, the African Union Commission's Regional Geothermal Coordination Unit hosted a GRMF geothermal heating and cooling market sounding webinar. The purpose of the webinar was to ascertain demand for heating and cooling projects in the East African Rift region, in order to establish a funding facility to support the development of heating and cooling in its next round of funding (GRMF Round 8). In December 2022, GRMF launched a risk mitigation facility focussed on heating and cooling applications (GRMF HEAT), in response to increasing interest in developing applications requiring geothermal heat in the region. The fund will offer grants for surface studies, infrastructure development and feasibility studies to geothermal heating and cooling projects.

International collaboration

The growth of geothermal heating and cooling has benefited tremendously from international and multilateral collaborations. The European Technology & Innovation Platform on Deep Geothermal (ETIP-DG) – a consortium of academia, industry, associations and research centres along the deep geothermal value chain – promotes the use of deep geothermal technology throughout Europe by achieving social, environmental and technological cost reduction (GIZ, 2022). Countries with longer histories of heat generation and well-developed technical and project development experience in geothermal heating and cooling, such as Germany, Iceland and New Zealand, are assisting countries with less mature or nascent geothermal markets. GIZ and the Central American Integration System (SICA) are co-operating intensively on geothermal technology development and initiatives, particularly for heating and cooling (Box 8).

A long-standing and wide-reaching collaboration between governments, companies and technical staff in Iceland and China has significantly contributed to accelerated development of the geothermal heating and cooling sector in China. Since the 1980s, Iceland has trained more than 70 Chinese geothermal technicians. In May 2005, the governments of Iceland and China signed memorandums of understanding, which included co-operation on environmental issues between the Ministry of Environment of the Republic of Iceland and the State Environmental Protection Administration of the People's Republic of China;

seismic research by the Ministry of Environment of Iceland and the China Seismological Bureau; and the development and utilisation of geothermal resources in Xianyang. In November 2006, Chinese and Icelandic companies established a joint venture, continuing the co-operation between the two countries in geothermal energy. The two companies have jointly developed a total of 26 million square metres of geothermal heating and built three “smoke-free cities”, in Xiongxian County and Rongcheng County in Hebei Province and Wugong County in Shaanxi Province. More than 40 cities in China have signed strategic co-operation agreements with the Icelandic entities. A China-Iceland geothermal technology R&D co-operation centre was established in December 2016. In September 2018, Iceland and China signed another memorandum of understanding on jointly building a geothermal co-operation working group made up of the Ministry of Foreign Affairs of Iceland and the Ministry of Commerce of the People’s Republic of China.

The Global Geothermal Alliance (GGA), a multi-stakeholder platform facilitated and coordinated by IRENA, offers an avenue for exchanging of experiences and best practices on geothermal development among its constituency. This includes 51 countries (represented by relevant ministries); and 55 partner institutions (such as industry associations, international organisations, multilateral development banks, academia and think tanks), as of January 2023. The GGA organised high-level meetings, workshops, webinars and other technical meetings to facilitate engagement among the stakeholders. In addition, it published various publications (see box 7) to promote geothermal development and utilisation.

The 2nd high-level meeting of the Global Geothermal Alliance.

Box 8 Using residual heat in geothermal fields to benefit local communities in El Salvador

The national company LaGeo operates two geothermal fields with total installed electricity generation capacity of 204 MW_e (95 MW_e in the Ahuachapán and 109 MW_e in the Berlin geothermal electricity plants) in El Salvador. As part of its corporate social responsibility programmes, LaGeo has envisaged using residual heat from its operating geothermal fields to benefit local communities. The geothermal heat use initiatives are managed by FundaGeo, a non-profit organisation created by LaGeo in 2006.

FundaGeo initially focused on applications tailored to the needs of the nearby communities and ways to promote the development of the local economy, with a focus on gender equality and the creation of economic opportunities for women. It undertook various investigations, created prototypes and piloted installations, in collaboration with national academic institutions, to harness heat recovered from geothermal brine pipes or abandoned wells for fruit dehydration, coffee drying, milk pasteurisation, handmade candle making and sauna bath facilities. In addition, steam condensate from the electricity plants is made available to water seedbeds that provide coffee seedlings of select quality to local growers.

GIZ has provided technical assistance to improve and scale up the geothermal heating and cooling initiatives in El Salvador and other countries in Central America. A new pilot coffee dryer was constructed to be used by communities neighbouring the Ahuachapán geothermal field. ESMAP, in co-ordination with GIZ, is providing technical assistance for the preparation of prefeasibility studies for commercial development of geothermal heating and cooling in El Salvador.

Photograph 7 **LaGeo-FundaGeo's geothermal heat use prototypes for melting wax for candle making and honey processing in El Salvador**

Source: Asunción Alas and Pabón Chavez (2019).

Photograph 8 **Geothermal-powered coffee dryer in El Salvador**

Source: IRENA (2022a).

2.3.2 Challenges and opportunities for market growth of geothermal heating and cooling

Challenges

Except in China and Europe, the geothermal heating and cooling industry is less mature than the geothermal electricity generation industry. It faces the following challenges:

- **Financing:** Access to capital is difficult and expensive, particularly for small heating and cooling projects that lack access to public financing, concessional financial instruments, cost-sharing risk mitigation schemes, fiscal incentives, grants, FiTs and subsidies, all of which usually go to large geothermal electricity generation projects.
- **Policy:** Promoting geothermal energy use for heating and cooling is a low policy priority; incentives are therefore lacking.
- **Regulatory:** Regulation typically focusses on geothermal electricity; specific legislation for heating and cooling uses is lacking. Many countries with geothermal electricity regulatory frameworks do not clearly address heating and cooling or geothermal by-products; in countries with geothermal heating and cooling regulatory frameworks, laws are often spread over many sectors.
- **Market:** The geothermal heating and cooling market is still weak or incipient in many regions. Geothermal heat for agri-food, space heating and industrial applications is more developed in China, Europe, and the United States than elsewhere. Other regions are at the demonstration stage or have only small projects; significant efforts are needed to scale the market. District heating (or cooling) systems have not yet been implemented in Latin America or Eastern Africa.
- **Institutional and technical capacity:** In many countries, technical and administrative capacity to develop geothermal heating and cooling projects is either not available or very low.
- **Technological/public awareness:** Pilot projects are needed to demonstrate technical feasibility and obtain stakeholder buy-in. Geothermal has great potential to provide integrated solutions within the renewable energy ecosystem, but integration is limited, because geothermal is less well known, technically more complex, and has a longer development time than other renewable energy sources. Pilot projects are needed to demonstrate technical feasibility and obtain stakeholder buy-in. GHPs are largely used in China, Europe and the United States; elsewhere they are not well known.
- **Resource knowledge:** Resource availability and development opportunities for geothermal heating and cooling are lacking in many countries, because reliable data, technical experience and certified technicians are not available.

Opportunities

An important recent trend is the increasing development of geothermal energy for heating and cooling. Direct utilisation of geothermal fluids for heating and cooling applications covers a wide range of resource types and characteristics (geological setting, depths, temperature, *etc.*) as well as end-user applications. Resource types range from conventional hydrothermal resources accessed by deep drilling to innovative solutions, such as the use of water in abandoned mines, the reuse of oil and gas wells for heat extraction, as well as shallow geothermal heat accessed by GHPs.

The trend is especially evident in the formation of new geothermal markets centred on the use of low-temperature resources. The opening of these markets reflects heightened awareness of the opportunities and benefits of heating and cooling applications, including economic development and job creation at the local and regional levels. Improvements in regulatory frameworks, technical assistance programmes and information dissemination will encourage the development of low- and medium-temperature geothermal resources for heating and cooling. Demonstration projects applying best practices are expected to stimulate development of these resources.

Geothermal heat pumps

The global GHP market grew by 10-11% per year between 2010 and 2020. In 2020, GHPs provided 72% of geothermal heating and cooling, with installed capacity of 77.5 GW_{th} (Lund and Toth, 2021). This capacity increased 54% from 2015 to 2020, more than doubling since 2010. The majority of GHPs are found in Europe, North America and China, although they were in use in 54 countries in 2020 (Lund and Toth, 2021). China (26.45 GW_{th}) and the United States (20.2 GW_{th}) have the most installed thermal capacity, followed by Sweden (6.7 GW_{th}), Germany (4.4 GW_{th}) and Finland (2.3 GW_{th}).

In China, the success of the GHP industry is driven primarily by strong national policies for clean heating, environmental and climate policies to reduce pollution in cities, and heating demand throughout the country and cooling demand in southern China. It is estimated that by 2035, the geothermal heat and electric installed capacities in China will double that of 2025.

In the United States, national and state policies – such as Renewable Portfolio Standards for seven states that have eligibility for geothermal heat – have been instrumental in promoting heat pumps and providing access to GHP tax credits (Box 9). The GHP industry in the United States has been steadily growing, albeit at a slower rate (3.7%) in 2015-2020 than in 2010-2015 (8.0%) (Lund and Toth, 2021; NREL, 2021).

In Europe, the GHP industry is expected to continue growing, as countries seek energy security and independence in response to the volatile price of natural gas driven by regional geopolitical conflict in 2022.

Box 9 **Geothermal heat pumps in the United States**

GHPs accounted for 98% of the total geothermal installed capacity (20.2 GW_{th}) for heating and cooling in the United States in 2020. Approximately 90% of all GHPs are closed-loop systems; 10% are open-loop systems using aquifers. 40% of GHPs are used in residential installations; 60% are for institutional and commercial use. Although GHPs are used in all states, most are installed in the eastern, midwestern and southern states (Lund and Toth, 2021).

Ball State University, in Indiana, has the largest GHP installation in the United States. It heats 20 buildings and cools 47 buildings. Installed in 2012, it includes 3 600 vertical closed-loops (Ball State University, 2012; Lund and Toth, 2021).

Heat pump manufacturers claim that GHPs are the most cost-effective, energy-efficient and environmentally friendly way to heat and cool buildings (Atlantic Council, 2021). The large number of installed heat pumps in the United States and the rapid growth of the industry are likely related to the federal tax credit system and rebates in several states. A 30% federal tax credit was available in 2008-2016 (Dandelion Energy, 2022). In 2018, it was reinstated, although reduced. A 26% federal tax credit for residential ground-source heat pumps was in effect until 31 December 2022. In 2023, it decreased to 22% expires at the end of 2023.

Regulatory conditions have also created incentives to use residential GHPs. In communities without access to gas where new pipelines will not be built, consumers and utilities turn to GHPs as renewable energy alternatives (Atlantic Council, 2021).

Barriers to upscaling GHP utilisation are related mostly to permitting and licensing, which are often complicated and vary across the country (Atlantic Council, 2021).

Photograph 9 **Ball State University's geothermal heat pump system, the largest in the United States**

Source: Contractor Magazine (2011).

Advances in district heating and cooling systems

Geothermal district heating systems are found in 30 countries, predominantly in Eurasia, where more than 240 systems have been installed. The regions with the largest installed capacity for geothermal district heating systems are Asia (China) and Europe (France, Germany, Iceland and Türkiye) (Lund and Toth, 2021). In Iceland, geothermal space heating is prevalent throughout the country. Geothermal energy provides 90% of heat for the capital city (Reykjavík); 28 communities and cities that use geothermal energy for district heating; and 200 small systems in rural areas that supply hot water to farms, greenhouses and other users.

Geothermal district heating systems are less common outside Eurasia. Small-scale systems can be found in Japan, the Republic of Korea, New Zealand and the United States.

In North America, geothermal district heating has seen limited development since the early 1990s. Significant potential could be rapidly developed in many sites in the United States and Canada, driven by national efforts to decarbonise the heating and cooling sectors. Improvements in policy, regulation, federal funding for technological innovation, tax credits and subsidies are required to trigger faster growth (Strauss, 2022; NREL, 2021).

More than 25% of Europe's people live in areas suitable for geothermal district heating representing a large area for growth, especially in transitional and nascent markets. Key areas to improve the enabling environmental for geothermal district heating in Europe include the removal of regulatory barriers, the simplification of procedures for operators, the development of innovative financial models for capital-intensive projects, and the training of technicians and decision makers of regional and local authorities, so that they have the technical background necessary to approve and support projects (GeoDH, 2014).

Agri-food and industrial uses

Geothermal energy provides heat for a range of agri-food and industrial uses, depending on the temperature of geothermal fluids. Lower-temperature applications, such as greenhouses and fish farming, are used throughout the world. Industrial processes such as milk pasteurisation and food dehydration require higher-temperature geothermal fluid and are therefore often developed in association or cascaded with electricity-producing geothermal fields, as they are in El Salvador, Iceland, Kenya, Mexico and New Zealand. Cascading utilising residual heat from operating electricity plants occurs at geothermal fields in Mexico (Domo San Pedro, for fruit dehydration) and El Salvador (Ahuachapán and Berlín, for fruit drying, coffee drying and candle making) (Box 8). In Kenya, geothermal heating is implemented at Eburru (for agricultural drying); at the Oserian flower farm near Olkaria (for greenhouse heating using a cyclic geothermal well that is not usable for electricity generation); at the Menengai Geothermal Field (for laundry washing and drying, milk pasteurisation, aquaculture, greenhouse heating and a grain dryer demonstration project); and at the Olkaria Spa.

Development of geothermal heating and cooling–powered agri-food projects is often slowed by the lack of policy and regulatory framework and the lack of financing (*e.g.* in Eastern Africa, Latin America). In order to improve the economics of smaller geothermal electric projects, countries on the western branch of the East African Rift are considering integrating the development of heating and cooling with electricity generation. In Uganda, feasibility studies indicated that the combination of binary electricity generation and heating and cooling applications such as heated aquaculture, greenhouses, and fish and salt drying are economically viable. In the United Republic of Tanzania, the state-owned geothermal company is developing heating and cooling applications using hot water discharged from a shallow slim well drilled in 2021. In Zambia, in 2022, firms were invited to take part in the development of heating and cooling projects, including aquaculture, drying of crops and chicken production using hot water discharged from slim wells drilled in the Bweengwa River project area.

Geothermal agri-food and industrial applications are being incorporated into eco-industrial parks (see Box 10). These developments aim to foster economic growth, create jobs, encourage sustainable development, encourage community collaboration and offset climate change while lowering costs and energy use by increasing efficiency (UNIDO, 2016). Industrial eco-parks can be built around a primary geothermal heat and electricity source. Geothermal installations have stable production and a low geographic footprint; they can be low cost and relatively low maintenance.

Geothermal heat in an eco-industrial park is typically distributed through a cascading approach, supplying energy to off takers with progressively lower temperature demands. At the Kawerau geothermal field in New Zealand, a geothermal industrial park with several heating and cooling applications (paper and pulp mill, wood drying, dairy processing and greenhouses) has been in operation since 1957, in association with 156 MW_e of electricity generation. The heat generated can also be used outside the industrial eco-park, for district heating and other lower-temperature applications (USEA, 2020). In Svartsengi, Iceland, a geothermal plant that combines electricity generation (75 MW_e) and hot water production provides the heat for a 150 megawatts thermal (MW_{th}) district heating system that serves 21 000 homes. The waste heat from the geothermal plant is used in the Blue Lagoon for bathing and algae production. A methanol plant uses 5 MW_e of geothermal electricity and captures 10% of the CO_2 emitted by the geothermal plant, producing 5 million litres of methanol and recycling 500 tonnes of CO_2 annually. Between each cascading step, heat pumps can boost the temperature of the geothermal-heated water. Depending on the location, the geothermal resource can produce water, CO_2 and other gases, and/or mineral resources, making geothermal energy particularly beneficial for an eco-industrial park that creates symbiosis between industries with water, heat and electricity demands.

Collaboration with local communities to ensure their involvement in development is vital to fully achieve the socio-economic potential of an eco-industrial park and the positive effects it can have locally (UNIDO, 2016). At Kawerau, a Maori organisation, Ngati Tuwharetoa Geothermal Assets Limited (NTGA), owns and manages the resource that provides steam for industrial processes and electricity generation.

In 2020, global installed geothermal capacity for agri-food and industrial uses was 14 GW_{th}, 35% more than in 2015. This sector grew at an annual rate of 4-7% between 2000-2020 and is expected to continue growing at similar rates (Lund and Toth, 2021). Market opportunities are expected from using geothermal energy to provide refrigeration in the supply chain and desalinisation using geothermal heat.

Box 10 Opportunities for geothermal industrial eco-parks

Geothermal eco-parks represent an area for growth in the agri-food and industrial sector. Opportunities exist in Guatemala, Kenya, New Zealand and Türkiye.

Guatemala

San Michkael is a mini-geothermal industrial park in Amatitlan that has been in operation since 2013. Two wells provide energy to generate 25 kW of electricity and heating applications in cascade. Separated steam is used to make wax candles; separated hot water is used to dry fruits, vegetables and grains; and to melt plastic (Paiz, 2021). Planned additions to the park include installation of refrigeration units and a small-scale binary electric plant for internal consumption, with the ultimate goal of converting San Michkael into an economically self-sustaining demonstration pilot project (Paiz, 2021).

Kenya

At least three industrial parks are planned for development at the Menengai and Olkaria geothermal fields, where geothermal energy will support local agro-businesses. Given the importance of agriculture in Kenya, there is significant potential for application of geothermal heat in agri-food, horticulture and food processing; geothermal energy could also be used to produce textiles and process leather (Kiruja, 2017). The eco-industrial parks would be developed within special economic zones, which provide tax exemptions and other fiscal incentives to investors.

Türkiye

Türkiye has more than 300 organised industrial zones across more than 80 cities, many of which are incorporating "green" infrastructure and renewable energy sources (World Bank, 2021). Eleven geothermally heated greenhouses are located within agricultural specialised organised industrial zones (ASOIZs), which aim to integrate the agriculture and industrial sectors (Ülgen, 2022). Modern hi-tech commercial geothermal greenhouses (fully automated and energy efficient, with 100% reinjection) are eligible for a variety of tax exemptions, grants, loans and state-supported greenhouse insurance, as well as access to social facilities, laboratories, export offices and infrastructure within the ASOIZ (Photograph 10).

New Zealand

He Ahi is a 45-hectare industrial zone site owned by the Maori trust Te Pae o Waimihia (Photograph 11). The planned energy park will offer custom-built business lots (less than 1 hectare each) that have access to geothermal heat for industrial processing and heating purposes supplied by Contact Energy (Amplify, 2022). The eco-park is expected to create new jobs, stimulate local investment, reduce environmental impact, preserve Maori values, benefit local communities and contribute to a sustainable energy future (ThinkGeoEnergy, 2022f).

Box 10 Continued

Photograph 10 Commercial greenhouses in an industrial zone in Türkiye

Source: Ülgen (2022).

Photograph 11 Planned He Ahi Clean Energy Park in New Zealand

Source: Amplify (2022).
Note: The site of the energy park is outlined in white.

3. REGIONAL HIGHLIGHTS AND OPPORTUNITIES

Chapter 3 elaborates on specific regional highlights, challenges and opportunities. The selection of the geothermal regions is introduced in Chapter 2 (Figure 4). Each region's distinct geography, geologic conditions, electricity markets, national policies and enabling frameworks have led to different paths in the development and use of geothermal resources.

3.1. ASIA AND OCEANIA

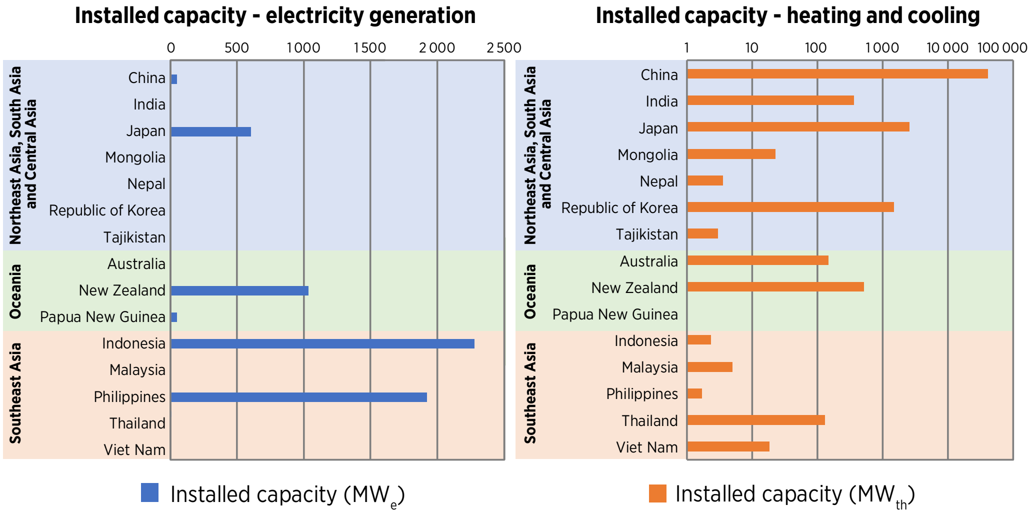
The Asia and Oceania region extends from Mongolia to New Zealand, encompassing the western Pacific countries. The region can be sub-divided into three significant geothermal sub-regions: namely (i) Northeast Asia, South and Central Asia; (ii) Southeast Asia; and (iii) Oceania.

3.1.1. Electricity generation

The Pacific Ring of Fire along the western Pacific Ocean is the source of the magmatic heat that underlays the considerable high-temperature geothermal resources of many of the countries in the region. Exploration and development first took place in New Zealand in the 1950s (Wairakei and Kawerau geothermal fields) and in Japan in the 1960s (Matsukawa and Otake geothermal fields). Soon after, development began in Indonesia (Kamojang geothermal field) and the Philippines (Palinpinon/Southern Negros geothermal field) with assistance from the New Zealand government in the 1980s. National governments carried out the initial developments; today there is a mix of public, public-private and private ownership. In recent decades, other countries such as China (Yangbajing Geothermal Plant in 1991) and Papua New Guinea (Lihir geothermal plant in 2003) have brought geothermal electric plants online.

As of 2022, seven countries in the region operated geothermal plants: China, Indonesia, Japan, New Zealand, Papua New Guinea, the Philippines and Thailand. The region's total installed geothermal capacity for electricity generation is about 6 GW_e, representing 37% of the world's installed geothermal electricity capacity. Three countries from the region are among the "top 10" geothermal electricity-producing countries worldwide. Indonesia leads with the region's largest installed capacity for electricity generation (2 267 MW_e), followed by the Philippines (1 918 MW_e) and New Zealand (1 037 MW_e). Japan is fourth with an installed capacity of 603 MW_e (Huttrer, 2021; ThinkGeoEnergy, 2022a). In New Zealand, geothermal satisfies 22% of the national electricity demand; in other countries the contribution is smaller (*e.g.* 12% in the Philippines, 6% in Indonesia and 0.3% in Japan). Installed geothermal electricity capacity is 46.7 Mw_e in China, 56 MW_e in Papua New Guinea and 0.3 MW_e in Thailand (where resources are lower temperature).

Figure 11 Installed geothermal capacity by country in Asia and Oceania region - 2021



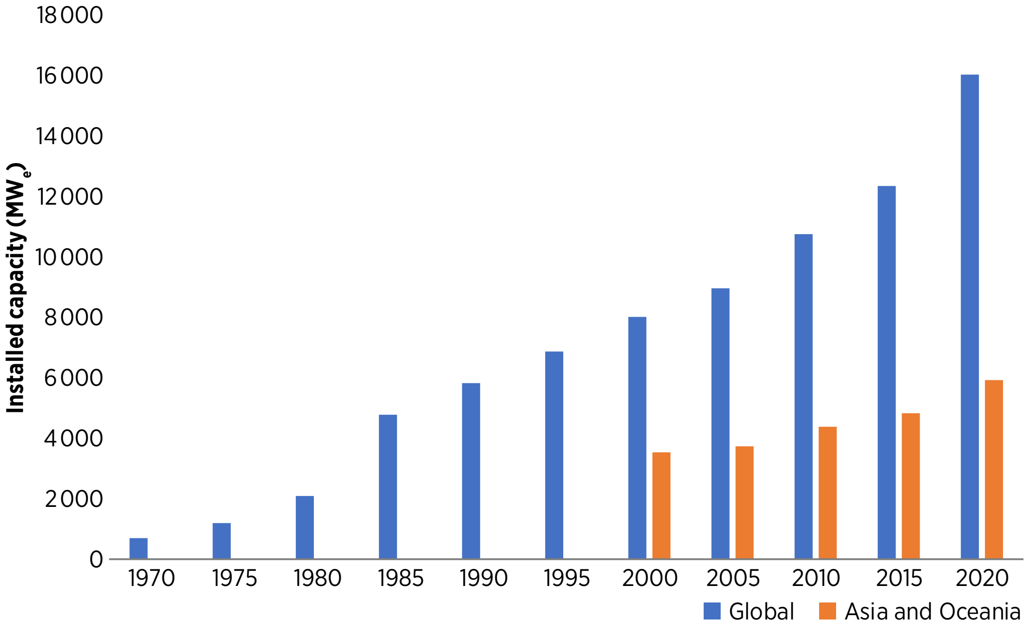
Source: Huttrer (2021); ThinkGeoEnergy (2022b); Lund and Toth (2021).

Figure 12 compares the Asia and Oceania region's geothermal growth trend with that of the world. In the last 20 years, global geothermal electricity capacity increased at an average annual rate of 3.2%; Asia and Oceania experienced a slightly slower pace of 2.4% per year, driven by growth in Indonesia and New Zealand (Figure 13).

In Indonesia, large-scale geothermal electricity production continues to increase rapidly thanks to expansions of existing projects and new development in Sumatra. Since 2015, Indonesia has added over 930 MW_e; this is an 8% increase per year, or almost three times the global average. Despite logistical challenges due to the global pandemic in 2020 and 2021, drilling operations continued uninterrupted in many Indonesian fields. In 2021, 143 MW_e were added in Indonesia (the 45 MW_e Sorik Marapi Unit 2 and the 98 MW_e Rantau Dedap). The same year, 32 MW_e were added in New Zealand (through the Ngawha expansion project).

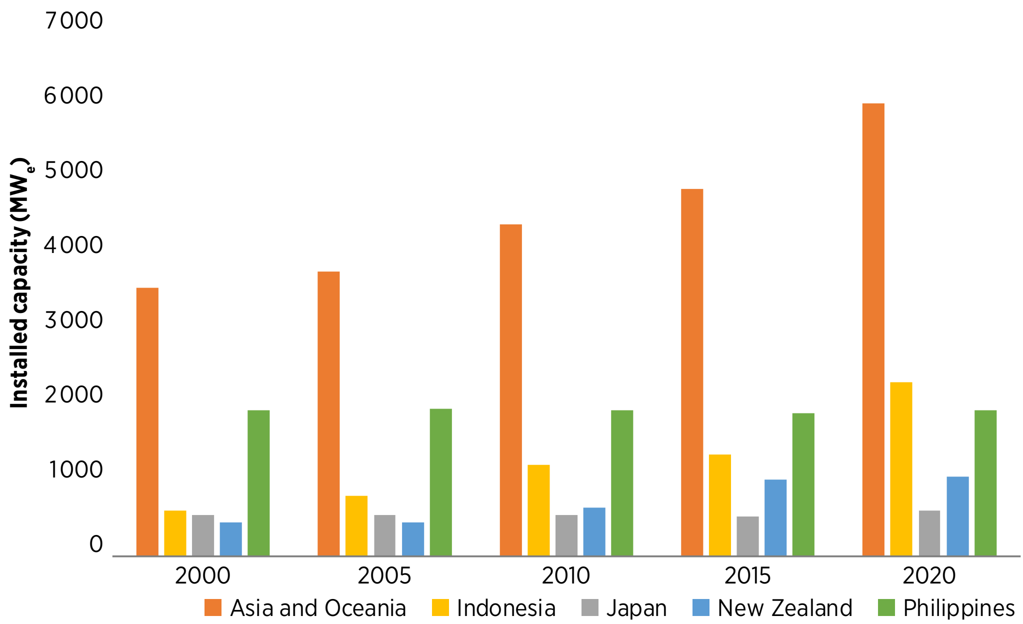
In Japan, many smaller-scale projects (*i.e.* of less than 5 MW_e each) have come online in recent years. Since 2015, the growth rate in Japan (at 2.8% per year) has overtaken that of New Zealand (0.6% per year) and the Philippines (0.5% per year)

Figure 12 Growth of geothermal electricity capacity in the Asia and Oceania region



Sources: ThinkGeoEnergy statistics, ThinkGeoEnergy (2022b), Huttrer (2021), Uihlein (2018), and Bertani (2015).

Figure 13 Growth of installed geothermal electricity capacity in Asia and Oceania; national level



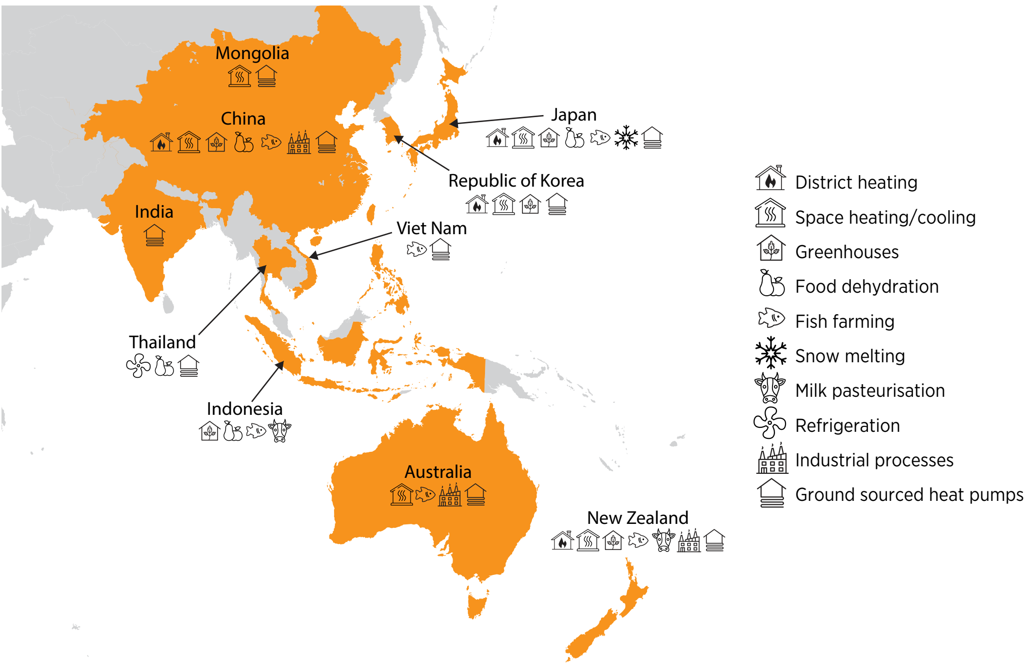
Sources: ThinkGeoEnergy statistics, ThinkGeoEnergy (2022b), Huttrer (2021), Uihlein (2018), and Bertani (2015).

3.1.2 Heating and cooling applications

Utilisation of geothermal heat is widespread throughout the Asia and Oceania region, especially in China, Republic of Korea, Japan, New Zealand and India (Figure 14). Heating and cooling agri-food applications include fish farming, greenhouses, milk pasteurisation and food dehydration. With the exception of China, geothermal district heating systems are not common in the region, mainly owing to the warm climate in Southeast Asia.

With an installed capacity of 40.6 GW_{th}, which accounts for 38% of geothermal heating and cooling utilisation worldwide, China is a global leader in ground-source heat pumps and geothermal district heating. China promotes the development of geothermal energy and encourages its development and utilisation. Cities implement geothermal energy development action plans suitable for local development, including planning guidance, policy support, demonstration projects, geothermal standards and scientific research. Geothermal energy has been developed according to local climate, environmental, rural revitalisation and other policies in both north and south mainland China. Most cities in northern China actively support geothermal heating technology through clean heating policies and environmental climate control. Meanwhile, in certain prosperous areas of southern China, characterised by hot summers and short but cold winters, there is a strong demand for heating and cooling with geothermal energy, with corresponding supply chains and skilled technicians.

Figure 14 Geothermal heating and cooling applications in Asia and Oceania



Base map prepared using https://mapchart.net/.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

3.1.3 Regional market and technology trends

Electricity generation

New government policies and fiscal incentives for renewable energy sources, including geothermal energy, have been launched in China, Indonesia and Japan.

Indonesia aims to achieve 3.3 GW_e of installed geothermal capacity by 2030. To promote accelerated investment in geothermal, the Indonesian Presidential Regulation for the Acceleration of Renewable Energy Development for Power Supply was issued in 2022. The new regulation forecasts reduced dependence on coal, establishes a tariff ceiling structure for renewable energy sources and provides government support for geothermal-specific incentives (Assegaf Hamzah & Partners, 2022). The tariff ceiling for geothermal power plants ranges from USD 0.065/kWh to USD 0.107/kWh depending on plant size and location. These prices are lower than power purchase agreement (PPA) prices for some operating geothermal power plants and lower than other feed-in tariffs (FiTs) in the region (*e.g.* in China and Japan). It is yet to be seen if the new tariff structure will accelerate investment as intended. In 2020, the World Bank launched the Geothermal Resource Risk Mitigation Project in Indonesia. The project established a USD 455 million drilling risk mitigation fund, as well as a USD 10 million fund for technical assistance and capacity building.

Renewable energy FiTs for geothermal are offered in China and Japan. In Japan, developers have favoured the development of small binary plants, enabled by government-supported incentives in the aftermath of the Fukushima nuclear incident of 2011 (as highlighted in Box 2 in Chapter 2). Small-scale electricity plants (15 MW_e or less) carry less risk than larger plants, do not require extensive exploration for operationalisation and have been incentivised by a higher FiT – JPY 40/kWh (USD 0.35) – than that for larger plants, JPY 26/kWh (USD 0.23). Since the FiT scheme was launched in 2012, more than 60 geothermal plants of less than 2 MW_e each have been built across 45 geothermal fields in Japan (Imamura *et al.*, 2020).

Meanwhile in China, in 2021 and 2022, the FiT for geothermal electric power was divided into two categories by project size: USD 0.21/kWh for plants less than 2 MW_e and USD 0.19/kWh for plants greater than 2 MW_e. In 2022, the Ministry of Economic Affairs added a new incentive for indigenous communities to benefit from profits (MOEA, 2022).

In New Zealand, local indigenous communities' co-operation in geothermal development and Maori project ownership is recognised as an achievement worldwide in community involvement in geothermal projects. These types of programmes can provide valuable lessons for other countries seeking to ensure geothermal projects' co-benefits for indigenous communities.

The rising number of small-scale binary plants in Asia and Oceania centre on abundant hot springs in Japan; residual heat from a high-enthalpy-producing field in the Philippines; and medium- and low-enthalpy geothermal reservoirs in China and Indonesia.

In the Philippines, a 3.6 MW_e organic Rankine cycle (ORC) bottoming binary plant at Mindanao-3 came online in April 2022. Built during the global pandemic, the plant uses residual heat from the geothermal brine of the existing Mindanao-1 and Mindanao-2 flash plants, thus increasing the total electricity generation at Mindanao without drilling more wells. This represents an innovation in fields with existing flash plants, to optimise the use of the resource and improve project economics (Exergy, 2022). The chemical composition of the geothermal brine restricts how much energy can be extracted without resulting in excessive scaling.

Meanwhile in Indonesia, a small-scale 0.5 MW_e low-temperature demonstration pilot plant at Lahendong was constructed by government-owned Pertamina Geothermal Energy (PGE) with funding from the German government (GeoForschungsZentrum [GFZ] German Research Centre). The intention is that PGE would apply similar small-scale developments at its other concession areas across Indonesia. The private sector has also shown interest in developing small-scale binary plants (*e.g.* at Flores Island in East Nusa Tenggara).

The Cingshuei plant in China, with 4.2 MW_e installed capacity producing from a 180°C geothermal reservoir, was inaugurated in November 2021. The project was made possible by favourable FiTs, government incentives and simplification of the concession application procedures to encourage private sector investment.

Heating and cooling

China has rapidly developed its geothermal resources, becoming a global leader in the utilisation of geothermal heat. Regulations requiring energy conservation and pollution reductions are the catalysts of this rapid development. The average annual growth rate is more than 20%. The country's first geothermal industry plan, the "13th Five-Year Plan for Geothermal Energy Development and Utilisation", provides policy support to enable this rapid growth. In addition, China is leveraging its oil and gas experience to support geothermal development through joint ventures with geothermal industry players. In recent years, China has developed cities such as Xiongxian within the Xiong'an special economic zone, where heating is 100% clean, using geothermal district heating systems.

In New Zealand, there is a push to further develop geothermal industrial parks. He Ahi is planned as a clean energy park in Taupo, New Zealand (described in further detail in Chapter 2, Box 10). New ventures build on 60 years of experience at the Kawerau geothermal field, where there are multiple heating and cooling applications – a paper and pulp mill, wood drying, dairy processing and greenhouses – in addition to electricity production.

Indonesia is focussing on geothermal heating and cooling as it progresses towards its energy transition targets. Several geothermal laws and regulations enacted since 2020 have streamlined permitting and licensing procedures. These include Law No. 11 of 2020 (the legal basis for job creation) and Regulation No 5 (geothermal exploitation business licensing standards). In November 2022, the Government of Indonesia convened sessions for project developers and investors to receive technical guidance on applying for geothermal heating and cooling permits (EBTKE, 2022).

Geothermal heat pumps

Heat pumps are growing in popularity in China, Japan and the Republic of Korea. China leads the world in heating and cooling use of geothermal energy, including geothermal heat pumps (GHPs), in terms of installed capacity (40 610 MW_{th}) and annual energy use (443 492 terajoules/year) (Lund and Toth, 2021). In 2020, GHPs accounted for 65% of the installed capacity of geothermal energy in China and 55% of annual geothermal energy use. In the Repulic of Korea, GHP installation has increased rapidly, with 100 MW_{th} installed per year from 2012 to 2020. Growth was mainly driven by a new renewable energy policy; several government subsidies for building local, residential and hybrid programmes (up to 50% of total installation costs subsidised); as well as an agricultural energy efficiency programme under which farmers bear only 30% of the cost for greenhouses and aquaculture (Song and Lee, 2021). Since 2014, the agricultural energy efficiency programme has supported approximately 10 MW_{th} of new installations annually. GHP use in Japan is still minimal (163 MW_{th}) but is anticipated to grow rapidly owing to government incentives (Yasukawa *et al.*, 2021).

Research in supercritical fluids

In line with New Zealand's aspiration to be "carbon neutral" by 2050, a research consortium is developing a supercritical heat strategy for 2020-2050. The strategy addresses legal, regulatory, technological, economic and other challenges to utilising supercritical resources, building upon scientific research which leverages international experience (Climo, Carey and Mroczek, 2016). Research focusses on delineating supercritical resources in the Taupo Volcanic Zone, understanding the thermochemical characteristics of supercritical fluids and communicating scientific findings to stakeholders.

Japan is also conducting research on supercritical fluids through the New Energy and Industrial Technology Development Organization (NEDO). NEDO's project, "Subduction origin for supercritical geothermal resources", targets electricity generation using supercritical geothermal resources by 2050 (Yasukawa *et al.*, 2021).

Enhanced geothermal systems

In 2010, a DESTRESS enhanced geothermal (EGS) demonstration project was launched in Pohang, Republic of Korea, with the objective of generating 1 MW_e using a doublet system. Following the drilling of two deep wells (greater than 4 km depth), hydraulic stimulations were conducted in 2016 and 2017. A magnitude 5.5 earthquake occurred in November 2017, two months after the last hydraulic stimulation, in the vicinity of the site (Song and Lee, 2021). The earthquake prompted the suspension of all research activities at Pohang and multiple investigations, which determined that the earthquake was a result of geothermal hydraulic stimulation (Lee *et al.*, 2019). As of 2021, all deep geothermal exploration nationwide was on hold amid public concerns over seismic hazards and potential damage caused by EGS activities (Song and Lee, 2021). The Pohang earthquake was the largest earthquake caused by EGSs, and this experience highlights the challenge of managing induced seismicity from EGS projects.

Mineral extraction from geothermal brine

New Zealand is advancing technology to extract minerals like silica, lithium, boron, rubidium and caesium from geothermal brines. Research on the commercial potential and processing technology of mineral recovery from geothermal brines was carried out from 2013 to 2015 by scientific institutions funded by the government programme "From Waste to Wealth" (Climo, Carey and Mroczek, 2016). A resulting study highlighted the interconnections between technology, economics, market drivers, business risks and legal frameworks, which contribute to economic viability – the main driver of mineral recovery projects' successful development. Removing silica from reinjection brine reduces scaling potential and the need to chemically treat brine, reducing operation and maintenance costs, and well workovers, thus streamlining plant operations and generating a productive use of geothermal fluids. In 2021, the world's first sustainable large-scale commercial silica recovery plant from geothermal brine was commissioned at Ohaaki geothermal field, New Zealand (Geo40, 2022). Tests to extract lithium from the brine were also performed, and a pilot project is planned for this same field (Box 4, Chapter 2).

3.2 AFRICA AND THE MIDDLE EAST

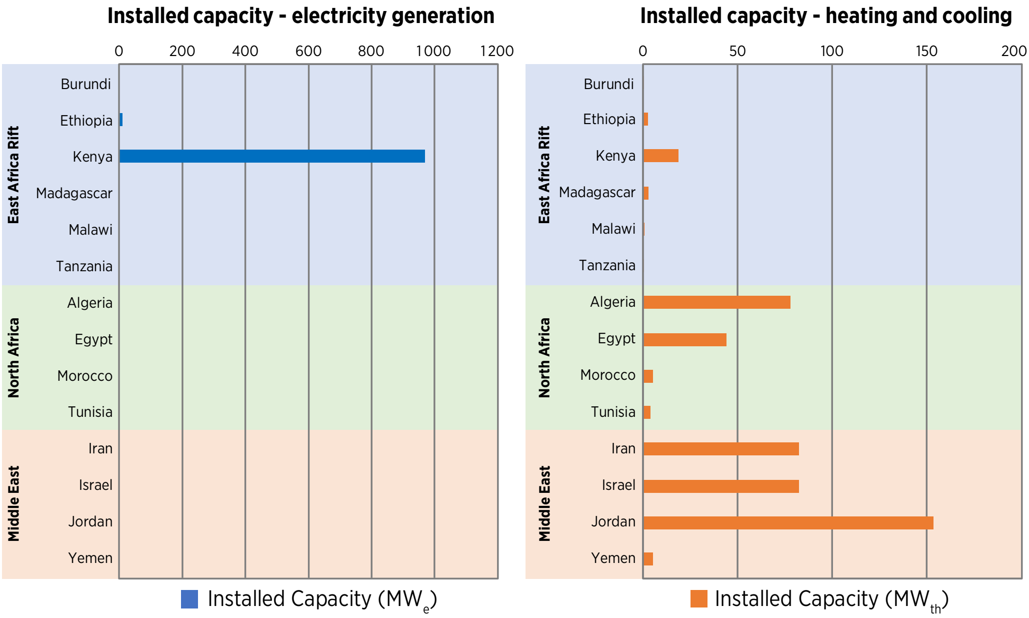
The Africa and Middle East region covers the entire African continent and extends across the Arabian Gulf to the Islamic Republic of Iran. The region can be sub-divided into three major geothermal sub-regions: the East African Rift, North Africa and the Middle East.

3.2.1 Electricity generation

The volcanically heated geothermal systems of the East African Rift extend across eastern and southern Africa. The first geothermal power plant in the region was developed in 1953 at Kiabukwa (Katanga) in the Democratic Republic of Congo as a pilot with a capacity of 0.45 MW_e. At Kiabukwa, geothermal electricity was generated from a hot spring to supply electricity for mining operations until the nearby mine was abandoned in 1960. Today, the Eastern Africa sub-region has an installed capacity of 978 MW_e. The vast majority of geothermal electricity is generated in the Olkaria geothermal field in Kenya, where six electricity plants produce 967 MW_e, including wellhead units with a total capacity of 81 MW_e. Smaller power plants are at Eburru geothermal field in Kenya (2.52 MW_e) and Aluto Langano geothermal field in Ethiopia (8.5 MW_e) (Figure 15).

Kenya is among the top ten geothermal electricity-producing countries worldwide (Huttrer, 2021; ThinkGeoEnergy, 2022a). In 2019, geothermal comprised 29% of the national electricity installed capacity and 47% of the electricity consumed (Omenda *et al.*, 2021).

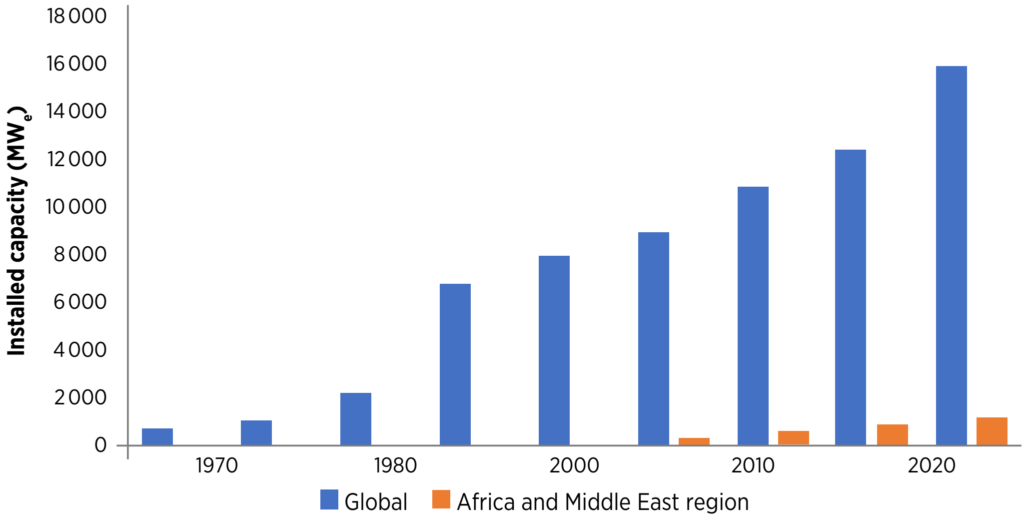
Figure 15 Installed geothermal capacity by country in the Africa and Middle East region - 2021



Source: Huttrer (2021); ThinkGeoEnergy (2022b); Lund and Toth (2021).

The current installed capacity of the region is 978 MW_e, which accounts for about 5% of the global total (16 GW_e). Figure 16 compares the region's growth with the global trend. Kenya's geothermal market is one of the fastest-growing worldwide. In the last ten years, Kenya sustained an annual growth rate of 6-13% per year, well above the worldwide average of 2-4.6% per year. During 2000-2014, 472 MW_e were brought online, followed by 218 MW_e more during 2014-2019 (Omenda *et al.*, 2021). In 2022, a further 86.6 MW_e were brought online. Kenya's rapid growth is attributed to substantial public financing and risk mitigation funding combined with favourable government policy that supports private sector investment and incentives.

Figure 16 Growth of installed geothermal electricity capacity – global vs Africa and Middle East



Source: ThinkGeoEnergy statistics and ThinkGeoEnergy (2022b), and other recent geothermal market updates (Huttrer, 2021; Bertani, 2015).

The East African Rift has great geothermal potential for electricity generation; many projects are in the exploration and development phases in Djibouti, Ethiopia, Kenya, United Republic of Tanzania and Uganda. Projects at advanced phases of development include production drilling and surface facilities installed at Menengai, where a 35 MW_e unit (still under construction as of October 2022) is anticipated to be developed and expanded to 105 MW_e. Also in Kenya, exploration drilling has been conducted in the Baringo-Silale geothermal block, and the Olkaria geothermal field is to be expanded. Djibouti is host to exploration drilling and well testing at Asal-Fiale, and exploration drilling at Gale-Le-Goma (ongoing as of October 2022). Ethiopia has seen exploration drilling at Tendaho and Tulu Moye, and production drilling at Aluto Langano; exploration drilling is also planned at Corbetti (150 MW_e anticipated) (IRENA, 2020). Advanced surface exploration projects in the region include planned exploration drilling at Karthala volcano in Comoros; drilling of a shallow slim well at Keijo Mbaka in the United Republic of Tanzania; drilling temperature gradient wells in Kibiro and Panyimur in Uganda and drilling of temperature gradient and slim wells along the Bweengwa River in Zambia.

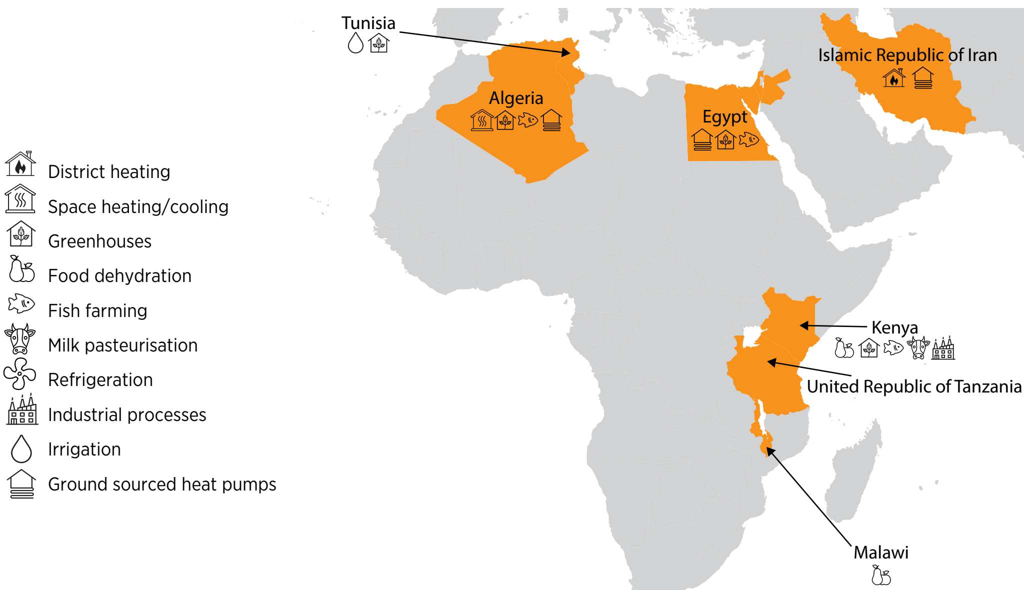
Beyond the East African Rift sub-region, the Islamic Republic of Iran is the only other location in the Africa and Middle East region with near-term potential for electricity generation development. Exploration drilling and resource evaluation at the Meshkinshahr geothermal field indicate the short-term viability of installing 5 MW_e with a long-term goal of generating 55 MW_e (Huttrer, 2021; Mousavi and Jalilinasrabady, 2021).

The Government of Oman recently initiated a project to assess the country's geothermal potential using data obtained from over 7 000 oil and gas as well as water wells. In Saudi Arabia, efforts to develop geothermal resources along the Red Sea coast are at an early stage.

3.2.2 Heating and cooling

Geothermal energy is used for heating and cooling throughout the Africa and Middle East region (475 MW_{th} installed capacity). The Middle East sub-region (323 MW_{th} installed capacity) leads, followed by North Africa (131 MW_{th} installed capacity) and the East African Rift (24 MW_{th} installed capacity) (Figure 17). Aside from swimming and bathing, geothermal heating and cooling applications across the region include fish farming in Algeria, Egypt, Israel, Jordan and Kenya; greenhouses in Algeria, Egypt, Israel, Kenya, United Republic of Tanzania and Tunisia; agricultural drying in Kenya and Malawi; milk processing in Kenya; irrigation in Tunisia; heat pumps in Algeria, the Islamic Republic of Iran and Jordan (Lund and Toth, 2021); and an egg hatchery in Tanzania (Kajugus, 2022).

Figure 17 **Geothermal heating and cooling applications in the Africa and Middle East region**



Source: Base map prepared using https://mapchart.net/.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

3.2.3 Regional market and technology trends

Electricity generation

To a large extent, geothermal development in the region has been led by the public sector, particularly in the East African Rift. For example, in Kenya, the state-owned utility/generating company developed geothermal projects until the late 1990s, when regulatory reforms allowed independent power producers to generate geothermal electricity. Kenya's state-controlled electricity generator accounts for 799 MW_e of the country's total installed geothermal electricity capacity of 970 MW_e. Other countries in the region, such as Djibouti and the United Republic of Tanzania, have also established state-owned corporations to lead geothermal development. Such public entities are involved in the de-risking of geothermal fields in their respective countries by carrying out surface studies and early-stage drilling, mobilising funds for geothermal development, building the geothermal expertise of the countries through recruitment and training, and acquiring drilling rigs and laboratory equipment. Also, regulatory reforms in many countries have opened up the geothermal sector to private developers. A private developer in Kenya has set up installed capacity of 171 MW_e. Geothermal fields in Ethiopia, Kenya, Malawi, Uganda and Zambia are licensed to private sector developers. The government-controlled electricity generator in Kenya is in the process of engaging in a public-private partnership for the construction and operation of a 140 MW_e geothermal electric plant.

Policy instruments, such as FiTs and PPAs, in addition to tax incentives in some countries like Ethiopia and Kenya, have contributed to making the markets attractive for private sector investment (IRENA, 2020). In 2021, Kenya constituted a presidential task force to review PPAs and address high electricity tariffs. The task force recommended the suspension of negotiations for new PPAs amid idle capacity which the utility is obliged to take or pay. It also recommended the renegotiation of existing PPAs, particularly those with high tariffs. Any future PPAs, the task force suggested, should be based on the principles of least-cost development, which favours renewable energy (ENS Africa, 2021). In Ethiopia, the signing of PPAs with two private developers allowed projects in Tulu Moye and Corbetti to move forward and raised the financing for exploration drilling. Drilling in Tulu Moye began in 2020; an initial planned capacity of 50 MW_e will, over time, be expanded to 150 MW_e and eventually 500 MW_e (Hawilti, 2022). Corbetti is expected to be developed in similar phases. However, lengthy PPA negotiations slow the development of geothermal projects in Ethiopia, as indicated by several private developers.

Ongoing regulatory and legal reforms in the region's geothermal sector aim to establish dedicated licensing procedures for geothermal development. The only countries in the region with dedicated geothermal laws are Ethiopia and Kenya, while Ethiopia is the only one with a law dedicated to geothermal heating and cooling. The Comoros and Djibouti have already initiated developing dedicated regulatory frameworks focussing on the geothermal sector (IRENA, 2020).

The Geothermal Risk Mitigation Facility for Eastern Africa (GRMF) has been in operation in the region since 2012 to support early-stage development of geothermal projects in 12 countries: Burundi, the Comoros, the Democratic Republic of Congo, Djibouti, Eritrea, Ethiopia, Kenya, Rwanda, Somalia, United Republic of Tanzania, Uganda and Zambia.

As of December 2022, about USD 131 million had been awarded in grants to 40 projects across six countries in the region (GRMF, 2022). However, various regulatory and policy barriers, as well as difficulty in raising counterpart funding, have limited fund utilisation. Another risk mitigation scheme in the region is the insurance-based facility, Geofutures GreenInvest, which targets Ethiopia and Kenya. Although not yet in operation, the facility will seek to crowd in private sector insurance underwriting funds from both local and international companies to support geothermal development in the region (GeoFutures GreenInvest, 2022).

The Africa Rift Geothermal Facility (ARGeo Programme) was established in 2010 to promote geothermal development in the East African Rift through the building of networks, capacity development, awareness creation, policy advice and technical assistance for surface studies. The programme is hosted by the United Nations Environment Programme. Within the framework of ARGeo, the African Geothermal Centre of Excellence (AGCE) was established to support regional capacity-building efforts. AGCE's mandate was to address the shortfall in skills to enable the region to achieve its geothermal development goals by supporting training to establish a critical mass of geothermal engineers and scientists.

Heating and cooling

The East African Rift comprises two main branches – the eastern and the western – each with distinct geological settings. The eastern branch runs through Djibouti, Ethiopia, Eritrea and Kenya, and is characterised by high-temperature volcano-hosted geothermal resources. The western branch, running through Uganda, United republic of Tanzania, Malawi, Mozambique and Zambia, is characterised by fault/fracture-hosted low-medium temperature geothermal resources. This means that while the eastern branch's resources are suitable for developing large-scale electric power projects using flash steam technology, those in the western branch are more suited to smaller-scale electricity projects using binary technology as well as heating and cooling uses.

A 2016 regional workshop focussed on the western branch suggested that the development of direct heating and cooling applications presents significant opportunities for economic advancement. The outcome statement of the 7th African Rift Geothermal Conference, held in 2018, recommended mainstreaming direct heating and cooling applications of geothermal energy across African countries.

Consequently, geothermal developers in Kenya and the United Republic of Tanzania have developed demonstration projects for geothermal heating and cooling, such as greenhouses and aquaculture heating, milk pasteurisation, grain drying, egg hatcheries and bathing. Developers are at different stages of developing geothermal energy/industrial/resource parks to attract commercial-scale developers of geothermal heating and cooling projects. Other countries, including Uganda, Somalia, Malawi and Zambia, among others, are considering developing geothermal heating and cooling applications prior (or in combination with) electricity generation projects.

In May 2022, the GRMF organised a geothermal direct-use market-sounding webinar to gain an understanding of whether there was sufficient interest in geothermal heating and cooling in the region, to justify the establishment of a financing facility. Following the positive outlook obtained during the webinar, the facility launched the GRMF HEAT, a funding facility to support geothermal heating and cooling projects to undertake surface and feasibility studies.

To support accelerated development of geothermal energy in Africa, the Long-Term Joint EU-AU Research and Innovation Partnership on Renewable Energy (LEAP-RE) is supporting the mapping of geothermal resources in the continent. The support, which entails mapping of geothermal resources for both electricity generation and a variety of heating and cooling applications, will result in the development of a Geothermal Atlas for Africa. In addition, LEAP-RE is supporting the development of a concept for the utilisation of geothermal energy for electricity generation and heating and cooling applications in remote African communities. The concept is referred to as the "Geothermal Village" and is being piloted in Djibouti, Ethiopia, Kenya and Rwanda.

Some countries in the Middle East are considering geothermal energy for cooling systems in buildings. In the United Arab Emirates, the National Central Cooling Company "Tabreed" won the concession of the Masdar City cooling system and is exploring the possibility of using two geothermal wells drilled in Masdar city for cooling (International District Energy Association, 2020). In Jordan, Mena Geothermal constructed a geothermal heating and cooling system at the American University of Madaba, renowned as the largest such system in the Africa and Middle East region. The ground heat exchanger system of this project annually saves 200 000 kWh of electricity for cooling and 100 000 litres of diesel fuel for heating (MENA Geothermal, n.d.).

Wellhead generators

Wellhead geothermal electricity generators have been deployed in the region, mainly in Eastern Africa. They are used as part of strategies for early electricity generation or for operationalising geothermal wells that would otherwise not be utilised due to their distance from power plants or characteristics that hinder their connection to the power plants.

As of 2019, 15 wellhead generators were installed in Kenya with a total generation capacity of 81 MW_e (Omenda *et al.*, 2021). Before this, in 2012 in Eburru, Kenya, a wellhead unit of 2.5 MW_e had been commissioned and connected to an existing exploration geothermal well drilled in the early 1990s. Also, in the Oserian flower farm, two wellhead units with a total capacity of 3.6 MW_e were commissioned in 2006 using exploration wells located at the boundary of the Olkaria geothermal field.

Ethiopia is in the process of developing 5 MW_e in the Aluto-Langano geothermal field with support from the Japan International Cooperation Agency to utilise appraisal wells drilled in 2014.

Desalinisation

North Africa and the Middle East are the sub-regions with the greatest water scarcity: they include 15 of the world's 20 most-water-scarce countries (UNICEF, 2018). The desalinisation of seawater to generate fresh water is an important activity in the region. Oman, Qatar, Saudi Arabia, the United Arab Emirates and some North African countries are already adjusting practices and policies around water (Nature Middle East, 2017). Solar power is the renewable energy source leading desalinisation in these countries, but geothermal energy may provide an alternative, whether on its own or combined with other renewables.

3.3. LATIN AMERICA AND THE CARIBBEAN

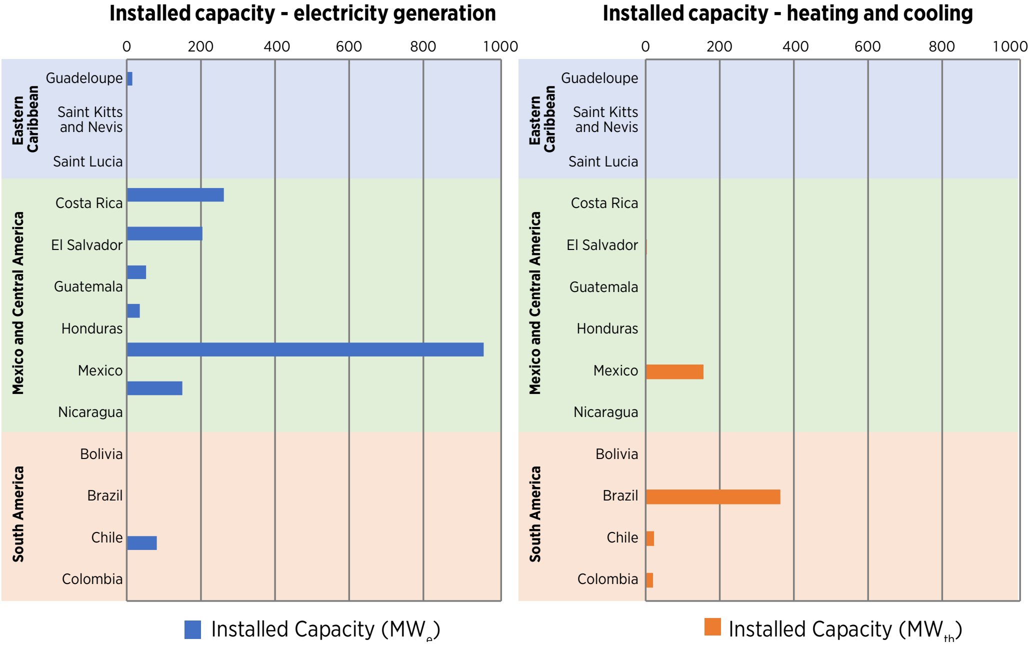
The Latin America and Caribbean region encompasses the segment of the American continent extending from Mexico to Chile, as well as the Caribbean islands. Its three major sub-regions, as discussed here, are Mexico and Central America, the Caribbean islands and South America.

3.3.1 Electricity generation

The region's high-temperature geothermal resources are associated with magmatic-hosted systems heated by recent volcanism. These resources have been extensively explored and used for electricity generation in many geothermal fields. Countries in the region started to assess the potential for geothermal electricity generation at several sites in the early 1970s, when the first global oil crisis kickstarted the investigation of alternative energy sources worldwide.

Mexico and Central America have developed more geothermal electricity generation capacity than have South America and the Caribbean. In fact, Mexico ranks among the top ten geothermal-electricity-producing countries worldwide, with 963 MW_e of installed capacity (ThinkGeoEnergy, 2022a). In several Central American countries with small or limited electricity markets, a few hundred megawatts electric of geothermal installed capacity account for a substantial portion of national electricity demand (*e.g.* 24.9% in El Salvador, 20.8% in Nicaragua, 14.6% in Costa Rica, according to the authors' calculations based on CEPAL [2021]). In the Caribbean, a power plant with an installed geothermal capacity of 15 MW_e, in operation in Guadeloupe since 1996, contributes approximately 6% of the island's electricity output (US DoE, 2020). In South America, a small (670 KW_e) geothermal pilot unit operated from 1988 to 1997 in the Copahue field in Argentina. The sub-region's first large-scale operation (48 MW_e) was commissioned in 2017 at the Cerro Pabellón geothermal field, in northern Chile, and recently expanded to 81 MW_e (Figure 18). In Colombia, a small (100 KW_e) pilot plant fed by co-produced hot water from the Las Maracas oilfield was commissioned in 2021.

Figure 18 Installed geothermal capacity by country in the Latin America and the Caribbean region – 2021

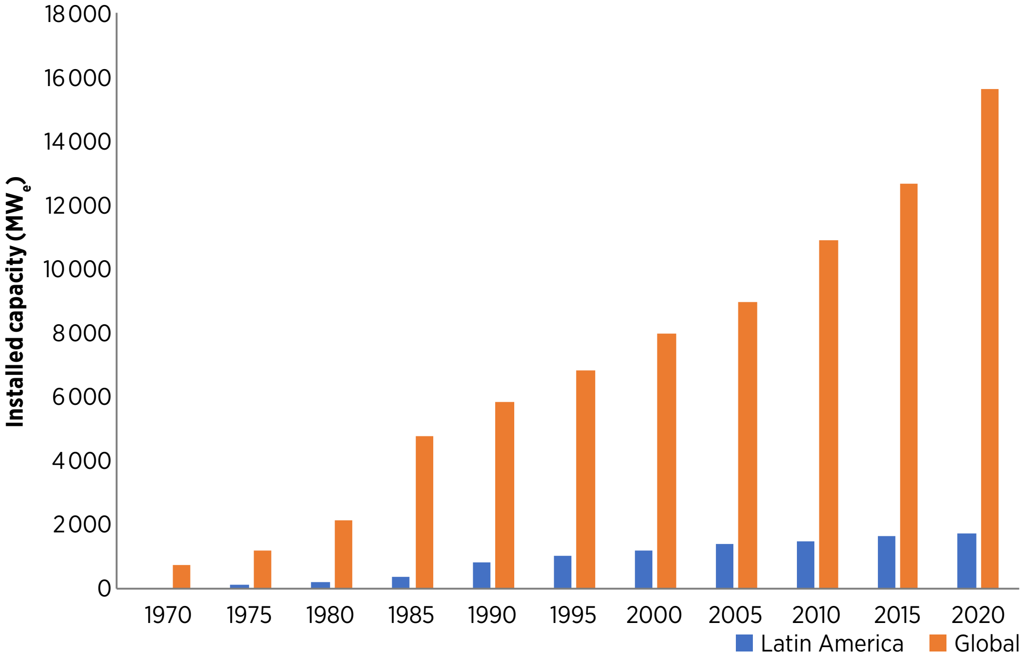


Based on: Huttrer (2021); IDB (2020); Lund and Toth (2021); ThinkGeoEnergy.

Note: Right-side graph related to the next section on heating and cooling.

The geothermal electricity industry in the region has been growing since the early 1970s, when the first large-scale commercial plants in Mexico and El Salvador went online. Today, about 1.7 GW_e of capacity have been deployed in the region, or 11% of global installed capacity (about 16 GW_e). Regional growth (1.5-2.0% a year on average) during the last 20 years is compared to the global trend (3%) in Figure 19.

Figure 19 Growth of installed geothermal electricity capacity – global vs Latin America and the Caribbean



Sources: Sources: ThinkGeoEnergy statistics, ThinkGeoEnergy (2022b), Huttrer (2021), Uihlein (2018), and Bertani (2015)

Geothermal electric plants operate in 17 fields, distributed across nine countries, most in Central America and Mexico. Four of these fields – Cerro Prieto and Los Azufres (Mexico), Ahuachapán (El Salvador) and Momotombo (Nicaragua) – have been continuously operating for more than 40 years. The bulk of the installed capacity uses high-temperature volcano-hosted hydrothermal resources. Exceptions include the lower-temperature hydrothermal system at the Platanares field in Honduras, and a pilot plant co-producing hot water at the Las Maracas oilfield in Colombia.

3.3.2 Heating and cooling

Geothermal heating and cooling installed capacity in the region is estimated at 0.8 GW_{th}, with a significant contribution (more than 90%) from Argentina, Brazil and Mexico (see the right side of Figure 18). The region's 0.8 GW_{th} represents a minimal fraction (less than 1%) of global installed capacity (108 GW_{th} in 2020).

Though bathing is the most common application in many countries, there are other heating and cooling installations as well as pilot projects throughout the region (Lund and Toth, 2021). Figure 20 maps heating and cooling initiatives and applications (beyond bathing) by country.

Figure 20 Geothermal heating and cooling, beyond bathing, in Latin America and the Caribbean

Based on: Lund and Toth (2021).

Base map created using https://mapchart.net/.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

Argentina, Brazil and Mexico use geothermal heat to develop applications that include agro-industry, fish farming, desalination, snow melting and heating/cooling in buildings. Heating and cooling are nascent in Chile, Colombia, Ecuador, El Salvador and Guatemala, where pilot projects have been developed. In Guatemala, geothermal heat has been used since the late 1990s to dehydrate fruit and cure concrete blocks in small facilities; also, a mini geothermal industrial park is being developed. Many of these heating and cooling applications are stand-alone projects. Cascading applications utilising residual heat from operating electricity plants are found at geothermal fields in Mexico (Domo San Pedro – fruit dehydration) and El Salvador (Ahuachapán and Berlín – coffee drying, candle making and sauna). The utilisation of shallow geothermal resources with GHPs, mainly in hotels, schools, hospitals and universities, is most advanced in Chile and Mexico, but some projects are also found in Brazil (cooling of residential and public buildings), Colombia (industrial cooling) and Ecuador (greenhouse heating, under construction) (Lund and Toth, 2021).

3.3.3 Regional market and technology trends

Electricity generation

In the region, government technical and financial support has helped explore and develop geothermal fields through state-owned companies: ENDE in the Plurinational State of Bolivia, ENAP in Chile, ICE in Costa Rica, CELEC in Ecuador, LaGeo in El Salvador, INDE in Guatemala, CFE in Mexico and ENEL in Nicaragua.

In Mexico and Central America, geothermal resources are located in accessible areas close to the transmission grid, and geothermal drilling industries are mature.

In South America, the abundance of other autochthonous power sources (particularly hydropower and hydrocarbons) has historically provided a more straightforward energy solution than geothermal. More recently, the accelerated deployment of other renewable energies, particularly solar photovoltaic and wind at large scale and progressively cheaper tariffs, as well as a lack of policies explicitly addressing the effective integration of geothermal electricity into the energy matrix, has further hindered the development of logistically more complex and higher-risk geothermal projects. Many geothermal projects in South America are located in remote high-elevation sites of the Andean region, far from the main transmission grids, hence associated higher costs.

Geothermal development in the Caribbean, particularly in the Eastern Caribbean islands, has been challenged amid limited electricity demand due to small energy markets in remote locations. Thus, although these islands host significant electricity-grade geothermal resources, they attract limited interest from investors and developers.

At the country level, constraints on the development of geothermal electricity projects include environmental restrictions on geothermal development in fields located in national park areas in Costa Rica; gaps in energy policy and electricity market instability (*i.e.* in Honduras and Mexico); competition or barriers to energy market entry in countries with de-regulated energy markets managed through energy auctions (*i.e.* in Argentina, Chile, Guatemala and Perú); or political instability, as in Nicaragua.

Geothermal electricity generation is envisaged to continue expanding in the region, supported by extensive technical capacity and experience and facilitated by risk mitigation and financing mechanisms made available by international organisations and programmes such as the Geothermal Development Facility (GDF Latin America) led by the German bank KfW, and other financing programmes provided by multilateral banks (Caribbean Development Bank, Inter-American Development Bank and World Bank). Set up in 2016, the GDF Latin America has since fostered geothermal projects in 11 selected countries: Plurinational State of Bolivia, Chile, Colombia, Ecuador and Peru in South America; Costa Rica, El Salvador, Guatemala, Honduras, and Nicaragua in Central America; and Mexico. As of 2021, about EUR 63 million (USD 68.5 million) were reportedly awarded to 26 projects; however, the effective utilisation of the funds has been so far limited by the diverse challenges discussed above (Dewhurst, 2022).

Though many of the region’s geothermal electricity projects are in Mexico and Central or South America, there is an emerging interest in the Eastern Caribbean, where geothermal exploration intensified in several islands during the last decade. This led to the preparation of development projects in Dominica and Nevis and progress in exploratory drilling in other islands (Saint Vincent and the Grenadines, Montserrat, St. Lucia).

Among the ongoing projects, it is also worth observing the presence of bottoming ORC installations, which utilise residual heat from existing electricity plants to increase the generation capacity of a field in operation without drilling additional production wells. Experiments with bottoming ORC applications have been seen in Mexico (starting in 1993 with 2 x 1.5 MW_e ORC units at the Los Azufres geothermal field, now de-commissioned) (Torres-Rodriguez, Mendoza-Covarrubias and Medina-Martinez, 2005; Gutiérrez-Negrín *et al.*, 2021), then in Nicaragua (Momotombo geothermal field, 7 MW_e since 2002) (Porras, 2008) and El Salvador (Berlin geothermal field, 9 MW_e since 2007) (Monroy, 2013). Ongoing projects in Nicaragua (San Jacinto – Tizate field) and El Salvador (additional bottoming unit in the Berlin geothermal field) demonstrate a recent new trend with these technological applications, while in Mexico, the state-owned electricity company CFE, with support from the French co-operation agency FASEP, has recently identified significant potential to increase generation capacity with the application of bottoming ORC technology (ThinkGeoEnergy, 2022g).

Heating and cooling

The region’s geothermal heating and cooling market is mainly associated with thermal bathing. Incipient development of small applications in agro-industry, space heating/cooling and fish farming, among other uses, has been seen since the mid-1990s in some countries (Argentina, Brazil, Chile, Guatemala and Mexico). Also, some countries (*e.g.* Chile, Costa Rica and El Salvador) have expressed interest in improving the regulation of non-electrical utilisation of geothermal resources. Technical assistance has been received from co-operation agencies and multilateral organisations (GIZ in Central America, the World Bank in Chile, the New Zealand government in the Caribbean). Pilot projects are reported in many countries, such as Colombia, Costa Rica, the Dominican Republic, Ecuador, El Salvador, Honduras and Mexico.

The application of geothermal heating and cooling is expected to take off, driven by improvements in regulatory frameworks, technical assistance programmes and information dissemination, particularly in Chile and the countries of Central America. By introducing good practices and demonstration projects, these initiatives are expected to encourage more comprehensive development at the regional level. The utilisation of shallow geothermal resources through heat pump applications for heating and cooling has been breaking ground in relatively advanced economies, such as Brazil, Chile, Colombia and Mexico, and may grow rapidly in the coming years, particularly in Chile, where the geothermal regulatory framework is being modified to support heating and cooling. Chile is also investigating opportunities for district heating projects based on geothermal energy, particularly in cities in the south, to control air pollution derived from the inefficient burning of fossil fuels and firewood for heating during winter.

Developments in resources and technology for electricity and/or heating and cooling

There has been limited interest in non-conventional and/or low-temperature resources in the region. Some relevant cases of research and pilot installations are outlined below.

Sedimentary geothermal and co-production in oilfields

Lower-temperature geothermal resources are mostly unexplored in the region but likely represent significant potential for heating and cooling applications and electricity generation with binary technologies. Regional heat flow investigations (Prol-Ledezma and Morán-Zenteno, 2019; Vieira and Hamza, 2014, 2019) and a global study on aquifer temperatures (Limberger *et al.*, 2018) indicate attractive geothermal potential in sedimentary basins on the Mexican Gulf coast (with geo-pressurised systems), in the Andean foreland, and other sedimentary basins in South America. Oil and gas operations in several sedimentary basins in Mexico and South America may provide valuable information, as demonstrated by recent assessments of sedimentary geothermal resources in Colombia (Pinto *et al.*, 2021) and pilot projects to generate electricity from co-produced water in Colombian oilfields (El Heraldo, 2021).

The development of electricity generation and heating and cooling from co-produced water in oilfields has potential, particularly in South America and Mexico where abandoned oil and gas wells may be repurposed for geothermal utilisation, significantly reducing project costs and risks. In Mexico, Prol-Ledezma and Morán-Zenteno (2019) suggest that reusing abandoned onshore oil and gas wells in deep geo-pressured reservoirs along the Gulf of Mexico coast (Burgos Basin, and Campeche-Tabasco area, with reported thermal gradients above 70°C/kilometre) could significantly increase Mexico's geothermal reserves. This may initially represent a clean technology option for generating the electricity required for oil field operations in remote locations and for nearby communities. Further development may occur, supported by more extensive utilisation of geothermal resources contained in sedimentary basins (independent of their hydrocarbon content), driven by the experience of co-produced projects.

Research in EGS and supercritical fluids

Along the Pacific border of Latin America and in the Eastern Caribbean islands, active volcanism and high-temperature geothermal systems present potential for developing EGSs and supercritical geothermal resources. EGS development was investigated in the early 2000s for the Berlin geothermal field of El Salvador (Majer *et al.*, 2007). More recently (2016-2021), the GEMex Project, a Europe-Mexico co-operation initiative, investigated supercritical resources and potential EGS applications in Mexico's Los Humeros geothermal field and Acoculco geothermal prospect area (GEMex, 2020).

Geothermal green hydrogen opportunities

Several Latin American and Caribbean countries' energy transition and decarbonisation strategies mention green hydrogen. Argentina, Brazil, Chile, Colombia, Costa Rica and El Salvador have recently introduced directives or prepared specific roadmaps to promote hydrogen and to facilitate private investment in this new energy sector (García, Gischler and Hallack, 2021).

The development of green hydrogen represents an opportunity to expand geothermal development in the region, and its evaluation is receiving support from international organisations such as the Green Climate Fund, the Clean Technology Fund, the Global Environment Fund, and the Inter-American Development Bank, among others. Initially, interest focussed on countries where the available geothermal resource is greater than the demand (such as in the Caribbean islands or Costa Rica) or where geothermal projects are stalled due to unattractive conditions in the electricity market (*e.g.* Chile). Green hydrogen is being evaluated as an option to improve economies of scale for local geothermal projects in the Caribbean islands (commonly constrained by demand). In an industrial facility in Trinidad and Tobago, hydrogen, methanol and ammonia processing and export infrastructure are already in place. The Government of Dominica has engaged a private company to undertake the development of its vast geothermal resource with associated green hydrogen production potential (ThinkGeoEnergy, 2021f).

Another opportunity being evaluated (in Colombia and Mexico) is the combination of geothermal co-production in oil fields with hydrogen production, taking advantage of existing wells and associated infrastructure.

AGS closed-loop geothermal

The application of innovative closed-loop technology is being considered in Saint Vincent and the Grenadines (Eastern Caribbean) to reverse the setback in geothermal electricity development that resulted after three deep exploratory wells failed to demonstrate sufficient permeability in the reservoir, though the recorded well temperatures were adequate for geothermal electricity generation. The local government recently started talks with a private developer to resume the project, applying advanced geothermal system (AGS) technology to overcome geothermal reservoirs' lack of permeability (Eavor, 2022; Saint Vincent Times, 2022).

Hybrid geothermal-solar thermal

Research and prototype testing of a combined concentrating solar-geothermal application was conducted in 2007-2008 at the Ahuachapán geothermal field and during 2011-2012 at the Berlin geothermal field (El Salvador). The first test was designed to enhance the geothermal electricity output, gaining additional steam by heating separated geothermal brine with concentrated solar energy. Experimental results were promising, indicating that a similar larger-scale hybrid solar-geothermal system could provide peak electric power during high-demand periods (Alvarenga, Handal and Recinos, 2008). The second pilot project produced steam at 250°C and 30 bar by flowing geothermal residual water through a 100-metre-long parabolic solar concentrator. The results showed a silica scaling film which was removed with a fast rinse after daily testing. However, both initiatives did not proceed with further investigation and development.

Mineral recovery

The potential to extract minerals from geothermal brine in operating fields in the region is mostly unassessed. In the Andean region of Northern Argentina and Chile , and southern part of the Plurinational State of Bolivia, huge lithium brine deposits are hosted in salars. Several geothermal prospects also occur in the same areas, including the operating geothermal field at Cerro Pabellon (Chile), and the Sol de Mañana field being developed in the Plurinational

State of Bolivia. Lithium recovery, where possible, could make geothermal development and operation more feasible and attractive. Investigations of mineral extraction potential are ongoing at Cerro Pabellon and other geothermal sites in northern Chile. A German-Chilean research project BrineMine (KIT, 2021) is investigating the selective separation of lithium, other minerals and freshwater from geothermal brines.

3.4 NORTH AMERICA

The North America region comprises Canada and the United States, including Alaska, and the Aleutian and the Hawaiian islands. Generation of electricity and heating and cooling are mostly developed in the western United States and Hawaii, while the application of geothermal heat pumps has been growing throughout the more populated areas of North America, particularly in the eastern United States and south-western Canada (Lund and Toth, 2021).

The region has favourable geologic conditions for high-temperature geothermal resources, particularly in its western portion, where these conditions are associated with volcano-hosted systems and recent volcanism (along the Pacific rim, Cascades, Garibaldi, Northern Cordillera and Aleutian volcanic ranges), and with regional fault systems in the basin and range and along the San Andreas fault in southern California. Additional lower-temperature resources might be found in sedimentary basins in the southern United States (including geo-pressurised systems along the Gulf Coast), central United States and Canada.

3.4.1 Electricity generation

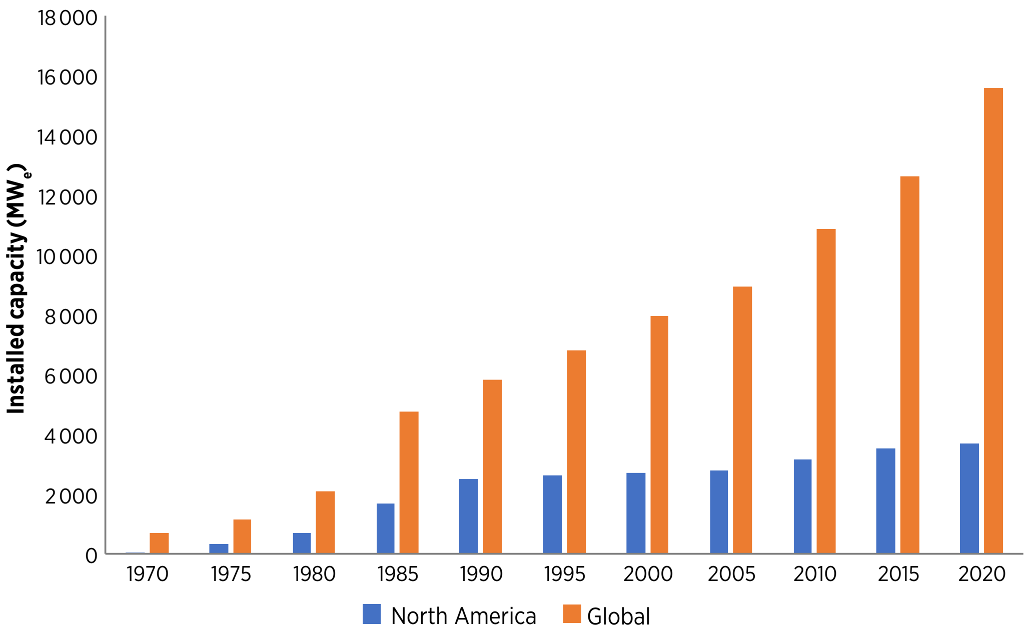
The potential to generate electricity from North America's geothermal resources was first assessed in the 1950s; today there are 32 geothermal fields, all within the United States, with 93 geothermal electric plants in operation (NREL, 2021). The first commercial geothermal electric plant (11 MW_e) came online in 1960 in California, at the Geysers field, where geothermal steam had been harnessed for electricity generation starting in the early 1920s, when small geothermal pilot units were installed to provide electricity to a tourist resort (Cataldi and Súarez Arriaga, 2016; Hodgson, 1997). In Canada, endeavours to harness geothermal electricity date back to the early 1970s, reaching an advanced exploration stage at the Mount Meager geothermal field (British Columbia) in 2005, when a commercial development project stalled. A 20 KW_e demonstration plant was temporarily operated at Mount Meager during flow testing in 1982-1984 (ThinkGeoEnergy, 2021g; Grasby *et al.*, 2012). Other initiatives to develop geothermal electricity in Canada have been undertaken at sites along the Garibaldi Volcanic Range (British Columbia), and also in deep sedimentary basins, and through emerging EGS and AGS technologies in central and western Canada (Alberta, Saskatchewan, British Columbia). Several projects are underway at various stages of progress.

With 3.7 GW_e of geothermal electricity capacity (as of year-end 2021; ThinkGeoEnergy, 2022a), the United States accounts for 23% of the world's installed capacity. Most of this share of capacity is in two states – California (2.6 GW_e; 72%) and Nevada (0.8 GW_e; 22%) – which together contribute more than 90% of geothermal electricity generated in the United

States (and in the North America region). The remaining contributions come from other western states (Idaho, New Mexico, Oregon, Utah) and Hawaii, with installed generation capacities ranging between 15 MW_e in New Mexico to 90 MW_e in Utah. In central Alaska, a small geothermal electric plant has been operating since 2006 in the remote Chena Hot Springs resort (400 KW_e in 2006, expanded to 680 KW_e in 2008). Overall geothermal generation capacity in the United States contributes to about 0.4% of the national electricity output (Huttrer, 2021).

The United States geothermal electricity industry has been growing since the late 1960s. Its complex development history is characterised by a "geothermal boom" in the 1980s and early 1990s (more than 2 000 MW_e were installed in a decade), which resulted from a combination of state policy decisions, a favourable tax climate, and direct government support through cost-shared drilling programmes and government loan guarantees (ESMAP, 2016). Successive reductions in government support, variably associated with other challenges, but particularly the end of federal programmes and the Public Utility Regulatory Policies Act, which was a major motivator for geothermal investments, determined a slower and irregular development trend. During the last 30 years, geothermal electricity capacity grew at an average annual rate of 1.4%, slower than the global average of 3.6% in the same period (Figure 21). The rate of growth has ranged between 1.6% in the last 10 years and 1.1% in the last 5 years).

Figure 21 **Growth of installed geothermal electricity capacity – global vs North America (United States)**



Sources: ThinkGeoEnergy statistics, ThinkGeoEnergy (2022b), Huttrer (2021), Uihlein (2018), and Bertani (2015).

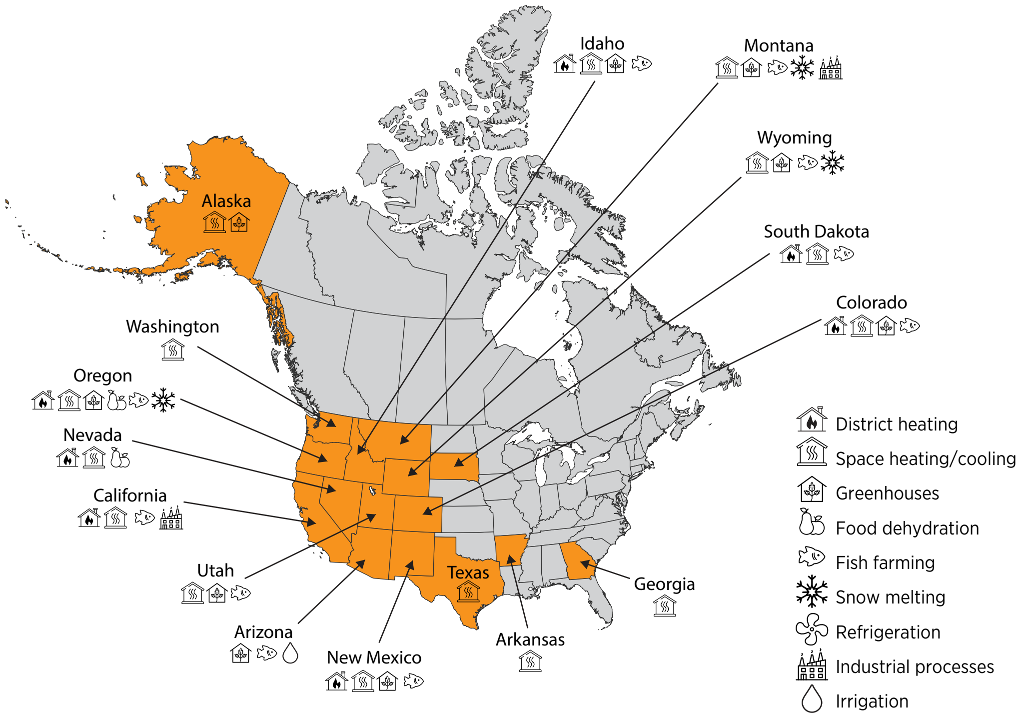
3.4.2 Heating and cooling

With 22.54 GW_{th}, North America represents over 20% of global 107 GW_{th} geothermal heating and cooling installed capacity as of 2020. This is mainly contributed by the United States, with 20.71 GW_{th} (91%); the remaining 1.83 GW_{th} are from Canada (Lund and Toth, 2021).

The region's geothermal heating and cooling industry is largely represented by GHP applications which are widely deployed and have seen continuous growth during the last decade. GHP accounts for 98% of the installed geothermal heating and cooling capacity in the United States and over 99% in Canada, where other uses are still limited to thermal bathing. In the United States, GHP installations account for 20.23 GW_{th} and are distributed nationwide, though mostly in the eastern, midwestern and southern states, while in Canada, they are distributed throughout the country, with considerable concentration in southern Ontario and Quebec, totalling 1.82 GW_{th}. Thermal bathing is also common throughout the region, with an approximate installed capacity of 99 MW_{th} (89.85 MW_{th} in the United States and 8.78 MW_{th} in Canada) (Lund and Toth, 2021; Thompson, Harmer and Fong, 2021).

Beyond widely distributed GHP and thermal bathing, several heating and cooling applications have been historically developed in the United States, such as greenhouses and aquaculture, individual space heating, district heating, agro-food processing, snow melting and other applications, totalling about 393 MW_{th}, mostly located in Idaho, California and Oregon (Figure 22). Among these, fish farming is the most significant, with an installed capacity of 122 MW_{th}, followed by heating applications, including district heating (90 MW_{th}), individual space heating (89 MW_{th}), and greenhouse heating (80 MW_{th}), which jointly have 381 MW_{th}, while another 12 MW_{th} correspond to other uses (Lund *et al.*, 2021).

Figure 22 **Geothermal heating and cooling applications, beyond GHP and bathing, in North America (United States)**



Based on: Lund *et al.* (2021).

Base map created using mapchart.net (https://mapchart.net/).

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Geothermal heating technology was initiated in the United States over a century ago; the first district heating system was developed in the early 1890s in Boise (Idaho). This was soon followed by similar applications in Klamath Falls (Oregon) in 1900, and successively expanded to greenhouse heating in the late 1920s (Stober and Bucher, 2013). Twenty-three geothermal district heating systems are now operating in the United States, ranging from 0.1 MW_{th} to over 20 MW_{th}. Many of these systems were installed in the 1980s, while only four have been added since 2000; thus, most geothermal district heating facilities are now more than 30 years old (NREL, 2021).

In more general terms, the traditional heating and cooling use of geothermal resources (excluding GHP) in North America, and particularly in the United States, stalled over the last 30-40 years. Many facilities have been closed over the last decades. Of a total of 550 heating and cooling applications historically recorded in the United States, more than 100, or about 19%, have been abandoned for various reasons, including high operating costs, lack of expert personnel for operation and maintenance, and little interest at the government level (Lund *et al.*, 2021).

3.4.3 Regional market and technology trends

Geothermal development in the region has been led by private developers. Excluding the GHP industry, which has been growing steadily, the geothermal market has seen little growth in recent years, whether for electricity or heating and cooling. In the United States (which represents the largest segment of the regional market for GHP), even GHP installation slowed in recent years, from a growth rate of 8% in 2010-2015 to 3.7% in 2020 (Lund and Toth, 2021; NREL, 2021).

Geothermal development faces diverse challenges in the region, mainly associated with limited policy support and regulatory issues in competitive energy markets; yet signs of awakening have started to appear. The US Department of Energy (US DoE) recently undertook comprehensive analysis of geothermal development opportunities and perspectives for both electric and heating and cooling uses. The resulting report could help steer the geothermal industry in the coming years (US DoE, 2019). The US DoE forecasts that improved geothermal technologies will reduce the investment costs and resource risks of geothermal development, and subsequently increase the deployment of geothermal electricity, particularly through the commercial deployment of EGS resources. Overcoming regulatory and permitting barriers is key to stimulate market growth, particularly in the geothermal heating and cooling sector. However, few policies support the development of geothermal district heating. According to projected scenarios, by 2050, geothermal generation capacity could reach 6 GW_e, under a business-as-usual scenario; 13 GW_e if permiting was optimised; and 60 GW_e if technological advances succeeded in reducing project costs and triggering the deployment of deep EGSs, considered to have the most potential to drive growth in the geothermal electric sector (US DoE, 2019).

The National Renewable Energy Laboratory (NREL) analysed the status and potential for further growth of the geothermal sector in the United States (NREL, 2021), while the Atlantic Council analysed policy and regulatory barriers in the relevant market, and recommended policy improvements to scale up the use of geothermal resources in decarbonising the energy sector. Key actions recommended by the Atlantic Council include improving energy planning to increase the share of geothermal procured, and its tariffs, increasing federal tax credits and funding for technology and innovation, streamlining permitting and leasing processes, and expanding subsidies and incentives for GHP deployment (Strauss, 2022). In Canada, the efforts of geothermal organisations and industry players have successfully pushed the industry forward. Several new projects are geared towards unlocking the extensive low- to medium-temperature resource potential of deep sedimentary basins for electricity and heating and cooling use.

Electricity generation

Across North America, only the United States has a geothermal electricity sector; new additional capacity has been partly counter-balanced by the de-commissioning of old plants. Nevertheless, the sector has been active for more than 70 years in the United States and counts on a well-developed industry, technical capacity, extensive assessment of the available resources and development opportunities. NREL (2021) reports 58 active developing projects and prospects for geothermal electricity generation across several states in the western United States. Five such projects, distributed across California and Nevada, are at an advanced development stage, close to project completion.

In Canada, several geothermal electricity or combined heat and electricity projects are underway at different development stages. Many of these projects are taking advantage of oil and gas exploration data to harness lower-temperature geothermal resources in sedimentary basins by repurposing or co-producing from existing wells or drilling new wells. Other initiatives are based on innovative AGSs (Matthews, 2021).

In the United States, recent renewable energy policy trends may foster the geothermal electricity industry to resume growth. In late 2019, fiscal incentives such as the Production Tax Credit (PTC) mechanism were reactivated for geothermal projects starting construction before January 2021. The PTC allows eligible geothermal plants to benefit from tax credits during the first ten years of operation. Under this mechanism, geothermal operators can alternatively opt for an Investment Tax Credit at a 30% rate deduction of investment costs. In 2020, a new Energy Act improved the conditions for renewable energy developers, including geothermal, to access federal lands, and set goals for renewable electricity production on federal lands. Additionally, the 2020 Energy Act authorised a USD 170 million annual budget for geothermal research, development and demonstration projects assigned to the Geothermal Technology Office of the US DoE. At the state level, geothermal policy and legislation improvements are under development in California, Hawaii, Nevada, New Mexico and Washington, seeking a major contribution from geothermal towards reaching decarbonisation goals.

These actions had a positive effect on the geothermal market. Geothermal PPAs have increased since 2019, indicating a growing interest in geothermal electricity generation. Recent PPAs were mostly signed between geothermal developers and electricity offtakers located in California, where a 100% zero-carbon electricity goal is set by 2045, but also in Nevada, Utah, Hawaii and the Aleutian Unalaska Island (NREL, 2021; Ormat, 2022).

Renewable Portfolio Standards (RPSs), which constrain power utilities to procure defined amounts of renewable energy, might also be stimulating the US geothermal market. RPSs that include geothermal as an eligible resource are in place in 28 US states; in seven states, they indicate renewable-based heating and cooling. Though RPS mechanisms have mostly facilitated the deployment of wind and solar PV (Heeter, Speer and Glick, 2019), a promising factor for geothermal is that several states have set RPSs with a 100% renewable target. This may not be functionally met by only variable renewable electricity sources, and thus provide increased opportunities for the integration of sources with stable output, such as geothermal. Seven states in the United States have an RPS of 100% (NREL, 2021).

Heating and cooling

Geothermal energy is widely under-utilised for heating and cooling in the region. It has the potential for significant growth and contribution to decarbonisation goals, primarily supported by harnessing shallow resources through GHP and developing accessible hydrothermal resources throughout the western United States and Canada. Technological improvements in EGS are also envisioned to contribute to the significant growth of district heating and other heating and cooling projects, allowing the expansion of these applications to wider portions of North America (US DoE, 2019; NREL, 2021).

The GHP sector is expected to keep growing both in residential and commercial applications, offering reliable and energy-efficient heating and cooling solutions. In the United States, GHPs in the residential sector alone have a market potential of 235 GW_{th}, or 28 million households, representing 23% of the projected residential heating and cooling demand by 2050 (US DoE, 2019).

The geothermal district heating (GDH) sector has seen limited development since the early 1990s. However, there is significant potential for rapid development at many sites across Canada and the United States, driven by ongoing national efforts to decarbonise the heating and cooling sectors. Nonetheless, improvements in policy, regulation, federal funding for technological innovation, tax credits, subsidies and enabling environment are required to trigger faster growth (Strauss, 2022; NREL, 2021). Beyond the lack of federal and state incentives, the competition from alternative heating sources and, in particular, natural gas is identified as one of the major barriers to the widespread expansion of GDH, while the limited availability of geothermal professionals is also a challenge (US DoE, 2019). The United States has a large resource base that can be harnessed with existing technology, combined with expected advances in the EGS technology (320 GW_{th} by 2050). The potential growth of GDH for the United States is estimated at 17 500 installations, with capacity to provide reliable energy-efficient heating and cooling to 45 million households (US DoE, 2019).

Geothermal deep direct use (DDU) and its emerging technology (which allows harnessing the geothermal resource also in regions with lower geothermal gradients) represents significant opportunities for expanding the application of geothermal heating and cooling to vast portions of North America, such as the central and eastern states of the United States and Canada. Feasibility studies for DDU applications started in the United States in 2017, financed by the US DoE and conducted by teams of government and academic institutions, with the objective of demonstrating innovative technological solutions that make the GDH applicable in much of the north-eastern United States (NREL, 2021; US DoE, 2017). Advanced feasibility studies supported by US DoE grants are being conducted at Cornell and West Virginia University to showcase the viability of GDH solutions in largely populated areas of the eastern United States.

Developments in resources and technology for electricity and/or heating and cooling

Technological innovation has been seen over the last decades in North America's geothermal industry, particularly in the United States, with significant support from government and academic institutions, participation of private developers and cross-industry collaboration. Several new approaches and opportunities have been investigated and, in some cases, implemented in pilot projects or integrations in existing geothermal fields. A review of the main technological innovation efforts ongoing in the North America region is reported below.

Enhanced geothermal systems

Investigations to harness geothermal heat from low-permeability hot rocks started in New Mexico in 1974 at the Fenton Hill demonstration site, conducted by Los Alamos National Laboratory. Building on this early experience, in recent decades EGS demonstration projects in the United States - mostly led by private developers - have achieved advances in existing geothermal fields to increase or counteract decreasing production capacities. Locations include Desert Peak and Brady (Nevada), Raft River (Idaho), and the Geyser and Bottle Rock (California). The projects at Desert Peak, Raft River, and the Geysers succeeded in obtaining commercial results and are still active, while at Bottle Rock, the EGS initiative was converted into a research project (NREL, 2021).

In recent years, the US DoE intensified efforts to foster the technological development of EGS with the Frontier Observatory for Research in Geothermal Energy (FORGE) and other initiatives. FORGE started in 2015 near Milford (Utah) as a dedicated underground field laboratory to accelerate research and technological advances for the utilisation of EGS resources. The first highly deviated (65° to the vertical) deep well and two vertical monitoring wells were successfully completed in 2021, with significant improvement in the drilling schedule. Hydraulic fracturing research and testing are ongoing, and project data are publicly available on the project website (Utah FORGE, 2022).

Additionally, the US DoE is providing diverse funding opportunities dedicated to EGS development, such as the Geothermal Wells of Opportunity Programme (WOO), the EGS Collab project, and other facilities addressed to specific aspects of the EGS development process, such as drilling efficiency, zonal isolation, waterless stimulation and machine learning. Advanced research on improving technologies and methodology for exploration, development and management of EGS resources is ongoing under WOO at existing geothermal fields in Nevada and California. The EGS Collab project is developed in collaboration with the Sanford Underground Research Facility (South Dakota) to investigate and model the creation of EGS reservoirs (NREL, 2021).

Canada also has significant EGS potential, with the most promising targets along the Canadian Cordillera (southern British Columbia and southern part of Yukon), in the Mackenzie Basin (north-eastern British Columbia), north-western and central Alberta, and parts of Saskatchewan (Grasby *et al.*, 2012).

AGS closed-loop geothermal

The closed-loop concept, which uses sealed wells, or sealed circuits with heat exchangers within existing wells, has been investigated since the early 1980s and, in recent years, has received renewed interest from innovative geothermal developers. More research and testing are needed to prove the commercial viability of this technology. Two demonstration projects are active in the region, one in the United States, at Coso geothermal field (California), and one in Canada, near Rocky Mountain House (Alberta). At Coso, closed-loop field-scale testing, funded by the California Energy Commission, has been conducted with a downhole heat exchanger installed within an existing conventional well, abandoned because of excessive non-condensable gas content. Promising results are reported using water and supercritical carbon dioxide as heat transport fluid, so the applied technology could leverage unproductive hydrothermal wells (Amaya *et al.*, 2020, 2021: Higgins *et al.*, 2021).

The Eavor-lite demonstration facility in Alberta is a full-scale prototype closed-loop built in 2019 to demonstrate the innovative Eavor-Loop™ technology. With the application of advanced drilling and completion methods developed in the oil and gas industry, two vertical wells were interconnected through multilateral legs at 2.4-kilometre depth to form an extensive underground U-tube system. Water is circulated to heat up in the sub-surface loop without pumping because natural circulation is induced by the density difference between the cold inlet fluid and the hotter fluid in the outlet well. This prototype was reported to successfully demonstrate the technical feasibility of the closed-loop system and its operation purely driven by a thermosiphon effect, unlocking a potential new source of geothermal energy (Eavor Technologies, 2021). The thermal energy obtained can be used for electricity generation or heating and cooling applications.

Dispatchable/flexible geothermal

The increasing deployment of variable electricity sources in electric grids requires the greater availability of dispatchable generation. Geothermal has commonly been used as a constant output electricity source, but it can work also in dispatchable mode, increasing its value and widening its development opportunities, particularly in deregulated or isolated grids with high penetration of variable renewable electricity sources. Despite technical and economic issues, dispatchable geothermal is technologically feasible with both flash and binary plants, with diverse strategies of flexible generation. This was a practice until the early 1990s in geothermal plants at the Geysers (California) and then abandoned due to limited demand and increased operating costs. More recently, the viability of dispatching geothermal has been demonstrated in Hawaii, where the binary ORC Puna Geothermal Venture plant is the first to operate in a flexible mode in North America (Millstein, Dobson and Jeong, 2021; NREL, 2021).

Hybrid geothermal

In 1989, a first hybrid application of geothermal energy was successfully implemented at the Honey Lake electric plant in northern California, where a 30 MW_e woody biomass electrical generation facility was enhanced using hot water extracted from local geothermal wells to preheat the inlet water of the biomass boiler, with a resulting reduction of biomass consumption (Geothermal Hot Line, 1988; GeoProducts Corp., 1988; Greenleaf Power, 2022). Over the last ten years, geothermal operators in the United States have started to develop geothermal-solar hybrid systems at a commercial or demonstration scale. The Stillwater, Patua and Tungsten Mountain geothermal electric plants in Nevada have been combined with solar PV arrays. At Stillwater, a solar thermal system to preheat the brine in the 33-MW_e geothermal binary plant was also deployed, with a resulting increase in electricity generation of 3.6% compared with production from geothermal alone (DiMarzio *et al.*, 2015; NREL, 2021; Enel Green Power, 2021).

Underground thermal energy storage

Underground thermal energy storage is rising as a significant technological opportunity in the geothermal sector, particularly when combined with district heating and cooling systems. A pioneering example is the use, since 1989 and still in operation, of a flooded abandoned coal mine in Springhill (Nova Scotia, Canada) for heating and cooling of industrial and commercial edifices located above the mine. The underground mine works extend to a depth of about 1 350 metres and are estimated to contain 4 million cubic metres of water that naturally circulate by convection with a resulting near-surface temperature of about 18-20°C. The mine water is pumped through boreholes to feed heat pump-driven heating and cooling systems of surface edifices, and then returned to the mine works through reinjection wells. The operation balance of the biggest industrial user is such that the heat disposed into the mine in summer exceeds the heat retrieved in winter, while other users have a small net drain of heat; thus, the resulting overall annual heat balance is such that the system operates without depleting the heat stored in the mine (Grasby *et al.*, 2012; Jessop, MacDonald and Spence, 1995).

Also in Canada, a district heating demonstration project that uses solar heat in combination with borehole thermal storage was commissioned in 2007 at Drake Landing Solar Community (Alberta) as the first of its kind in North America. The facility, designed to perform with over 90% solar fraction, has been operating successfully, with an average solar fraction of over 96%, including 100% during the 2015-2016 heating season (Mesquita *et al.*, 2017).

Investigations on underground thermal energy storage have recently started in the United States, mainly through the DDU programme backed by the US DoE Geothermal Technologies Office. Under this programme, Portland State University assessed the suitability of a permeable reservoir in fractured volcanic rocks to store heat during summer and retrieve it in winter for heating a hospital campus (Bershaw *et al.*, 2020).

The Solar Augmented Geothermal Energy concept, patented in the United States in 2006, is another initiative of innovative hybridisation and underground thermal energy storage. It utilises a solar system to heat a geothermal fluid, which is then pumped and stored underground in a "synthetic" geothermal reservoir to be later dispatched when needed. This integrated approach is reportedly ready to begin testing on existing geothermal wells in Nevada (RenewGeo, 2022).

Sedimentary geothermal and co-production in oilfields

The North America region has significant potential to expand geothermal utilisation by harnessing large geothermal resources contained in sedimentary basins through new dedicated wells, repurposing abandoned wells or co-production from existing oil and gas wells. Estimates provided by the GeoVision report (US DoE, 2019) indicate an accessible geothermal resource contained in sedimentary basins throughout the United States at 28 000 exajoules (EJ) or 7.5 million GW_{th}, which is a vast potential compared with the national thermal demand (33.5 EJ in 2008) (Fox, Sutter and Tester, 2011; NREL, 2021).

Great potential is also available in Canada, where several projects have been initiated in recent years. Test drilling was conducted in a sedimentary basin in Saskatchewan (Canada), where the first geothermal power plant of 35 MW_e is under development using a 125°C resource at a 3.5-kilometre depth (DEEP Corp., 2022).

Alberta No.1 is a geothermal project in a sedimentary basin at Greenview (Alberta, Canada), where the drilling of five, 4 000-metre-deep wells is planned for a combined heat and electric power development targeted to produce 10 MW_e of electricity and 985 terajoules of heat. A private developer and local academic institutions are partnering to investigate the opportunity of combining geothermal and carbon sequestration to create a carbon-negative energy project (Terrapin, 2022).

Other projects in sedimentary basins are taking advantage of abandoned oil and gas wells, repurposing them for geothermal use. An interesting case is provided by the Tu Deh-Ka project in British Columbia (Canada), led by the Fort Nelson First Nation indigenous community and funded by the Canadian government, with a development goal of between 7 MW_e and 15 MW_e of electricity generation, in a region which is not connected to British Columbia's main electric grid and totally depends on gas-fired generation. Two geothermal drillings were reportedly completed at Clarke Lake in late 2021, with one of the wells developed by repurposing and deepening an existing gas borehole. The wells confirmed the existence of a highly porous reservoir with a temperature of at least 120°C. Further well testing and investigations to characterise the resource are planned before proceeding with commercial development (Tu Deh-Kah, 2022).

Canada is also advancing with initiatives to use geothermal resources in sedimentary basins in co-produced systems. One such initiative is the hybrid geothermal–natural gas project being developed at South Swan Hills (Alberta). It will produce electricity using a natural gas generator bottomed by an ORC binary plant that jointly recovers the gas plant exhaust heat and geothermal heat, with a planned total generation of 21 MW_e, 30% of which is from geothermal (FutEra Power, 2022).

In the United States, there have been investigations into the use geothermal fluids contained in sedimentary basins and particularly geo-pressured resources since the 1980s at the Pleasant Bayou test site in Texas, where a 1 MW_e hybrid plant running on methane gas and geothermal energy generated more than 3 400 megawatt hours from November 1989 to May 1990, before being decommissioned due to low electricity prices and production issues (US DoE, 2010).

In 2010-2011 a new assessment was conducted at the Sweet Lake Oil and Gas Field (Louisiana) under a US DoE award but was terminated after evaluation of existing data showed high technical and financial project risk (Louisiana Tank Inc., 2012). The potential use of by-product hot water from oil and gas wells for electricity generation was then investigated at the Rocky Mountain Oilfield Testing Centre in Wyoming, where a 250 kW_e binary plant achieved the first successful generation in 2008 (Reinhardt, Johnson and Popovich, 2011; US DoE, 2010). A successive market assessment for co-produced geothermal fluids from known formations in existing oil and gas fields in the United States has indicated a modest potential of about 300 MW_e (Augustine and Falkenstern, 2014). More recent studies conducted at the Bakken oilfield in North Dakota concluded that co-production might be less viable than converting existing oil and gas wells for exclusive geothermal use (Gosnold *et al.*, 2020). However, the investigation of sedimentary geothermal and co-production continues in the United States, where the US DoE is supporting, with a USD 8.4 million grant, four selected projects to harness the geothermal resource available in abandoned oil and gas wells. An achievement was recently reported from the Blackburn oilfield in Nevada, where a small binary plant (up to 1 MW_e) fed by co-produced water is being prepared (US DoE, 2022; ThinkGeoEnergy, 2022h).

Geothermal for cooling

Besides geothermal heat pumps, which are widely deployed for space heating and cooling, geothermally driven absorption chillers are feasible to provide solutions for diverse cooling applications and processes, such as district cooling, ice production, and industrial refrigeration, among others, using medium-temperature geothermal resources. In the early 1980s, an absorption chiller system driven by geothermal heat was put into operation at the Oregon Institute of Technology campus and worked until 1999, when it was decommissioned due to its high water use and low cooling efficiency (NREL, 2021). More recently, a successful application has been developed at the remote off-grid community of Chena Hot Spring (Central Alaska), together with several other geothermal heating and cooling installations and small-scale electricity generation. A geothermal absorption chiller powered by geothermal heat extracted from shallow wells at 73°C was installed at Chena in 2005 to keep the Aurora Ice Museum frozen year round. The operation of the geothermal chilling system was reported to save approximately two-thirds of the cost required to alternatively run the backup system (Erickson, Kyung and Holdmann, 2005).

Recent investigations sponsored by NREL and the Oak Ridge National Laboratory show increasing interest in geothermal chilling in the United States. In collaboration with Southern Methodist University and private companies, NREL assessed the viability of a DDU project to refrigerate water at a chemical plant in Longview (Texas) based on geothermal-powered absorption chillers. Though the study estimated relatively low costs for the geothermal chilling solution, the economic feasibility was not attractive within the local electricity market (Turchi *et al.*, 2020). The Oak Ridge National Laboratory investigated an innovative solution to provide space conditioning also at distances of several miles from the geothermal site. This solution is based on decoupling the absorption cooling process by concentrating the binary fluid near the geothermal source, transporting it to the site of use and then back to regenerate (Liu, Gluesenkamp and Momen, 2015).

Low-temperature electricity generation and geothermal micro-grids

Small-scale geothermal plants have been successfully operating in many countries and, in recent years, have benefited from improved ORC design that led to the modularisation of small electric plants optimised to work with lower-temperature fluids (70–120°C). In North America, the Wabuska geothermal plant was the first to operate from low-temperature fluids (107°C), with two initial binary units commissioned in 1984 and 1987 (0.6 MW_e). The installed equipment was successively retrofitted and expanded to the current generation capacity of 4.4 MW_e (NBMG, 2012; ThinkGeoEnergy, 2018).

Chena Hot Spring (Central Alaska) is also an excellent example of an isolated geothermal micro-grid, in operation since 2006, with 680 KW_e of binary units integrated with cascaded heating and cooling applications. The electric plant is fed by hot water wells drilled in a shallow 74°C aquifer, the lowest-temperature geothermal electricity source worldwide, thanks to favourable local conditions for power cycle heat rejection (nearby very cold river water source and sub-zero average temperature during winter). During its first year of operation, this geothermal plant reduced the cost of electricity from USD 0.30/kWh to USD 0.05/kWh, saving more than USD 650 000 in diesel fuel (Holdmann, 2007).

Another interesting case of low-temperature electricity generation is a micro-geothermal plant installed at the Florida Canyon gold mine (Nevada), using a 110°C co-produced geothermal brine. A first 50 KW_e experimental low-temperature ORC unit was installed in 2009. The project received a US DoE research grant to optimise, and manufacture improved 75 KW_e generation equipment, later commissioned at the Florida Canyon mine site in 2012 (ElectraTherm, 2022; NBMG, 2014; ThinkGeoEnergy, 2013). Operational data of the plant were publicly reported on the OpenEi Geothermal Data Repository (GDR, 2014) and showed the plant went offline in April-July 2014 due to technical problems. Similar equipment was also tested in 2011 using 95°C co-produced water at the Denbury oilfield (Mississippi) in a six-month demonstration test supported by a grant from the US DoE's Research Partnership to Secure Energy for America (ElectraTherm, 2012).

Geothermal green hydrogen

The production of green hydrogen has been recently envisioned as a new opportunity for the development of the Meager Creek geothermal field (British Columbia, Canada). A private developer acquired the lease of this stalled geothermal project with the idea of reviving it, focussing on the production of green hydrogen. Commercial operation is planned by 2025 (ThinkGeoEnergy, 2021g).

Research and testing on mineral extraction from geothermal brines

Several studies conducted in the United States have shown significant potential for mineral recovery in geothermal fields, principally in the Salton Sea in southern California, where lithium concentrations in geothermal brine are as high as 440 milligrammes per litre. Other geothermal fields with promising conditions are East Mesa (California) and Roosevelt (Utah). However, their estimated potential is much lower than at the Salton Sea, where lithium reserves of about 2 million tonnes are comparable with other world-class lithium deposits (Neupane and Wendt, 2017; Stringfellow and Dobson, 2021).

The content of precious and base metals in geothermal brines, and technologies for their extraction have been studied at geothermal plants in the Salton Sea area since the 1970s. Studies were initially sponsored by the US Bureau of Mines and then with the participation of private developers that began to explore opportunities for additional revenues from geothermal electric plants operating in the field. Several tests were conducted, and a pilot zinc recovery facility went into operation from 2002 to 2004, but it was shut down due to poor results (Warren, 2021). The US DoE Geothermal Technology Office and the California Energy Commission have also supported several mineral extraction initiatives at the Salton Sea, including pilot plants that succeeded in demonstrating technically feasible processes for extracting lithium, zinc, manganese and other metals.

The lithium recovery process is now close to commercialisation in the United States, and pilot plants based on improved technologies are being implemented at the Salton Sea (NREL, 2021). The Hell's Kitchen Integrated Lithium and Power Project, a private venture focused on a hybrid electricity generation and lithium extraction operation, secured a PPA for electricity sales and commenced construction in late 2021. The project is planned to deliver 49.9 MW_e of geothermal electricity in 2024 and about 260 MW_e in 2026, and 20 000 tonnes of lithium carbonate equivalent in 2024 and about 80 000 tonnes in 2026. (ThinkGeoEnergy, 2021h; Controlled Thermal Resources, 2022).

3.5 EURASIA

Eurasia comprises all European countries, the Russian Federation and the southern Caucasus countries. The region can be divided into three sub-regions, namely Western Europe; Southeast Europe; and Russian Federation, Eastern Europe and the Southern Caucasus.

High-enthalpy geothermal resources in Eurasia are present mainly in volcanic areas in the central Mediterranean region (Italy), the eastern Mediterranean region (Greece, Türkiye), the Atlantic islands (the Azores and Iceland), the northern Caucasus area and the easternmost part of the Russian Federation along the Ring of Fire (Kamchatka and the Kuril Islands) (Limberger *et al.*, 2014). Elevated temperatures are also present in sedimentary basins such as the Pannonian Basin (Bosnia and Herzegovina, Croatia, Hungary, Poland, Romania, Serbia, Slovenia, Slovakia and Ukraine), the Upper Rhine-Graben (France and Germany) and the Southern Permian Basin (from Poland to the United Kingdom).

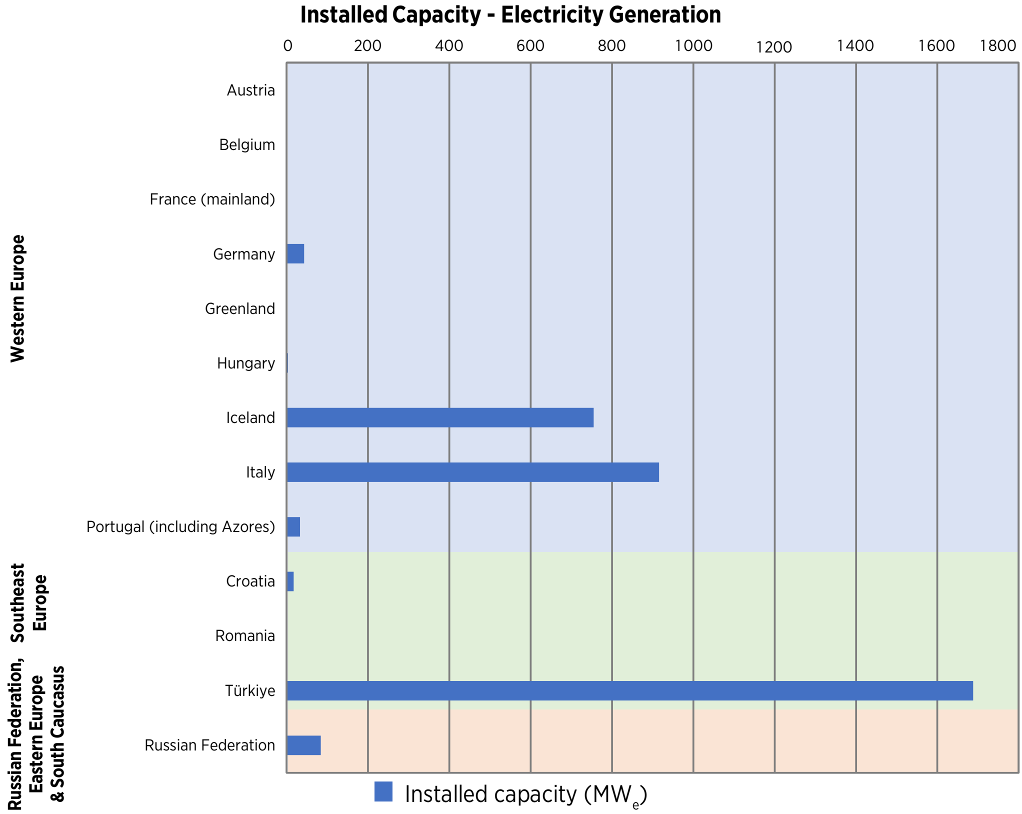
3.5.1 Electricity generation

The first experiments to power an electricity generator with geothermal steam were conducted in 1904 in Larderello (Tuscany, Italy). A commercial geothermal electric plant was completed in 1913 in the Devil's Valley (Tuscany). After this development, geothermal became more utilised in the region during the 20th century. Most of Tuscany's geothermal heat results from a magmatic intrusion. In 2020, a total of 916 MW_e were installed in Italy from more than 30 geothermal electric plants (Huttrer, 2021), which increased to 944 MW_e in 2021 (ThinkGeoEnergy, 2022a) (Figure 23). Iceland has significant geothermal potential because of its location on top of the mid-Atlantic Ridge, a volcanically active zone. Iceland's geothermal electricity sector has grown significantly during the last decades. Its first geothermal electric plant started operating in 1969, and eight plants are currently operational (Ragnarsson, Steingrímsson and Thorhallsson, 2018). Now, the total installed capacity in Iceland is 754 MW_e. Besides Iceland, other volcanic islands in the Atlantic with significant geothermal potential are the volcanic islands of the Azores Archipelago (Portugal), where 33 MW_e is installed and about 23% of the total electricity consumption of the islands is fed by geothermal plants (Nunes *et al.*, 2021). Although geothermal resources in Germany are generally lower temperature, 43 MW_e were installed in 2020 in ten plants using Kalina or ORC systems (Huttrer, 2021). In France, the Soultz-Sous-Forets power plant was established at the site for an EGS project, where it utilises a resource at a temperature of 155°C and flow rate of 32 kilogrammes per second to generate 1.7 MW_e of geothermal electricity. This power plant was inaugurated in 2016 and replaced the pilot project, which had been at the site since 2008 (ThinkGeoEnergy, 2016). Other power plants in Western Europe are found in Belgium (4.5 MW_e) and Austria (0.2 MW_e).

The geothermal sector in Türkiye has been proliferating during the last decade, with 30 MW_e installed in 2008 (IGA, 2017), 1 549 MW_e in 2019 (Huttrer, 2021; EGEC, 2021, 2022a) and 1 676 MW_e in 2022 (JED, 2022). In Croatia, the country's first geothermal power plant, a 17.5 MW_e Velika Ciglena unit, was inaugurated in 2019. Smaller units are also found in Hungary (3.35 MW_e) and Romania (0.05 MW_e)

In Russia, geothermal electric plants are installed in Kamchatka and the Kuril Islands, where high-temperature resources are part of the Pacific Ring of Fire (Butuzov *et al.*, 2022). Huttrer *et al.* (2021) and Svalova and Povarov (2021) report that 82 MW_e were installed in 2020, while Butuzov *et al.* (2022) indicate a total of 83.9 MW_e in 2019. Five geothermal electric plants are in operation in this eastern-most part of Russia, of which the largest is the Mutnovsky plant which produces 50 MW_e.

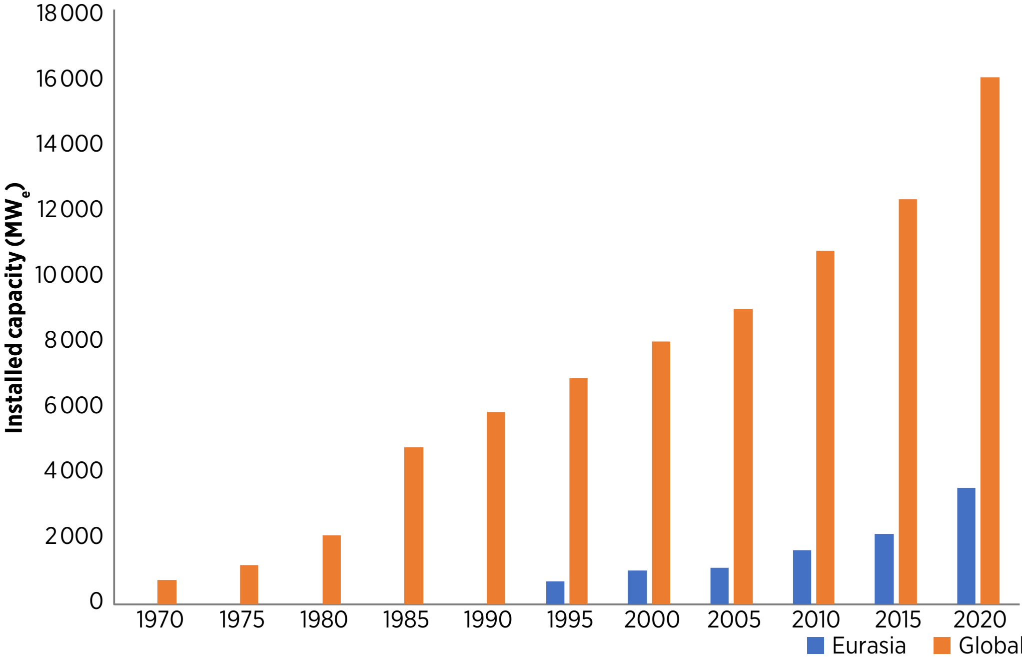
Figure 23 **Installed geothermal electricity capacity by country in the Eurasia region - 2021**



Source: Huttrer (2021); EGEC (2022a); Gavriliuc; Rosca and Cucueteanu (2019); Butuzov *et al.* (2022); ThinkGeoEnergy (2022b).

Installed geothermal capacity for electricity in Eurasia is about 3.54 GW_e, which accounts for approximately 22% of the global geothermal electricity installed capacity (16 GW_e). Figure 24 compares the growth of capacity in Eurasia with that of the world from 1995. In the last 20 years, global geothermal electricity capacity increased at an average annual rate of 3.2%, while the growth in Eurasia occurred at a faster pace of 5.2% per year. This is driven by a major expansion in installed capacity in Türkiye starting around 2005. The installed capacity in Türkiye grew from 91 MW_e (2010) to 397 MW_e (2015) to 1 688 MW_e (2020). The growth in Italy started much earlier; by 1995, 632 MW_e had already been installed. Iceland experienced an increase from 170 MW_e in 2000 to 575 MW_e in 2010 to 755 MW_e in 2020.

Figure 24 Growth of installed geothermal electricity capacity – global vs Eurasia

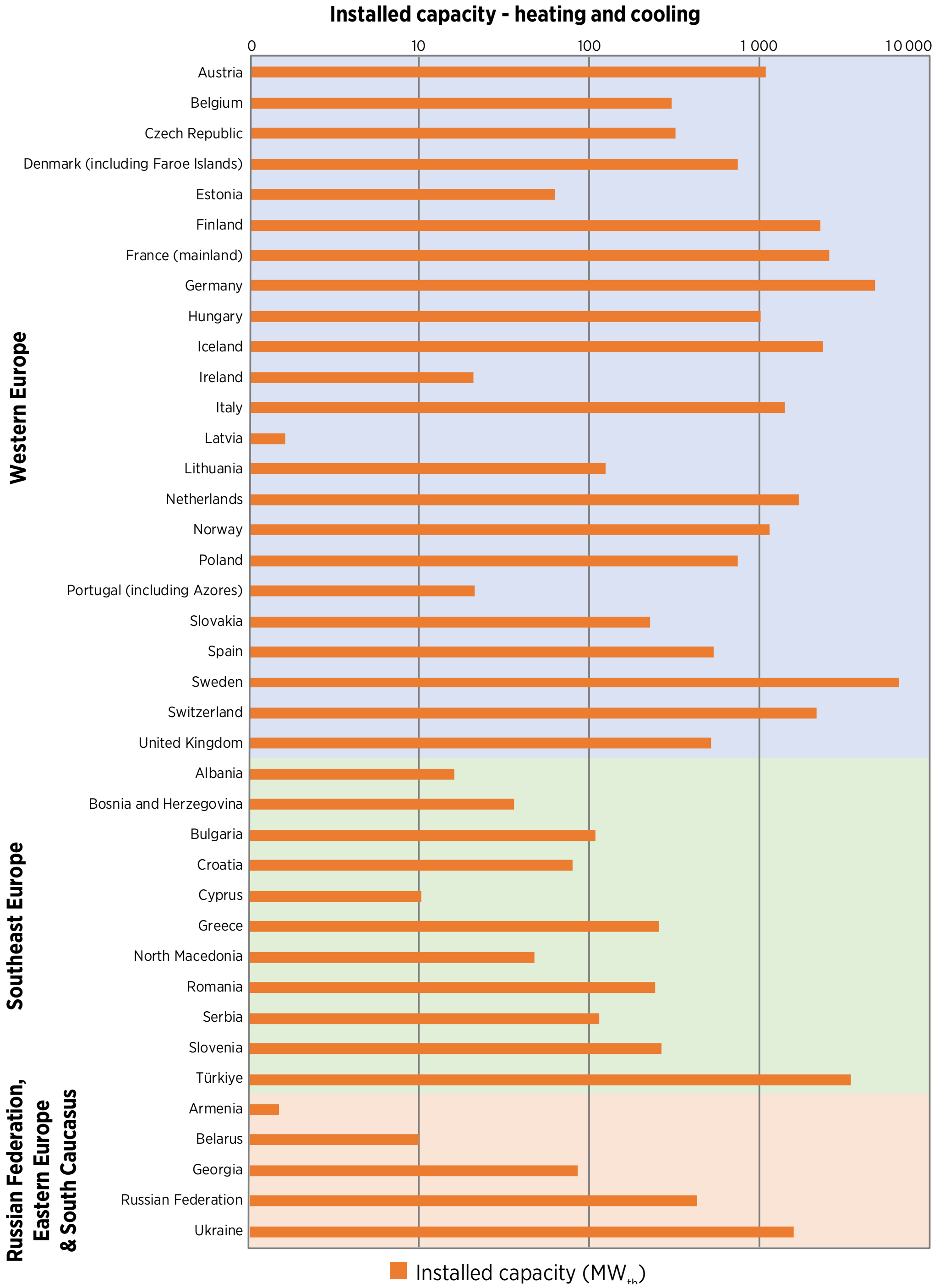


Sources: ThinkGeoEnergy statistics, ThinkGeoEnergy (2022b), Huttrer (2021), Uihlein (2018), and Bertani (2015).

3.5.2 Heating and cooling

Although the extent of high-enthalpy geothermal resources is limited in Eurasia, the utilisation of geothermal energy for heating and cooling is widespread in the region (Figure 25). Many countries in Eurasia have more than 100 MW_{th} of installed geothermal heating capacity, with several countries in Western Europe having a capacity of 1 000 MW_{th} or more. When including the use of heat pumps, Germany, Sweden, and Türkiye are the leading countries in Eurasia concerning installed capacity for heating and cooling, but the differences between countries are much smaller compared to geothermal electricity capacity (Lund and Toth, 2021). Europe is a leading market for geothermal district heating (EGEC, 2022a). Worldwide, the installed capacity for district heating systems is greatest in China, Iceland, Türkiye, France and Germany (Lund and Toth, 2021).

Figure 25 Installed geothermal capacity for heating and cooling (including heat pumps) in the Eurasia region - 2021



Source: Lund and Toth (2021).

When comparing the installed geothermal capacity for heating and cooling by population, the global top five countries are Iceland (2 373 MW_{th} total), Sweden (6 680 MW_{th} total), Finland (2 300 MW_{th} total), Switzerland (2 197 MW_{th} total) and Norway (1 150 MW_{th} total) (Lund and Toth, 2021). Iceland is a world leader in the use of heat for heating and cooling applications; over 90% of the buildings are heated using geothermal energy. Geothermal heat pump use is also significant in Eurasia compared to the other continents. Sweden, Germany and Finland are in the top five countries worldwide with respect to installed geothermal capacity used for heat pumps, following China and the United States (Lund and Toth, 2021). In Sweden, mostly shallow closed-loop systems are utilised, while in Germany, deeper wells are used for heat pumps. Within Eurasia, the use of district heating is largest in Iceland (1 650 MW_{th}), Türkiye (1 033 MW_{th}), France (509 MW_{th}) and Germany (346 MW_{th}). Geothermal energy is also widely used for greenhouse heating in Eurasia (EGEC, 2022a). The Netherlands and Hungary are among the top five countries worldwide with regard to geothermal greenhouse heating (Lund and Toth, 2021). Together with China, the Russian Federation and Türkiye, they account for about 83% of the world's total geothermal energy use for greenhouses.

In Southeast Europe, Türkiye is the leader in geothermal heating and cooling, with 3 488 MW_{th} installed (Lund and Toth, 2021). It is mostly used for bathing and swimming, district heating, greenhouse heating and individual space heating (Figure 26). There are many other countries in Southeast Europe using geothermal heat, for instance, Slovenia, with 31 locations (266 MW_{th} total installed capacity) primarily used for bathing and individual space heating; Greece, with 25 locations (259 MW_{th} total installed capacity) mainly used for greenhouse heating and some individual space heating; and Romania, with 40 locations (245 MW_{th} total installed capacity) mostly used for bathing, individual space heating, greenhouse heating and district heating (Lund and Toth, 2021).

In Ukraine, a total of 1 607 MW_{th} of geothermal heating and cooling is installed, which is mainly used for heat pumps and also some bathing purposes (Lund and Toth, 2021). The use of geothermal energy in the Russian Federation for heating and cooling is most developed in the easternmost part of the country (Kamchatka and the Kuril Islands) and the southern part (Dagestan and Krasnodar Krai), with a total of 433 MW_{th} installed (Lund and Toth, 2021). The main heating and cooling applications in the Russian Federation are district heating, individual space heating, greenhouse heating and bathing. In Georgia, 69.2 MW_{th} are installed for greenhouse heating and bathing.

Figure 26 Geothermal heating and cooling applications in the Eurasia region

Base map prepared with https://mapchart.net/.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

3.5.3 Regional market and technology trends

There was an evident standstill in Eurasia's geothermal market in 2020 due to the global pandemic, followed by renewed growth in 2021 (EGEC, 2021, 2022a). The largest portion of Eurasia's energy demand is for heating and cooling. In 2021, there were 13 new district heating projects in Europe, mainly in France, Poland and Iceland (EGEC, 2022a). The use of geothermal heat pumps is also growing fast in Europe. Regarding electricity generation, Türkiye remained among the fastest-growing geothermal markets for electricity generation, but this growth has decreased due to the expiration of the previous Renewable Energy Support Scheme and its reintroduction, albeit with changes that investors find less attractive, such as the revised FiT scheme and domestic components incentive premia payment which are denominated in the local currency (Turkish lira) instead of the US dollar (EGEC, 2022a).

The global energy crisis of 2022 and the volatility of gas prices have prompted European countries, in particular, to fast-track efforts to achieve energy security and energy independence. As a result, countries with geothermal resources are turning their focus to geothermal energy as a potential source for heating and cooling, especially by geothermal heat pumps and district heating networks.

Many European countries have ambitions to speed up geothermal developments to secure energy supply and reach climate goals. In the Netherlands, for instance, there are robust regulatory and policy frameworks (see Box 6), but permitting processes generally take many years. Therefore, the Dutch geothermal sector handed over an action plan to the Ministry of Economic Affairs and Climate to speed up and streamline geothermal project development (Geothermie Nederland, 2022b).

In Europe, one of the main hurdles to the growth of the geothermal energy sector is the lack of political support and high-level vision. In April 2022, 150 businesses and industries together asked the European Commission to create a European strategy for developing geothermal energy and associated mineral extraction (EGEC, 2022c).

In the European Union, the European Commission is working on policy packages towards a climate-neutral Europe, such as "Fit for 55" and REPowerEU. Member states of the European Union are required to submit national strategies towards reaching a climate-neutral Europe. As part of these policy packages, there are several incentives for furthering geothermal energy. These include subsidies for geothermal energy through direct management funds, such as the Innovation Fund or Horizon Europe, as well as regional funding through, for example, Interreg. The strategic energy technology plan for geothermal energy covers research and Innovation, which encompasses stakeholder groups European Technology and Innovation Platforms (ETIP), including one for deep geothermal: ETIP-DG.

EU's Horizon 2020 Research and Innovation Programme funded several large research projects on geothermal energy, such as:

- The GEOENVI project (2018-2021) focussed on the environmental impacts, risks and public perception of geothermal projects (GEOENVI, 2021). A life cycle assessment methodology was developed to calculate the environmental impact and benefits of geothermal projects.
- The GEORISK project (2018-2021) aimed to develop risk insurance schemes to mitigate the impact of geothermal resource risks through financial instruments (GEORISK, 2021). The project promoted the development of new national risk mitigation schemes in three countries with under-utilised potential for geothermal heat production – Greece, Hungary and Poland – as well as a pan-European Geothermal Risk Insurance Fund.
- GeoERA (2018-2021) was an H2020 ERA-NET research programme and a collaboration between European geological surveys to work on several topics within applied geosciences. GeoERA funded different international projects on geothermal energy, such as HotLime (mapping and assessment of geothermal plays in deep carbonate rocks) and MUSE (Managing Urban Shallow geothermal Energy).
- The DESTRESS project (2016-2021) demonstrated EGS in geothermal reservoirs, expanded knowledge, and provided solutions for more economical, sustainable and environmental exploitation of underground heat.
- The DEEPEGS project (2015-2020) focused on the deployment of deep enhanced geothermal systems. Several stimulation technologies were tested within this project.

Electricity generation

Türkiye is pushing strongly for geothermal energy. In 2020, the Turkish Geothermal Energy Association was founded (Jeotermal Enerji Degerni, JED) by ten corporations in order to strengthen stakeholder relations, continue research and expand the utilisation of geothermal energy in Türkiye (ThinkGeoEnergy, 2021i; JED, 2022). An important part of the Turkish geothermal sector is the FiTs from the Renewable Energy Sources Support Mechanism (YEKDEM), which supports electricity production from renewable sources. The scheme was extended from 2021 to 2025. However, tariffs are ca. 36% lower in the new scheme and are based on Turkish lira instead of US dollars (ThinkGeoEnergy, 2021j). This has caused uncertainty for geothermal operators and investors in Türkiye, and the growth of the Turkish geothermal market slowed down as Turkish companies increasingly work in other countries (ThinkGeoEnergy, 2021j).

In the context of the Global Geothermal Development Plan, the World Bank also plays a vital role in the Turkish geothermal sector. The World Bank has a risk-sharing mechanism and offers a loan facility for resource development, with the aim of scaling up private sector investment in geothermal energy development in Türkiye (World Bank, 2022).

Support for geothermal electricity projects in the rest of Europe seems to lack stability. In 2021, the installed capacity increased by only 35 MW_e from six new plants (EGEC, 2022a). The European Union is funding geothermal projects through GEOTHERMICA and CETP, including innovative exploration methods, geothermal energy conversion and integration of geothermal electricity into the energy system (SET-plan Deep Geothermal [IWG, 2020]).

A lack of incentives and regulations in Italy is demonstrated in an open letter from the Italian Geothermal Union to the Minister of Ecological Transition in 2021 (ThinkGeoEnergy, 2021k). The FER1 decree, a support system for financing renewable energy sources and technologies, excluded geothermal energy. Together with the delay of the new FER2 decree, this has frozen support for geothermal projects, according to the Italian Geothermal Union. Also, the authorisation process for geothermal projects in Italy is complex and takes a long time.

In Iceland, the National Energy Fund has greatly impacted the geothermal sector since the 1960s by promoting geothermal developments through loans and risk mitigation (Atlantic Council, 2018). Loans for the drilling of geothermal wells, up to 60% of the total drilling costs, convert to a grant if the drilling stage is unsuccessful.

The Russian Federation has geothermal resources suitable for electricity generation in the Kamchatka region and the Kuril Islands. The potential is estimated to be much larger than the present installed capacity, allowing for future electricity generation expansion, possibly in combination with hydrogen production (Svalova and Povarov, 2021).

Heating and cooling

Europe has the largest geothermal heating and cooling sector worldwide. Although many district heating and cooling projects came to a halt during the global pandemic, a strong rebound was reported in 2021 (EGEC, 2022a). More than half of the new geothermal projects in 2021 relate to heating and cooling applications. Also, a substantial increase in the installation of geothermal heat pumps was observed after the pandemic in 2021, especially in France (73% growth), Austria (59%), Belgium (35%) and Germany (10%).

Western Europe has focused chiefly on developing new geothermal systems to replace the use of gas (EGEC, 2021). That effort has grown in importance since the energy crisis of 2022, as European countries prioritised their energy security and independence (EGEC, 2022a). In some western European countries, such as the Netherlands, regulatory and market challenges are being overcome to increase the role of geothermal energy and replace gas in the built environment (Box 6).

Eastern Europe's extensive network of district heating systems is mainly powered by natural gas. The countries in this region focus on protection from energy poverty, which causes competition between the development of geothermal projects and the use of natural gas (EGEC, 2021).

The use of large-scale thermal energy storage is also receiving increased attention. Combining heating/cooling supply from geothermal energy and other renewable energy sources with underground thermal energy storage would be beneficial, particularly in the storage of excess thermal energy from cooling applications or when demand for heating is low. There are numerous developments in this field in Europe, for instance, the HEATSTORE Geothermica project (HEATSTORE, 2022; www.heatstore.eu/).

There is a drive in Europe to improve energy efficiency in the built environment by making optimal use of heat sources in the energy mix and improving the insulation of the building envelope, thus decreasing the heat demand and lowering the supply temperature required for space heating. This opens up opportunities for geothermal heating and cooling as shallower- and lower-temperature sources can meet the energy and temperature demand.

In the Russian Federation, geothermal energy is historically used for local district heating or is directly applied in greenhouses, industrial processes and thermal health resorts. The areas where heating and cooling are most prevalent are the Northern Caucasus, the Eastern Ural, Lake Baykal and the Far East (Svalova, 2012). There is much potential for future development of geothermal heating and cooling as almost half of the total energy resources in the Russian Federation goes towards heat for settlements and industry (Svalova and Povarov, 2021). Geothermal resources in Russia have been mapped, and their development can be economically feasible. However, green heat sources, such as geothermal, are not developing quickly as the energy market is not fully liberalised, the climate's impact is not yet fully understood, interests of conventional fossil energy sources take priority, and the existence of regulatory and investment barriers (Shevchenko, Linovsky and Skrobot, 2020).

Of the other countries of the Caucasus that would be suitable for heating and cooling, Georgia is currently the only country producing heat from geothermal energy but uses only a small part of its resources (Melikadze, Vardigoreli and Kapandze, 2015). Both Armenia and Azerbaijan have considered the use of geothermal resources, but limited surface exploration has been done, and development has not yet started (Henneberger, Cooksley and Hallberg., 2000).

Developments in resources and technology for electricity and/or thermal use

Several EGS projects have been developed in Germany, France, Iceland, Austria, Switzerland and Italy. One well-known project is located in Soultz-sous-Forêts (France) in the Upper Rhine Graben, where EGS research started in 1987. Wells were drilled to fractured crystalline rocks at ca. 5 000 metre depth, and different hydraulic and chemical stimulation procedures were tested. This all led to the first electricity production in 2008 and a large amount of scientific data. Several other geothermal projects in Europe used EGS technology. Some of these projects experienced induced seismicity, for instance, in Basel (Switzerland) and Landau (Germany). Research into EGS continues, however, it appears difficult to scale up the EGS technology in Europe (EGEC, 2022a).

Within Europe, several projects have been developed using abandoned mines for geothermal heating and cooling or thermal energy storage, such as in Spain (Lara *et al.*, 2017), the United Kingdom (Coal Authority, 2021) and the Netherlands (Mijnwater, 2022).

Other technological developments in Europe (EGEC, 2021, 2022a) relate to, for instance:

- Multi-drain borehole design (Velizy-Villacoublay, Paris Basin, France). This technology was used already in the oil and gas industry and is now being implemented in a deep geothermal project for the first time. The use of a borehole with multiple tracks downhole can maximise the energy output from a reservoir with, for instance, low transmissivity.
- Plasma drilling (for instance, plans for Europe's deepest geothermal well in Finland (ThinkGeoEnergy, 2021). This is a new technology that allows deeper and faster drilling that is more cost-efficient and less dependent on rock type.
- Radial jet drilling (investigated in, for instance, the HIPE project in the Netherlands (Topsector Energie, 2018) and the SURE project in Iceland (Kaldal *et al.*, 2019)). High-pressure water is used to drill lateral (radial) wells from one borehole.
- Real-time monitoring corrosion in wells (Spain [EGEC, 2021]). This is done by electrochemical sensors, which can monitor very small changes in corrosion and therefore detect maintenance needs early on;
- Deep closed-loop systems (for instance, in Geretsried, Germany [Süddeutsche Zeitung, 2022]). In these systems, a working fluid is circulated in a deep closed loop that acts as a heat exchanger.

Mineral recovery

The first successful pilot for lithium extraction from a geothermal brine was conducted in 2021 at the Rittershoffen geothermal plant in northern Alsace, France (Eramet, 2021). In the European EuGeLi project framework, battery-grade lithium carbonate was produced from geothermal water later in 2021 in Soultz-sous-Forêts (Bas-Rhin), France (Eramet, 2022; BRGM, 2022). In April 2022, EGEC published an industry call to the European Union, asking for European public financial support for developing geothermal lithium resources (EGEC, 2022b). In the United Kingdom, projects to extract lithium from geothermal fluids are under development (Sanjuan *et al.*, 2022; Cornish Lithium, 2022b).

Carbon dioxide capture and storage

In Iceland, the Carbfix initiative to inject carbon dioxide and store it through natural underground mineralisation, which was developed in collaboration with the geothermal operator of the Hellisheiði geothermal field, started storing captured non-condensable gases from the geothermal electric plant and then expanded to apply the underground storage technology to carbon dioxide directly captured from the air. This technology is now expanding to multiple field sites and has received funding from the European Commission for the project Silverstone (ThinkGeoEnergy, 2022i; European Commission, 2021; Sigfússon *et al.*, 2018).

Geothermal power station in Iceland.

4. RECOMMENDATIONS

The purpose of this assessment is to provide actionable recommendations to guide policy makers, government and industry, potential investors, development partners, and public and private sector stakeholders on how to promote market growth, demonstrate the potential of geothermal energy and further expand its integration within the global energy systems. This chapter provides recommendations for the way forward for the geothermal energy sector addressing the wider audience targeted in this report. The recommendations focus on how stakeholders can support further development and implementation of geothermal energy, building on the existing market and technology dynamics.

Building on the challenges and opportunities described in Chapters 2 and 3, this report highlights the following recommendations to address existing barriers to geothermal electricity and heat generation in the global market context.

1. Promote widespread development and utilisation of all available sources of geothermal energy. The development of geothermal energy previously focussed on the identification and utilisation of high-temperature resources, mainly for electricity generation. However, the significant potential of the low- and medium-temperature resources, which are more widely available, still remains largely untapped.
    - Explore and develop low- and medium-temperature geothermal resources in volcanic zones and sedimentary basins for both electricity generation using binary turbine technology as well as geothermal heating and cooling.
    - Develop and utilise geothermal energy in previously developed sub-surface assets, such as abandoned mines or oil and gas wells, to minimise the cost and risk of geothermal projects, especially cost-intensive drilling activities.
    - Utilise geothermal energy in shallow ground or groundwater sources, through the application of heat pumps, mainly for heating and cooling applications.
    - Utilise favourable sub-surface conditions to store excess heat using underground thermal energy storage techniques for utilisation when demand increases.

2. Position geothermal as a key energy solution to drive the energy transition towards the achievement of the Sustainable Development Goals and climate action. Geothermal resources have many competitive advantages, which are often overlooked due to a focus on the challenges. The geothermal industry can elevate the contribution of geothermal to the energy transition space by appropriate messaging to highlight the opportunities as well as the benefits of geothermal energy development. At the same time, awareness creation could focus on increasing public acceptance of geothermal energy among the general public and the policy makers.

- Highlight the multiple opportunities geothermal resources can offer to advance the energy transition and climate action, including clean electricity generation, clean heating and cooling in the end-use sectors, as well as extraction of minerals such as lithium for battery manufacture.
- Quantify in comparable terms the competitive advantages and benefits of developing and integrating geothermal in the global energy systems, *e.g.* life-cycle greenhouse gas emissions, resource footprint such as land and water requirements per unit of energy produced, and others.
- Address the concerns regarding geothermal energy in an open and participatory manner to increase the understanding of the public and policy makers and minimise public resistance towards the development of geothermal resources through initiatives such as the GEOENVI Project in Europe.

3. Improve enabling frameworks to foster investments in geothermal energy. The development of geothermal is associated with high upfront costs and high resource risks, particularly in the early stages of development. This presents a major barrier to investment in geothermal energy projects. Furthermore, geothermal developers consider the licensing procedures for geothermal energy resources in many jurisdictions too lengthy and complex. In addition, limited policy instruments have been developed specifically to support geothermal development.

    - Establish new and enhance the existing risk mitigation schemes to cushion developers against the sub-surface geological risks of geothermal exploration, particularly in the early stages of development. The risk mitigation scheme should be tailor made to the sub-surface and market circumstances in a given country or region to promote both electricity generation as well as heating and cooling from geothermal resources.
    - Harmonise and simplify the licencing and permitting procedures for geothermal energy resources for electricity, heating and cooling projects, as well as mineral extraction from geothermal brines, production of geothermal energy from oil and gas wells, etc.
    - Develop energy and climate plans that take into consideration the contribution of geothermal energy, such as national energy strategies with targeted contributions from geothermal resources and nationally determined contributions.
    - Consider intrinsic characteristics of geothermal energy resources in the design of power purchase agreements, tariffs, and energy procurement rules and procedures to promote the integration of geothermal in the energy systems.
    - Promote the expansion of geothermal heat pump (GHP) technology in emerging GHP markets beyond the GHP global leaders (*i.e.* China, Europe and the United States) through awareness creation, enabling frameworks, subsidies and incentives, and demonstration projects.
    - Support the development of small-scale geothermal power plants through appropriate policy and regulatory measures.

4. Foster cross-industry synergies and harmonisation between geothermal and other sectors. The development and utilisation of geothermal energy are intertwined with various sectors such as other renewable energies like wind and solar, carbon capture and storage, hydrogen production, the extractives industry, and end-use sectors, including housing, industrial and agri-food sectors. Promoting synergy between geothermal and other sectors requires cross-sectoral collaboration as well as harmonisation of policies and regulations across those sectors.

   - Develop regulations to promote sharing of sub-surface data between the geothermal and extractive sectors, such as oil and gas and the mining sector, which have a repository of relevant data on sub-surface distribution of temperatures and geological formations.
   - Harmonise the legislation regarding the rights to access and extract geothermal energy and minerals, such as lithium, in situations where both co-exist.
   - Streamline policies and regulations in the end-use sectors such as in the building, agri-food and industrial sectors to promote their decarbonisation using geothermal energy, particularly at the local level, *e.g.* in municipalities where geothermal resources are found.
   - Encourage hybrid geothermal electricity generation with other renewables, such as concentrated solar power, solar photovoltaic and biomass, to maximise the efficiency of electricity production.

5. Promote technological innovation, research and development (R&D) to scale up geothermal development. Various innovations and R&D initiatives are ongoing in different countries, with a focus on the extraction of geothermal energy from hot dry rock (enhanced geothermal systems), large-scale closed-loop systems (advanced geothermal systems), green hydrogen, supercritical fluids and mineral extraction from brines. These initiatives are expected to enable the development of geothermal globally, improve the efficiency of geothermal electricity generation from low- and medium-temperature resources, reduce resource risks, improve the financial viability of new technologies and enable the economical extraction of minerals from geothermal brines.

   - Invest in innovation and R&D initiatives through the provision of grants or equity to incentivise the commercialisation of ongoing and future projects.
   - Implement pilot projects to demonstrate commercial project viability, as well as gain the confidence of communities, policy makers and other stakeholders.
   - Build upon the success of the world's first green hydrogen demonstration projects using geothermal energy in Iceland, Japan and New Zealand to ramp up the contribution of geothermal energy to the rapidly expanding hydrogen economy.

6. Strengthen international, regional and national co-operation among partners.
   - Adopt a regional or national approach to address common issues that hinder geothermal development, *e.g.* building in-house technical and institutional capacity, awareness creation and outreach to promote the integration of geothermal in energy systems.
   - Leverage the resources and expertise of bilateral, international and multilateral partners to advance geothermal development through technical assistance, capacity building, sharing of experiences and best practices, and financing.
   - Elevate geothermal discussions to international platforms in the presence of diverse stakeholders drawn from the energy and other relevant sectors, *e.g.* during global climate meetings.

5. REFERENCES

Alvarenga, Y., Handal, S. and Recinos, M. (2008), "Solar steam booster in the Ahuachapan geothermal field", GRC Transactions, *https://cir.nii.ac.jp/crid/1570572701372457984*.

Amaya, A., Chandrasekar, H., Scherer, J. and Higgins, B. (2021), "Closed-Loop geothermal in steam and 2-phase dominated reservoirs", National Geothermal Association of the Philippines Conference 2021, *www.greenfireenergy.com/research/* (accessed 1 September 2022).

Amaya, A., Scherer, J., Muir, J., Patel, M. and Higgins, B. (2020), "GreenFire energy closed-loop geothermal demonstration using supercritical carbon dioxide as working fluid", Proceedings of the 45th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, 10-12 February 2020, SGP-TR-216, *https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2020/Higgins.pdf*.

Amplify (2022), "Event week opening and showcase of He Ahi, the Tauhara Clean Energy Park", *www.taupo.biz/event-details/event-week-opening-and-showcase-of-he-ahi-the-tauhara-clean-energy-park?fbclid=IwAR0X1sKmIImoZ9ru9MgwWAI5RSDWZDnzCmE_rS4XI0diQfXv9UnyOvcG1yw* (accessed 1 September 2022).

Anderson, A. and Rezaie, B. (2019), "Geothermal technology: Trends and potential role in a sustainable future", *Applied Energy*, Vol. 248/August, pp. 18-34, *https://doi.org/10.1016/j.apenergy.2019.04.102*.

Assegaf Hamzah & Partners (2022), "Presidential regulation 112: Indonesia's commitment to renewable energy", *www.ahp.id/clientalert/AHPClientUpdate-23September2022.pdf*.

Asunción Alas, C. A. and Pabón Chavez, M. N. (2019), "Propuesta metodológica para la aceptación social de proyectos geotérmicos de usos directos en comunidades dentro de zonas de interés geotérmico en El Salvador", Universidad de El Salvador, Facultad de Ingeniería y Arquitectura, Escuela de Posgrado, Diplomado en Geotermia para América Latina, *https://ri.ues.edu.sv/id/eprint/20756/*.

Atlantic Council (2021), "EnergySource innovation stream: Decarbonizing homes with geothermal heat pumps", *www.atlanticcouncil.org/event/esis-decarbonizing-homes-with-geothermal-heat-pumps/* (accessed 1 September 2022).

Atlantic Council (2018), "A geothermal leader: The case of Iceland", *www.atlanticcouncil.org/blogs/energysource/a-geothermal-leader-the-case-of-iceland/* (accessed 5 December 2022).

Augustine, C. and Falkenstern, D. (2014), "An estimate of the near-term electricity-generation potential of co-produced water from active oil and gas wells", *Society of Petroleum Engineers Journal*, Vol. 19/3, pp. 530-541, *https://onepetro.Org/SJ/article-abstract/19/03/530/205877/An-Estimate-of-theNear-Term-Electricity?redirectedFrom=fulltext*.

Ball State University (2012), "Geothermal energy system: Nation's largest project of its kind goes live", *www.bsu.edu/about/geothermal* (accessed 1 September 2022).

BBC News Mundo (2020), "Qué es el litio geotérmico y por qué puede revolucionar las energías limpias", *www.bbc.com/mundo/vert-fut-55223891* (accessed 5 December 2022).

Benton, T. G., Froggatt, A., Wellesley, L., Grafham, O., King, R., Morisetti, N., Nixey, J. and Schröder, P. (2022), "The Ukraine war and threats to food and energy security", *www.chathamhouse.org/2022/04/ukraine-war-and-threats-food-and-energy-security* (accessed 1 September 2022).

Bershaw, J., Burns, E. R., Cladouhos, T. T., Horst, A. E., Van Houten, B., Hulseman, P., Kane, A., Liu, J. H., Perkins, R. B., Scanlon, D. P., Streig, A. R., Svadlenak, E. E., Uddenberg, M. W., Wells, R. E. and Williams, C. F. (2020), "An integrated feasibility study of reservoir thermal energy storage in Portland, Oregon, USA", Proceedings of the 45th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, 10-12 February 2020, SGP-TR-216, *https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2020/Bershaw.pdf*.

Bertani, R. (2015), "Geothermal power generation in the world 2010-2014 update report", Proceedings of the World Geothermal Congress 2015, Melbourne, Australia, 19-25 April 2015, *www.geothermal-energy.org/pdf/IGAstandard/WGC/2015/01001.pdf*.

Bertani, R. (2010), "Geothermal power generation in the world 2005-2010 update report", Proceedings of the World Geothermal Congress 2010, Bali, Indonesia, 25-29 April 2010, *www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0008.pdf*.

Bertani, R. (2005), "World geothermal generation 2001-2005: State of the art", Proceedings of the World Geothermal Congress 2005, Antalya, Turkey, 24-29 April 2005, *www.geothermal-energy.org/pdf/IGAstandard/WGC/2005/0008.pdf*.

Bloomquist, R. G. (2006), "Economic benefits of mineral extraction from geothermal brines", *www.geothermal-energy.org/pdf/IGAstandard/Russia/MEGB-2006/20Bloomquist.pdf*.

Boissavy, C. (2020), *Report Reviewing Existing Insurance Schemes for Geothermal*, GEORISK programme, *www.georisk-project.eu/wp-content/uploads/2020/02/D3.1_Report-reviewing-geothermal-risk-mitigation-schemes-v2.pdf*.

Bradley, T., Aarnes, I., Outrequin, D., Monneyron, N. and Reseaux, E. (2019), "Application of oil and gas methodology to geothermal formation evaluation: the value of data", *https://publications.mygeoenergynow.org/grc/1034186.pdf*.

BRGM (2022), "EuGeLi: Lithium extraction from geothermal brines in Europe", Bureau de Recherches Géologiques et Minières, *www.brgm.fr/en/current-project/esugeli-lithium-extraction-geothermal-brines-europe#:~:text=The%20European%20EuGeLi%20project%2C%20completed,a%20complement%20to%20renewable%20energy* (accessed 1 September 2022).

Burkardt, P. and Herbling, D. (2021), "The world's no. 1 in geothermal electricity, Kenya aims to export its know-how", Bloomberg, www.bloomberg.com/news/features/2021-07-19/kenya-aims-to-double-geothermal-capacity-by-2030 (accessed 1 September 2022).

Butuzov, V. A., Tomarov, G. V., Alkhasov, A. B., Aliev, R. M. and Badavov, G. B. (2022), "Geothermal energy of Russia: Resources, electric power generation, and heat supply (a review)", *Thermal Engineering*, Vol. 69/February, pp. 1-13, https://doi.org/10.1134/S0040601521120028.

Cataldi, R. and Súarez Arriaga, M. C. (2016), "Our geothermal legacy: A historic overview", IGA News, Newsletter of the International Geothermal Association, Special Number on the Anniversary of the IGA, www.lovegeothermal.org//IGAnews_archive/IGANews-Special%20Number-2.pdf.

Caulk, R. A. and Tomac, I. (2017), "Reuse of abandoned oil and gas wells for geothermal energy production", *Renewable Energy*, Vol. 112/November, pp. 388-397, https://doi.org/10.1016/j.renene.2017.05.042.

CEPAL (2021), Estadísticas del subsector eléctrico de los países del Sistema de la Integración Centroamericana (SICA), 2019 y avances a 2020, LC/MEX/TS.2021/14, Comisión Económica para América Latina y el Caribe, Ciudad de México, www.cepal.org/es/publicaciones/47019-estadisticas-subsector-electrico-paises-sistema-la-integracion-centroamericana (accessed 1 September 2022).

Climo, M., Carey, B. and Mroczek, M. (2016), M*ineral Extraction from Geothermal Brines in New Zealand*, GNS Science, www.researchgate.net/publication/316919684_Mineral_extraction_from_geothermal_brines_in_New_Zealand_2016_update.

Coal Authority (2021), "Mine water heat", www.gov.uk/government/collections/mine-water-heat (accessed 1 September 2022).

Contractor Magazine (2011), "Ball State University's geothermal system will be largest in U.S.", www.contractormag.com/green/article/20877656/ball-state-universitys-geothermal-system-will-be-largest-in-us (accessed 1 September 2022).

Controlled Thermal Resources (2022), "The power of California lithium valley", www.cthermal.com/projects (accessed 1 September 2022).

Cornish Lithium (2022a), "Lithium in geothermal waters", https://cornishlithium.com/projects/lithium-in-geothermal-waters/ (accessed 1 September 2022).

Cornish Lithium (2022b), "United downs lithium pilot plant delivered on time and on budget", https://cornishlithium.com/company-announcements/united-downs-lithium-pilot-plant-delivered-on-time-and-on-budget/ (accessed 5 December 2022).

Dandelion Energy (2022), "The 2021 federal geothermal tax credit: Your questions answered", https://dandelionenergy.com/federal-geothermal-tax-credit (accessed 1 September 2022).

DEEP Corp. (2022), "Progress continues for DEEP Earth Energy Production Corp.", *www.globenewswire.com/news-release/2022/04/21/2426851/0/en/Progress-Continues-for-DEEP-Earth-Energy-Production-Corp.html* (accessed 1 September 2022).

Dewhurst, W. (2022), "Fondo de Desarrollo Geotérmico Para Latinoamérica (GDF), Foro de Asistencia Técnica", Presentation at 9th Geothermal Congress for Latin America and the Caribbean (GEOLAC), Mexico City, 7 November 2022.

Dickson, M. H. and Fanelli, M. (2013), *Geothermal Energy: Utilization and Technology*, Routledge, Abingdon, Oxfordshire.

DiMarzio, G., Angelini, L., Price, W., Chin, C. and Harris, S. (2015), "The Stillwater triple hybrid power plant: Integrating geothermal, solar photovoltaic and solar thermal power generation", *Proceedings of the World Geothermal Congress 2015,* Melbourne, Australia, 19-25 April 2015, *https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/38001.pdf*.

DiPippo, R. (2012), *Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact*, Butterworth-Heinemann, Oxford, United Kingdom.

Eavor (2022), "SVG x Eavor – Advanced geothermal reversing setbacks in the Caribbean", *www.eavor.com/blog/svg-x-eavor-advanced-geothermal-reversing-setbacks-in-the-caribbean/* (accessed 1 September 2022).

Eavor Technologies (2021), Eavor-Lite Demonstration Project: 2506 (G2019000423)/R0160681, Final Report (Public), prepared for Emissions Reduction Alberta, *www.eralberta.ca/wp-content/uploads/2021/11/Eavor_ERA-Final-Public-Report.pdf*.

EBTKE (2022), "To support the energy transition, the Government encourages direct utilization of geothermal energy", Directorate General of New Renewable Energy and Energy Conservation, *https://ebtke.esdm.go.id/post/2022/11/21/3348/dukung.transisi.energi.pemerintah.dorong.pemanfaatan.langsung.panas.bumi?lang=en*.

EGEC (2022a), *EGEC Geothermal Market Report 2021*, European Geothermal Energy Council, Brussels, Belgium, *www.egec.org/media-publications/egec-geothermal-market-report-2021/*.

EGEC (2022b), "Renewable energy directive 2022 review: EGEC position paper", European Geothermal Energy Council, *www.egec.org/policy-documents/renewable-energy-directive-2022-review-egec-position-paper/*.

EGEC (2022c), "Industry call to the EU: 'We cannot lose the global race for this sustainable local resource", European Geothermal Energy Council, *www.egec.org/policy-documents/industry-call-to-the-eu-we-cannot-lose-the-global-race-for-this-sustainable-local-resource/*.

EGEC (2022d), "Geothermal industry call for a geothermal strategy", European Geothermal Energy Council,*www.egec.org/geothermal-industry-call-for-a-geothermal-strategy/* (accessed 8 September 2022).

EGEC (2021), *EGEC Geothermal Market Report 2020*, European Geothermal Energy Council, Brussels, Belgium, www.egec.org/media-publications/egec-geothermal-market-report-2020/.

EGEC (2020), *EGEC Geothermal Market Report 2019*, European Geothermal Energy Council, Brussels, Belgium www.egec.org/media-publications/egec-geothermal-market-report-2019/.

ElectraTherm (2022), "Remote geothermal heat recovery", https://electratherm.com/remote-geothermal-heat-recovery/ (accessed 1 September 2022).

ElectraTherm (2012), "Mississippi oilfield generates low-temperature, emission free geothermal energy at the wellhead", www.smu.edu/-/media/Site/Dedman/Academics/Programs/Geothermal-Lab/Documents/Oil-and-Gas-Publications/2012_Denbury_White_Paper.pdf?la=en.

El Heraldo (2021), "Geothermal power generation pilots are being developed in Colombia", www.elheraldo.co/economia/comienzan-pilotos-de-geotermia-en-colombia-826348 (accessed 5 December 2022).

Enel Green Power (2021), "Stillwater triple hybrid plant, USA", www.enelgreenpower.com/our-projects/operating/stillwater-hybrid-plant (accessed 5 December 2022).

Energy Matters (2021), "The rapid decline of fossil fuel power sources", www.energymatters.com.au/renewable-news/the-rapid-decline-of-fossil-fuel-power-sources/ (accessed 1 September 2022).

ENS Africa (2021), "A snapshot of the recommendations of the Presidential Task Force on review of power purchase agreements in Kenya", www.ensafrica.com/news/detail/4862/a-snapshot-of-the-recommendations-of-the-pres?utm_source=Mondaq&utm_medium=syndication&utm_campaign=LinkedIn-integration.

Eramet (2022), "EuGeLi project: Extracting European lithium for future electric vehicle batteries", www.eramet.com/en/activities/innovate-design/eugeli-project (accessed 1 September 2022).

Eramet (2021), "Eramet and Électricité de Strasbourg announce the success of the first pilot test to extract lithium from geothermal brine in Alsace, France", www.eramet.com/en/eramet-and-electricite-de-strasbourg-announce-success-first-pilot-test-extract-lithium-geothermal (accessed 1 September 2022).

Erickson, D., Kyung, I. and Holdmann, G. (2005), "Geothermal powered absorption chiller for Alaska Ice Hotel", *Geothermal Resources Council Transactions*, Vol. 29, pp. 57-59, www.geothermal-library.org/index php?mode=pubs&action=view&record=1022570.

ESMAP (2016), *Comparative Analysis of Approaches to Geothermal Resource Risk Mitigation: A Global Survey*, Energy Sector Management Assistance Program, World Bank, Washington, DC, https://documents1.worldbank.org/curated/en/621131468180534369/pdf/105172-ESM-P144569-PUBLIC-FINAL-ESMAP-GeoRiskMitigation-KS024-16-web.pdf.

ESMAP (2012), *Geothermal Handbook: Planning and Financing Power Generation: Technical Report 002/12*, Energy Sector Management Assistance Program, World Bank, Washington, DC, *www.esmap.org/sites/esmap.org/files/DocumentLibrary/FINAL_Geothermal%20Handbook_TR002-12_Reduced.pdf*.

EU Reporter (2022), "150 companies call on President Von Der Leyen to prepare a European strategy to unlock geothermal", *www.eureporter.co/energy/2022/04/13/150-companies-call-on-president-von-der-leyen-to-prepare-a-european-strategy-to-unlock-geothermal/* (accessed 1 December 2022).

European Commission (2021), "Silverstone: Full-scale CO_2 capture and mineral storage", *https://ec.europa.eu/clima/system/files/2022-07/if_pf_2021_silverstone_en.pdf* (accessed 1 September 2022).

Exergy (2022), "EDC's first geothermal brine recovery plant with Exergy technology is now operational in the Philippines", *www.exergy-orc.com/edcs-first-geothermal-brine-recovery-plant-with-exergy-technology-is-now-operational-in-the-philippines/* (accessed 1 September 2022).

Fox, D. B., Sutter, D. and Tester, J. W. (2011), "The thermal spectrum of low-temperature energy use in the United States", *Proceedings of the 36th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, CA, 31 January-2 February 2011, *https://es.stanford.edu/ERE/pdf/IGAstandard/SGW/2011/fox.pdf*.

Friðleifsson, G. Ó., Elders, W. A. and Albertsson, A. (2014), "The concept of the Iceland deep drilling project", *Geothermics*, Vol. 49/January, pp. 2-8, *https://doi.org/10.1016/j.geothermics.2013.03.004*.

FuelCellsWorks (2021), "Japan: Obayashi completes a demonstration plant for hydrogen production using geothermal", *https://fuelcellsworks.com/news/japan-obayashi-completes-a-demonstration-plant-for-hydrogen-production-using-geothermal/* (accessed 1 September 2022).

FutEra Power (2022), "Co-produced geothermal natural gas hybrid power project", *www.futerapower.com/* (accessed 1 September 2022).

García, J., Gischler, C. and Hallack, M. (2021), "Will hydrogen development in Latin America and the Caribbean be color blind?", Inter-American Development Bank blog, *https://blogs.iadb.org/energia/en/will-hydrogen-development-in-latin-america-and-the-caribbean-be-color-blind/* (accessed 1 September 2022).

Gavriliuc, R., Rosca, M. and Cucueteanu, D. (2019), "Geothermal energy use, country update for Romania", *Proceedings of the European Geothermal Congress 2019*, The Hague, The Netherlands, 11-14 June 2019, *https://europeangeothermalcongress.eu/wp-content/uploads/2019/07/CUR-23-Romania.pdf*.

GDR (2014), "April 2014 Green Machine Florida Canyon hourly data", *Geothermal Data Repository*, *https://gdr.openei.org/submissions/415 (accessed 1 September 2022)*.

GEMex (2020), "GEMex final conference", *www.gemex-h2020.eu/* (accessed 1 September 2022).

Geo40 (2022), "Geothermal silica", *https://geo40.com/geothermalsilica/* (accessed 1 September 2022).

GeoDH (2014), "Developing geothermal district heating in Europe", *http://geodh.eu/wp-content/uploads/2012/07/GeoDH-Report-2014_web.pdf*

GEOELEC (2013), Report Presenting Proposals for Improving the Regulatory Framework for Geothermal Electricity, *www.geoelec.eu/wp-content/uploads/2015/10/D-4.1-GEOELEC-Report-on-Geothermal-Regulations.pdf*.

GEOENVI (2021), "Tackling the environmental concerns for deploying geothermal energy in Europe", *www.geoenvi.eu/* (accessed 2 December 2022).

GeoFutures GreenInvest (2022), "Smart insurance for sustainable investment", *https://geofutures-greeninvest.com* (accessed 2 December 2022).

GeoProducts Corp (1988), *Preconstruction of the Honey Lake Hybrid Power Plant: Final Report*, Contract No: DE-AC07-84ID12477, GeoProducts Corporation, Oakland, CA, *www.osti.gov/biblio/6183994-preconstruction-honey-lake-hybrid-power-plant-final-report*.

GEORISK (2021), *Why De-Risking Is Key to Develop Large Geothermal Project?*, *www.georisk-project.eu/wp-content/uploads/2021/07/Final-Report.pdf*.

Geothermal Hot Line (1988), "Honey Lake power facility under construction", *The Geothermal Hot Line*, Vol. 18/2, pp. 61, ISSN 0735-0503, December 1988, *https://publications.mygeoenergynow.org/journals/hotline_18_2_Dec_1988.pdf*.

Geothermie Nederland (2022a), "Aardwarmte, een onmisbare bron van energie [Geothermal energy, an indispensable source of energy]", *https://geothermie.nl/* (accessed 1 September 2022).

Geothermie Nederland (2022b), "Actieplan versnelling geothermie [Geothermal acceleration action plan]", *https://geothermie.nl/over-ons/actieplan-versnelling-geothermie/* (accessed 2 December 2022).

GIZ (2022), "SICA: Making direct use of geothermal energy in Central America", German Agency for International Cooperation, *www.giz.de/en/worldwide/78071.html* (accessed 1 September 2022).

Gosnold, W., Ballesteros, M., Wang, D. and Crowell, J. (2020), "Using geothermal energy to reduce oil production costs", *GRC Transactions*, *www.geothermal-library.org/index.php?mode=pubs&action=view&record=1034249*.

Grasby, S. E., Allen, D. M., Bell, S., Chen, Z., Ferguson, G., Jessop, A., Kelman, M., Ko, M., Majorowicz, J., Moore, M., Raymond, J. and Therrien, R. (2012), *Geothermal Energy Resource Potential of Canada*, Geological Survey of Canada, Open File 6914 (revised), https://publications.gc.ca/collections/collection_2013/rncan-nrcan/M183-2-6914-eng.pdf.

Greenleaf Power (2022), "Greenleaf Power's Honey Lake power cogeneration plant reduces forest fire potential while providing emergency local power", https://greenleaf-power.com/honey-lake/ (accessed 1 September 2022).

GRMF (2022), "A catalyst for geothermal development", Geothermal Risk Mitigation Facility, https://grmf-eastafrica.org (accessed 1 December 2022).

Gutiérrez-Negrín, L. C. A., Canchola Félix, I., Romo-Jones, J. M. and Quijano-León, J. M. (2021), "Geothermal energy in Mexico: Update and perspectives", *Proceedings of the World Geothermal Congress 2020+1*, Reykjavik, Iceland, April-October 2021, www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01004.pdf.

Halcyon Power (2022), "Halcyon Power is a joint venture between New Zealand's Tuaropaki Trust and Obayashi Corporation", www.halcyonpower.nz/ (accessed 1 September 2022).

Hand, T. W. (2008), "Hydrogen production using geothermal energy", Utah State University, Utah, https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1038&context=etd.

Hawilti (2022), "TMGO steps up drilling operations at Ethiopia's flagship geothermal project", https://hawilti.com/energy/geothermal/tmgo-steps-up-drilling-operations-at-ethiopias-flagship-geothermal-project/.

HEATSTORE (2022), "HEATSTORE project update: High temperature underground thermal energy storage", *Proceedings of the World Geothermal Congress 2020+1*, Reykjavik, Iceland, April-October 2021, www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/35006.pdf (accessed 1 September 2022).

Heeter, J., Speer, B. and Glick, M. B. (2019), *International Best Practices for Renewable Portfolio Standard (RPS) Policies*, NREL/TP-6A20-72798, National Renewable Energy Laboratory, Golden, CO, www.nrel.gov/docs/fy19osti/72798.pdf.

Henneberger, R., Cooksley, D. and Hallberg, J. (2000), "Geothermal resources of Armenia", *Proceedings of the World Geothermal Congress 2000*, Kyushu-Tohoku, Japan, 28 May-10 June 2000, www.geothermal-energy.org/pdf/IGAstandard/WGC/2000/R0822.PDF.

Higgins, B., Scherer, J., Amaya, A., Chandrasekar, H. and Van Horn, A. (2021), "Closed-loop geothermal in steam dominated reservoirs", *Geothermal Resources Council Transactions*, Vol. 45, www.researchgate.net/publication/355575740_Closed-Loop_Geothermal_in_Steam_Dominated_Reservoirs/link/61771da3eef53e51e1ebc2c2/download.

Hodgson, S. F. (1997), *Geysers Album: Five Eras of Geothermal History*, California Department of Conservation Division of Oil, Gas, and Geothermal Resources, Sacramento.

Holdmann, G. (2007), *The Chena Hot Springs 400kW Geothermal Power Plant: Experience Gained during the First Year of Operation*, Unpublished report to Chena Power, *www.researchgate.net/publication/240610758_The_Chena_Hot_Springs_400kW_Geothermal_Power_Plant_Experience_Gained_During_the_First_Year_of_Operation*.

Huttrer, G. W. (2021), "Geothermal power generation in the world 2015-2020 update report", *Proceedings of the World Geothermal Congress 2020+1*, Reykjavik, Iceland, April-October 2021, *www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01017.pdf*.

IDB (2020), *Harnessing Geothermal Potential in Latin America and the Caribbean: A Perspective on the Road Ahead*, Inter-American Development Bank, Washington, DC, *http://dx.doi.org/10.18235/0002702*.

IGA (2021), "Green Pipeline: The oil and gas to geothermal connection", International Geothermal Association, *www.lovegeothermal.org/wp-content/uploads/The-Green-Pipeline-2021.pdf*.

IGA (2017), "Global geothermal development – An overview", Presentation by the International Geothermal Association at the Global Geothermal Alliance Meeting, IRENA, Florence, Italy, September 2017, *www.irena.org/-/media/Files/IRENA/Agency/Events/2017/Sep/Session-II_Alexander-Richter_International-Geothermal-Association.pdf?la=en&hash=19865720C184B9A090ED85E599C25C1D30080557*.

Imamura Y., Shiozaki, I. and Okumura, T. (2020), "A review of small-scale geothermal power plants in Japan and its opportunities for New Zealand's geothermal business", *Proceedings of the 42nd New Zealand Geothermal Workshop*, Waitangi, New Zealand, 24-26 November 2020.

International District Energy Association (2020), "Tabreed acquires Masdar City's 69.000RT district cooling plants", *www.districtenergy.org/blogs/district-energy/2020/01/21/tabreed-acquires-masdar-citys-69000rt-district-coo#:~:text=UAE's%20district%20cooling%20developer%20National,urban%20communities%20in%20Masdar%20City* (accessed 1 September 2022).

IRENA (2022a), *Powering Agri-Food Value Chains with Geothermal Heat: A Guidebook for Policy Makers*, International Renewable Energy Agency, Abu Dhabi, *www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jun/IRENA_Geothermal_Agri-food_Value_Chain_2022.pdf*.

IRENA (2022b), *Renewable Capacity Statistics 2022*, International Renewable Energy Agency, Abu Dhabi, *https://irena.org/publications/2022/Apr/Renewable-Capacity-Statistics-2022*.

IRENA (2022c), *Renewable Power Generation Costs in 2021*, International Renewable Energy Agency, Abu Dhabi, *www.irena.org/Publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021*.

IRENA (2021), *Geothermal: The Solution Underneath*, International Renewable Energy Agency, Abu Dhabi, *www.globalgeothermalalliance.org/-/media/Files/IRENA/GGA/Publications/Geothermal---The-Solution-Underneath.pdf*.

IRENA and Aalborg University (2021), *Integrating low-temperature renewables in district energy systems: Guidelines for policy makers*, International Renewable Energy Agency, Abu Dhabi, Aalborg University, Aalborg, *https://www.irena.org/Publications/2021/March/Integrating-low-temperature-renewables-in-district-energy-systems*.

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, 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, *www.irena.org/publications/2020/Nov/Renewable-energy-policies-in-a-time-of-transition-Heating-and-cooling*.

IWG (2020), *SET-Plan Deep Geothermal IWG Implementation Plan*, *https://setis.ec.europa.eu/system/files/2021-04/Implementation%20plan%20on%20deep%20geothermal%20energy.pd*f

JED (2022), "Clean, safe, renewable energy", Jeotermal enerji dernegi, *https://jeotermalenerjidernegi.org.tr/en* (accessed 1 September 2022).

Jessop, A. M., MacDonald, J. K. and Spence, H. (1995), "Clean energy from abandoned mines at Springhill, Nova Scotia", *Energy Sources*, Vol. 17/1, pp. 93-106, *https://doi.org/10.1080/00908319508946072*.

Jianchao, H., Mengchao, C. and Liu, P. (2018), "Development and utilization of geothermal energy in China: Current practices and future strategies", *Renewable Energies*, Vol. 125/September, pp. 401-412, *https://doi.org/10.1016/j.renene.2018.02.115*.

Jóhannesson, T. and Chatenay, C. (2014), "Industrial applications of geothermal resources", *https://rafhladan.is/bitstream/handle/10802/5446/UNU-GTP-SC-18-26.pdf*.

Kajugus, S. I. (2022), "Geothermal innovations in Tanzania: Geo-hatchery project", *https://grmf-eastafrica.org/wp-content/uploads/2022/05/01_Geo-Hatchery__May2022.pdf*.

Kaldal, G., Thorbjörnsson, I., Gautason, B., Árnadóttir, S., Einarsson, G. M., Egilsson, T., Ásgeirsdóttir, R. S., Kästner, F., Thorsteinsdóttir, U., Erlendsson, Ö., Vilhjálmsson, A. M., Tryggvason, H. and Haraldsdóttir, S. H. (2019), *The Horizon 2020 Project SURE: Deliverable 6.3 – Report on Field Scale RJD Stimulation for the Magmatic Site*, German Research Centre for Geosciences (GFZ), Potsdam,*https://doi.org/10.2312/GFZ.4.8.2019.013*.

Kavvadias, K. C. and Quoilin, S. (2018), "Exploiting waste heat potential by long distance heat transmission: Design considerations and techno-economic assessment", *Applied Energy*, Vol. 216/April, pp. 452-465, *https://doi.org/10.1016/j.apenergy.2018.02.080*.

Kiruja, J. (2017), "The viability of supplying an industrial park with thermal energy from Menengai geothermal field, Kenya", MSc thesis, Reykjavik University, *https://orkustofnun.is/gogn/unu-gtp-report/UNU-GTP-2017-01.pdf*.

KIT (2021), "BrineMine: A BMBF project of Chilean and German partners to develop a geothermal system for mineral extraction, provision of drinking water and heat generation", Karlsruhe Institute of Technology, *https://geothermics.agw.kit.edu/english/brinemine.php* (accessed 1 September 2022).

Lara, L. M., Colinas, I. G., Mallada, M. T., Hernández-Battez, A. E. and Viesca, J. L. (2017), "Geothermal use of mine water", *European Geologist*, no. 43, pp. 40-45, *http://eurogeologists.eu/wp-content/uploads/2017/07/EGJ43_LR.pdf#page=40*.

Lee, K. K., Ellsworth, W. L., Giardini, D., Townend, J., Ge, S., Shimamoto, T., Yeo, I-W., Kang, T-S., Rhie, J., Sheen, D-H., Chang, C., Woo, J-U. and Langenbruch, C. (2019), "Managing injection-induced seismic risks", *Science* Vol. 364/6442, pp. 730-732, doi:10.1126/science.aax1878.

Limberger, J., Boxem, T., Pluymaekers, M., Bruhn, D., Manzella, A., Calcagno, P., Beekman, F., Cloetingh, S. and van Wees, J-D. (2018), "Geothermal energy in deep aquifers: A global assessment of the resource base for direct heat utilization", *Renewable and Sustainable Energy Reviews*, Vol. 82/Part1/February, pp. 961-975, *doi:10.1016/j.rser.2017.09.084*.

Limberger, J., Calcagno, P., Manzella, A., Trumpy, E., Boxem, T., Pluymaekers, M. P. D. and van Wees, J-D. (2014), "Assessing the prospective resource base for enhanced geothermal systems in Europe", *Geothermal Energy Science*, Vol. 2, pp. 55-71, *https://doi.org/10.5194/gtes-2-55-2014*.

Liu, X., Gluesenkamp, K. and Momen, A. (2015), *Overview of Available Low-Temperature/Coproduced Geothermal Resources in the United States and the State of the Art in Utilizing Geothermal Resources for Space Conditioning in Commercial Buildings*, ORNL/TM-2015/131, Oak Ridge National Laboratory, Oak Ridge, TN, May 2015, *https://info.ornl.gov/sites/publications/Files/Pub54942.pdf*.

Louisiana Tank Inc. (2012), *Demonstrating the Commercial Feasibility of Geopressured-Geothermal Power Development at Sweet Lake Field – Cameron Parish*, Louisiana, Final Technical Report, US Department of Energy: Award No. DE-EE0002855, *https://doi.org/10.2172/1033104*.

Lund, J. W. and Toth, A. N. (2021), "Direct utilization of geothermal energy 2020 worldwide review", *Geothermics*, Vol. 90/February, 101915, *https://doi.org/10.1016/j.geothermics.2020.101915*.

Lund, J. W., Sifford, A., Hamm, S. G. and Anderson, A. (2021), "The United States of America direct utilization update 2019", *Proceedings of the World Geothermal Congress 2020+1*, Reykjavik, Iceland, *www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01011.pdf*.

Majer, E. L., Baria, R., Stark, M., Oates, S., Bommer, J., Smith, B. and Asanuma, H. (2007), "Induced seismicity associated with enhanced geothermal systems", *Geothermics*, Vol. 36/3, pp. 185-222, *www.sciencedirect.com/science/article/pii/S0375650507000387*.

Malek, A. E., Adams, B. M., Rossi, E., Schiegg, H. O. and Saar, M. O. (2022), "Techno-economic analysis of Advanced Geothermal Systems (AGS)", *Renewable Energy*, Vol. 186/March, pp. 927-943, *https://doi.org/10.1016/j.renene.2022.01.012*.

Matthews, R. J. (2021), "Canada's geothermal energy opportunity", *Renewable Energy World*, 31 August 2021, *www.renewableenergyworld.com/baseload/canada-geothermal-energy-opporuntity/#gref* (accessed 1 September 2022).

Melikadze, G., Vardigoreli, O. and Kapandze, N. (2010), "Country update from Georgia", *Proceedings of the World Geothermal Congress 2015*, Melbourne, Australia, 19-25 April 2015, *www.geothermal-energy.org/pdf/IGAstandard/WGC/2015/01064.pdf*.

MENA Geothermal (n.d.), "American University of Madaba", *www.menageothermal.com/index.php?TemplateId=2&ProjectId=2*

Mesquita, L., McClenahan, D., Thornton, J., Carriere, J. and Wong, B. (2017), "Drake Landing Solar Community: 10 years of operation", *ISES Solar World Congress 2017*, IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry, *www.dlsc.ca/reports/swc2017-0033-Mesquita.pdf*.

Mijnwater (2022), "Mijnwater", *https://mijnwater.com/en/* (accessed 1 September 2022).

Millstein, D., Dobson, P. and Jeong, S. (2021), "The potential to improve the value of U.S. geothermal electricity generation through flexible operations", *Journal of Energy Resources Technology*, Vol. 143/1, 010905, *https://doi.org/10.1115/1.4048981*.

Ministerie van Economische Zaken en Klimaat (2022), *Delfstoffen en aardwarmte in Nederland* [Minerals and geothermal energy in the Netherlands], Jaarverslag [Annual Report] 2021, Ministry of Economic Affairs and Climate Policy, The Netherlands, *www.nlog.nl/sites/default/files/2022-07/jaarverslag_2021_delfstoffen_en_aardwarmte_in_nederland.pdf* (accessed 13 December 2022).

MOEA (2022), "Draft of 2022 feed-in tariffs (FIT) rates for renewable energy electric power announced, opinions from all sectors to be collected in January", Bureau of Energy, Ministry of Economic Affairs, Republic of China, *www.moea.gov.tw/Mns/english/news/News.aspx?kind=6&menu_id=176&news_id=98736*.

Monroy Parada, A. F. (2013), *Geothermal Binary Cycle Power Plant Principles, Operation and Maintenance*, Geothermal Training Program, United Nations University, Reykjavik, Iceland, *https://orkustofnun.is/gogn/unu-gtp-report/UNU-GTP-2013-20.pdf*.

Mousavi, S. Z. and Jalilinasrabady, S. (2021), "Geothermal country update report of Iran (2015-2020)", *Proceedings of the World Geothermal Congress 2020+1*, Reykjavik, Iceland, April-October 2021, *www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01009.pdf*.

Nature Middle East (2017), "Harnessing solar and geothermal energy for desalination", *https://jwp-nme.public.springernature.app/en/nmiddleeast/article/10.1038/nmiddleeast.2017.170* (accessed 1 September 2022).

NBMG (2014), “Rye Patch Reservoir: Site description”, Nevada Bureau of Mines and Geology, *https://data.nbmg.unr.edu/Public/Geothermal/SiteDescriptions/RyePatchReservoir.pdf*.

NBMG (2012), “Mason Valley: Site description”, Nevada Bureau of Mines and Geology, *https://data.nbmg.unr.edu/Public/Geothermal/SiteDescriptions/MasonValley.pdf*.

Neupane, G. and Wendt D. S. (2017), “Potential economic values of minerals in brines of identified hydrothermal systems in the US”, GRC Annual Meeting, *www.osti.gov/servlets/purl/1402042*.

New Zealand Herald (2022), “Government invests in game-changing lithium recovery technology at Ohaaki near Taupō”, *www.nzherald.co.nz/rotorua-daily-post/news/government-invests-in-game-changing-lithium-recovery-technology-at-ohaaki-near-taupo/NESLVF7ZGNW566GZSSMAMQ5FKY/* (accessed 1 September 2022).

Nextrends Asia (2021), “Energy in China’s 14th five year plan”, *https://nextrendsasia.org/energy-in-chinas-14th-five-year-plan/* (accessed 1 September 2022).

Nikkei Asia (2017), “Small geothermal plants gaining steam in Japan”, *https://asia.nikkei.com/Business/Small-geothermal-plants-gaining-steam-in-Japan* (accessed 1 September 2022).

NLOG (2022), “Welcome to NLOG”, Dutch Oil and Gas portal, *www.nlog.nl/en* (accessed 1 September 2022).

NREL (2021), *2021 U.S. Geothermal Power Production and District Heating Market Report*, National Renewable Energy Laboratory, Golden, CO, *www.nrel.gov/docs/fy21osti/78291.pdf*.

Nunes, J. C., Coelho, L., Carvalho, J. M., do Rosário Carvalho, M. and Garcia, J. (2021), “Portugal country update 2020”, *Proceedings of the World Geothermal Congress 2020+1*, Reykjavik, Iceland, April-October 2021, *www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01080.pdf*.

Omenda, P., Mangi, P., Ofwona, C. and Mwangi, M. (2021), “Country update report for Kenya 2015-2019”, *Proceedings of the World Geothermal Congress 2020+1*, Reykjavik, Iceland, April-October 2021, *www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01055.pdf*.

Ormat (2022), “Ormat Technologies signs two PPAs with NV Energy for up to 160 MW of geothermal capacity”, *https://investor.ormat.com/news-events/news/news-details/2022/Ormat-Technologies-Signs-Two-PPAs-With-NV-Energy-for-Up-to-160-MW-of-Geothermal-Capacity/default.aspx* (accessed 5 December 2022).

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, *www.lovegeothermal.org/webinar-scaling-up-geothermal-direct-use-for-industrial-applications-in-latin-america/* (accessed 1 September 2022).

Pinto, O., Aguilera, P., Cideos, O. and Henriquez, J. L. (2021), "Towards the Use of geothermal resources available in oil and gas sedimentary basins in Colombia", *Proceedings of the World Geothermal Congress 2020+1*, Reykjavik, Iceland, April-October 2021, *www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/41004.pdf*.

Pollack, A., Horne, R. and Mukerji, T. (2021), "What are the challenges in developing enhanced geothermal systems (EGS)? Observations from 64 EGS sites", *Proceedings of the World Geothermal Congress 2020+1*, Reykjavik, Iceland, April-October 2021, *https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2020/31027.pdf*.

Porras, E. A. (2008), "Twenty five years of production history at the Momotombo Geothermal Field, Nicaragua", *30th Anniversary Workshop*, Geothermal Training Program, United Nations University, 26-27 August 2008, *https://orkustofnun.is/gogn/unu-gtp-30-ann/UNU-GTP-30-38.pdf*.

Prol-Ledezma, R. M. and Morán-Zenteno, D. J. (2019), "Heat flow and geothermal provinces in Mexico", *Geothermics*, Vol. 78/March, pp. 183–200, *https://doi.org/10.1016/j.geothermics.2018.12.009*.

Ragnarsson, A., Steingrímsson, B. and Thorhallsson, S. (2018), "Geothermal country update for Iceland", *Proceedings of the 7th African Rift Geothermal Conference*, Kigali, Rwanda, 31 October–2 November 2018, *http://theargeo.org/fullpapers/C7/Geothermal%20Country%20Update%20for%20Iceland.pdf*.

Reinhardt, T., Johnson, L. and Popovich, N. (2011), "Systems for electrical power from coproduced and low temperature geothermal resources", *Proceedings of the 36th Workshop on Geothermal Reservoir Engineering*, Stanford University, California, 31 January-2 February 2011 *http://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2011/reinhardt.pdf*.

Reinsch, T., Dobson, P., Asanuma, H., Huenges, E., Poletto, F. and Sanjuan, B. (2017), "Utilizing supercritical geothermal systems: A review of past ventures and ongoing research activities", *Geothermal Energy*, Vol. 5, pp.1-25, *https://doi.org/10.1186/s40517-017-0075-y*.

Renewables Now (2022), "EGEC urges EC to prepare geothermal strategies", *News release*, 15 April 2022, *https://renewablesnow.com/news/egec-urges-ec-to-prepare-geothermal-strategy-781194/* (accessed 1 September 2022).

RenewGeo (2022), "Solar renewable geothermal: The first solar charged geothermal storage technology", *www.renewgeo.com* (accessed 1 September 2022).

RHC (2014), *Geothermal Technology Roadmap: European Technology Platform on Renewable Heating and Cooling*, Renewable Heating and Cooling, *www.rhc-platform.org/content/uploads/2020/02/Geothermal_Roadmap-WEB.pdf*.

St. Vincent Times (2022), "Saint Vincent gov't re-adopts geothermal venture with Canadian company", News release, 6 May 2022, *www.stvincenttimes.com/st-vincent-govt-geothermal-energy-canadian-company-eavor/* (accessed 1 September 2022).

Sanjuan, B., Gourcerol, B., Millot, R., Rettenmaier, D., Jeandel, E. and Rombaut, A. (2022), "Lithium-rich geothermal brines in Europe: An up-date about geochemical characteristics and implications for potential Li resources", *Geothermics*, Vol. 101/May, Article 102385, *https://doi.org/10.1016/j.geothermics.2022.102385*.

Sanner, B. (2016), "Shallow geothermal energy – history, development, current status, and future prospects", *Proceedings of the European Geothermal Congress 2016*, Strasbourg, France, 19-24 September 2016, *http://sanner-online.de/media/c8848455cf28212fffff803cffffffff1.pdf*.

Santos, L., Dahi Taleghani, A. and Elsworth, D. (2022), "Repurposing abandoned wells for geothermal energy: Current status and future prospects", *Renewable Energy*, Vol. 194/July, pp. 1288-1302, *https://doi.org/10.1016/j.renene.2022.05.138*.

Shevchenko, A., Linovsky, S. and Skrobot, O. (2020), "Geothermal energy use in western Siberia and prospects for its innovative application in construction", *IOP Conference Series: Materials Science and Engineering*, IOP Publishing, *https://iopscience.iop.org/article/10.1088/1757-899X/953/1/012006/pdf*.

Sigfússon, B., Þór Arnarson, M., Ósk Snæbjörnsdóttir, S., Rós Karlsdóttir, M., Sif Aradóttir, E. and Gunnarsson, I. (2018), "Reducing emissions of carbon dioxide and hydrogen sulphide at Hellisheidi power plant in 2014-2017 and the role of CarbFix in achieving the 2040 Iceland climate goals", *Energy Procedia*, Vol. 146/July, pp. 135-145, *https://doi.org/10.1016/j.egypro.2018.07.018*.

Song, Y. and Lee, T. J. (2021), "Geothermal development in the Republic of Korea: Country update 2015-2019", *Proceedings of the World Geothermal Congress 2020+1*, Reykjavik, Iceland, April-October 2021, *www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01012.pdf*.

Sridharan, V., Broad, O., Shivakumar, A., Howells, M., Boehlert, B., Groves, D. G., Rogner, H., Taliotis, C., Neumann, J. E., Strzepek, K. M., Lempert, R., Joyce, B., Huber-Lee, A. and Cervigni, R. (2019), "Resilience of the Eastern African electricity sector to climate driven changes in hydropower generation", *Nature Communications*, Vol. 10, Article 302, *https://doi.org/10.1038/s41467-018-08275-7*.

Star Energy Geothermal (2022), *Star Energy Geothermal and Schlumberger Complete the World's First Geothermal Fracture Modelling Technique, A Breakthrough for Effective Well Placement*, *www.starenergygeothermal.co.id/2022/01/19/star-energy-geothermal-and-schlumberger-complete-the-worlds-first-geothermal-fracture-modelling-technique-a-breakthrough-for-effective-well-placement/* (accessed 23 January 2023).

Stober, I. and Bucher, K. (2013), "History of geothermal energy use", *Geothermal Energy*, pp. 15-24, Springer, Berlin, Heidelberg, https://doi.org/10.1007/978-3-642-13352-7_2.

Strauss, Z. (2022), *Unearthing Potential: The Value of Geothermal Energy to US Decarbonization*, Global Energy Center Report, Atlantic Council, Washington, DC, www.atlanticcouncil.org/wp-content/uploads/2022/03/Geothermal-Report-2022_FINAL.pdf.

Stringfellow, W. T. and Dobson, P. F. (2021), "Technology for lithium extraction in the context of hybrid geothermal power", *Proceedings of the 46th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, 15-17 February 2021, https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2021/Stringfellow.pdf.

Süddeutsche Zeitung (2022), "Erdwärme mit Schleifen", www.sueddeutsche.de/muenchen/wolfratshausen/geothermie-geretsried-gelting-eavor-loop-enex-erdwaerme-erneuerbare-energien-1.5683678 (accessed 1 December 2022).

Svalova, V. (2012), "Geothermal energy use in Russia", *Proceedings of the 4th African Rift Geothermal Conference*, Nairobi, Kenya, 21-23 November 2012, www.geothermal-energy.org/pdf/IGAstandard/ARGeo/2012/Svalova.pdf.

Svalova, V. and Povarov, K. (2021), "Geothermal resources and energy use in Russia", *Proceedings of the World Geothermal Congress 2020+1, Reykjavik*, Iceland, April-October 2021, www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01061.pdf.

Terrapin (2022), "Alberta No. 1 Geothermal Energy Project: Leading the next chapter of Alberta's energy story", www.albertano1.ca.

ThinkGeoEnergy (2022a), "ThinkGeoEnergy's Top 10 geothermal countries 2021 – installed power generation capacity (MW_e)", www.ThinkGeoEnergy.com/ThinkGeoEnergys-top-10-geothermal-countries-2021-installed-power-generation-capacity-mwe/#:~:text=Global%20geothermal%20power%20generation%20capacity,at%20the%20year%2Dend%202021 (accessed 1 September 2022).

ThinkGeoEnergy (2022b), "Green hydrogen: Geothermal's route to pseudo-commoditization?" www.ThinkGeoEnergy.com/green-hydrogen-geothermals-route-to-pseudo-commoditization/ (accessed 1 September 2022).

ThinkGeoEnergy (2022c), "Transitional energy generates geothermal energy from oil and gas well", www.ThinkGeoEnergy.com/transitional-energy-generates-geothermal-energy-from-oil-and-gas-well/ (accessed 1 September 2022).

ThinkGeoEnergy (2022d), "NZ government to fund geothermal lithium extraction technologies", www.ThinkGeoEnergy.com/nz-government-to-fund-geothermal-lithium-extraction-technologies/#:~:text=The%20New%20Zealand%20government%20will,Ohaaki%20field%2C%20located%20near%20Taupo (accessed 1 September 2022).

ThinkGeoEnergy (2022e), "Vulcan and Enel to jointly develop Cesano geothermal lithium project in Italy", *www.ThinkGeoEnergy.com/Vulcan-and-enel-to-jointly-develop-cesano-geothermal-lithium-project-in-italy/* (accessed 1 September 2022).

ThinkGeoEnergy (2022f), "NZ Geothermal Week highlights New Zealand's thriving geothermal industry", *www.ThinkGeoEnergy.com/nz-geothermal-week-highlights-new-zealands-thriving-geothermal-industry/* (accessed 1 September 2022).

ThinkGeoEnergy (2022g), "CFE confirms benefit of adding ORC units to existing geothermal fields", *www.ThinkGeoEnergy.com/cfe-confirms-benefit-of-adding-orc-units-to-existing-geothermal-fields/* (accessed 1 September 2022).

ThinkGeoEnergy (2022h), "Pilot project in Nevada aims to convert oil wells into geothermal producers", *www.ThinkGeoEnergy.com/pilot-project-in-nevada-aims-to-convert-oil-wells-into-geothermal-producers/* (accessed 1 September 2022).

ThinkGeoEnergy (2022i), "Additional geothermal plant in Iceland to capture and reinject CO_2", *www.thinkgeoenergy.com/additional-geothermal-plant-in-iceland-to-capture-and-reinject-co2/#:~:text=The%20Kold%C3%ADs%20project%20is%20currently,reinject%20into%20its%20natural%20environment* (accessed 5 December 2022).

ThinkGeoEnergy (2021a), "Geothermal energy production & utilisation", *www.ThinkGeoEnergy.com/geothermal/geothermal-energy-production-utilisation/* (accessed 1 September 2022).

ThinkGeoEnergy (2021b), "First geothermal power plant inaugurated in Colombia", *www.ThinkGeoEnergy.com/first-geothermal-power-plant-inaugurated-in-colombia/* (accessed 1 September 2022).

ThinkGeoEnergy (2021c), "First closed-cycle geothermal heat plant set up in Hungary", *www.ThinkGeoEnergy.com/first-closed-cycle-geothermal-heat-plant-set-up-in-hungary/* (accessed 1 September 2022).

ThinkGeoEnergy (2021d), "Record levels of lithium in geothermal water at United Downs project", *www.ThinkGeoEnergy.com/record-levels-of-lithium-in-geothermal-water-at-united-downs-project/* (accessed 1 September 2022).

ThinkGeoEnergy (2021e), "Vulcan Energy produces battery grade lithium from geothermal", *www.thinkgeoenergy.com/vulcan-energy-produces-battery-grade-lithium-from-geothermal/* (accessed 1 September 2022).

ThinkGeoEnergy (2021f), "New partnership to seek further geothermal push in Dominica", *www.ThinkGeoEnergy.com/new-partnership-to-seek-further-geothermal-push-in-dominica/* (accessed 1 September 2022).

ThinkGeoEnergy (2021g), "Meager Creek geothermal project to be revived focused on hydrogen", *www.ThinkGeoEnergy.com/meager-creek-geothermal-project-to-be-revived-focused-on-hydrogen/* (accessed 1 September 2022).

ThinkGeoEnergy (2021h), "CTR kicks off drilling at Salton Sea geothermal Lithium project", *www.ThinkGeoEnergy.com/ctr-kicks-off-drilling-at-salton-sea-geothermal-lithium-project/* (accessed 1 September 2022).

ThinkGeoEnergy (2021i), "Ten companies found Turkey Geothermal Association (JED)", *www.ThinkGeoEnergy.com/ten-companies-found-turkey-geothermal-association-jed/#:~:text=The%20founding%20partners%20(see%20below,contribution%20of%20ten%20founder%20members* (accessed 1 September 2022).

ThinkGeoEnergy (2021j), "Turkey introduces updated geothermal energy feed-in-tariff rates", *www.ThinkGeoEnergy.com/turkey-introduces-updated-geothermal-energy-feed-in-tariff-rates/* (accessed 1 September 2022).

ThinkGeoEnergy (2021k), "Lack of incentives and regulations disadvantage geothermal in Italy", *www.thinkgeoenergy.com/lack-of-incentives-and-regulations-disadvantage-geothermal-in-italy/* (accessed 5 December 2022).

ThinkGeoEnergy (2021l), "Plans announced on drilling Europe's deepest geothermal well", *www.thinkgeoenergy.com/plans-announced-on-drilling-europes-deepest-geothermal-well/* (accessed 5 December 2022).

ThinkGeoenergy (2020), "Innovation in geothermal energy utilization – the Icelandic story", *www.thinkgeoenergy.com/innovation-in-geothermal-energy-utilization-the-icelandic-story/* (accessed 23 January 2023).

ThinkGeoEnergy (2018), "4.4 MW Wabuska geothermal power plant in Nevada started operation", *www.ThinkGeoEnergy.com/4-4-mw-wabuska-geothermal-power-plant-in-nevada-started-operation/* (accessed 1 September 2022).

ThinkGeoEnergy (2016), "Interview: Alessandro Piubelli of Turboden on the new Soultz-sous-Forets plant", *www.thinkgeoenergy.com/interview-alessandro-piubelli-of-turboden-on-the-new-soultz-sous-forets-plant*/ (accessed 1 December 2022).

ThinkGeoEnergy (2013), "ElectraTherm commissions second Green Machine geothermal power plant using its ORC technology to generate power from low heat geothermal resources, in Nevada", *www.ThinkGeoEnergy.com/electratherm-commissions-low-heat-geothermal-plant-in-nevada/* (accessed 1 September 2022).

Thompson, A., Harmer, Z. and Fong, W. (2021), "Geothermal industry development in Canada – 2020 country update", *Proceedings of the World Geothermal Congress 2020+1*, Reykjavik, Iceland, April-October 2021, *www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01026.pdf*.

Topsector Energie (2018), "HIPE: High performance geothermal well", *https://projecten.topsectorenergie.nl/projecten/high-performance-geothermal-well-29150* (accessed 1 December 2022).

Torres-Rodriguez, M. A., Mendoza-Covarrubias, A. and Medina-Martinez, M. (2005), "An update of the Los Azufres Geothermal Field after 21 years of exploitation", *Proceedings of the World Geothermal Congress 2005*, Antalya, Turkey, 24-29 April 2005, www.geothermal-energy.org/pdf/IGAstandard/WGC/2005/0916.pdf.

Tu Deh-Kah (2022), "Tu Deh-Kah Geothermal", https://tudehkah.com/ (accessed 1 September 2022).

Turchi, C., McTigue, J., Akar, S., Beckers, K., Richards, M., Chickering, C., Batir, J., Schumann, H., Tillman, T. and Slivensky, D. (2020), *Geothermal Deep Direct Use for Turbine Inlet Cooling in East Texas*, NREL/TP-5500-74990, National Renewable Energy Laboratory, Golden, CO, February 2020, www.nrel.gov/docs/fy20osti/74990.pdf.

Türkiye Jeotermal (2020), "Geothermal investments safer now with risk sharing mechanism", https://rpmjeoturkiye.com/en/homepage/ (accessed 1 September 2022).

Uihlein, A., (2018), "JRC geothermal power plant dataset – Documentation", EUR 29446 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-79-97264-5, https://publications.jrc.ec.europa.eu/repository/bitstream/JRC113847/kjna29446enn_jrc113847.pdf.

Ülgen, U. B. (2022), "Implementation of the agricultural specialized organized industrial zone geothermal greenhouse loans and investment incentives in Türkiye", https://irena.org/-/media/Files/IRENA/Agency/Events/2022/Jul/Implementation-of-the-Agricultural-Specialized-Organized-Industrial-Zone--Geothermal-Greenhouse-Loan.pdf?la=en&hash=59A1B10C11FA37943C62ECF0181B07CDCC8B96B9 (accessed 1 September 2022).

UNICEF (2018), "The Middle East and North Africa is the world's most water-scarce region", www.unicef.org/mena/water-I-come-tap#:~:text=2.,region%20is%20likely%20to%20worsen (accessed 1 September 2022).

UNIDO (2016), Global Assessment of Eco-Industrial Parks in Developing and Emerging Countries, United Nations Industrial Development Organization, Vienna, Austria, www.unido.org/sites/default/files/2017-02/2016_Unido_Global_Assessment_of_Eco-Industrial_Parks_in_Developing_Countries-Global_RECP_programme_0.pdf.

UnLimited (2022), "UnLimited: Investigations into lithium production from hot deep waters in Germany", www.geothermal-lithium.org/en/project-description (accessed 1 September 2022).

US DoE (2022), "DOE awards $ 8.4 millions for accessing geothermal potential from abandoned oil and gas wells", News release, Office of Energy Efficiency and Renewable Energy, US Department of Energy, Washington, DC, 12 January 2022, www.energy.gov/eere/articles/doe-awards-84-million-accessing-geothermal-potential-abandoned-oil-and-gas-wells.

US DoE (2020), "Guadeloupe: Energy snapshot", Energy Transition Initiative, US Department of Energy, *www.energy.gov/sites/default/files/2020/11/f80/ETI-Energy-Snapshot-Guadeloupe-FY21.pdf*.

US DoE (2019), "GeoVision: Harnessing the heat beneath our feet", *www.energy.gov/eere/geothermal/downloads/geovision-harnessing-heat-beneath-our-feet* (accessed 1 September 2022).

US DoE (2017), "Energy department announces up to $4 million for geothermal deep direct-use feasibility studies", News release, US Department of Energy, Washington, DC, 30 June 2017, *www.energy.gov/eere/articles/energy-department-announces-4-million-geothermal-deep-direct-use-feasibility-studies*.

US DoE (2010), "Geothermal energy production with co-produced and geopressured resources", US Department of Energy, *www1.eere.energy.gov/geothermal/pdfs/low_temp_copro_fs.pdf*.

USEA (2020), "Potential impact of geothermal ecoparks in East Africa", United States Energy Association, *https://usea.org/sites/default/files/event-/GEIP%201st%20Webinar.pdf* (accessed 1 September 2022).

USGS (2003), *Geothermal Energy – Clean Power From the Earth's Heat*, USGS Circular 1249, US Geological Survey, Reston, Virginia, *https://pubs.usgs.gov/circ/2004/c1249/c1249.pdf*.

Utah FORGE (2022), "Frontier Observatory for Research in Geothermal Energy – FORGE", *https://utahforge.com/* (accessed 1 September 2022).

Van Nguyen, M., Arason, S., Gissurarson, M. and Pálsson, P. G. (2015), *Uses of Geothermal Energy in Food and Agriculture – Opportunities for Developing Countries*, Food and Agriculture Organization (FAO) of the United Nations, Rome, *www.fao.org/3/i4233e/i4233e.pdf*.

Vargas, C. A., Caracciolo, L. and Ball, P. J. (2022), "Geothermal energy as a means to decarbonize the energy mix of megacities", *Communications Earth & Environment*, Vol. 3, pp. 1-11., *https://doi.org/10.1038/s43247-022-00386-w*.

Vieira, F. and Hamza, V. (2019), "Assessment of geothermal resources of South America: A new look", *International Journal of Terrestrial Heat Flow and Applied Geothermics*, Vol. 2/1, pp. 46-57, *https://doi.org/10.31214/ijthfa.v2i1.32*.

Vieira, F. and Hamza, V. (2014), "Advances in assessment of geothermal resources of South America", *Natural Resources*, Vol. 5/14, pp. 897-913, *www.scirp.org/journal/paperinformation.aspx?paperid=51945*.

Warren, I. (2021), *Techno-Economic Analysis of Lithium Extraction from Geothermal Brines*, NREL/TP-5700-79178, National Renewable Energy Laboratory, Golden, CO, *www.nrel.gov/docs/fy21osti/79178.pdf*.

WeHEAT (2022), "Geothermal energy: Minimize your heating costs by using clean energy", *www.en.weheat.systems/* (accessed 1 September 2022).

Wendt, D. S., Neupane, G., Davidson, C. L., Zheng, R. and Bearden, M. A. (2018), *GeoVision Analysis Supporting Task Force Report: Geothermal Hybrid Systems*, Office of Scientific and Technical Information, US Department of Energy, Washington, DC, *www.osti.gov/servlets/purl/1460735*.

Western Balkans Green Center (2021), "Supporting the activities of geothermal-based heat generation projects", *www.wbgc.hu/hu/tamogatasi-felhivasok/jelenleg-futo-felhivasok/klima-es-termeszetvedelmi-akcioterv-geotermikus-alapu-hotermelo-projektek-tevekenysegeinek-tamogatasa* (accessed 1 September 2022).

World Bank (2022), "Turkey Geothermal Development Project", *https://projects.worldbank.org/en/projects-operations/project-detail/P151739*.

World Bank (2021), "Turkey's organized industrial zones to become more efficient, environmentally sustainable with help from World Bank", *www.worldbank.org/en/news/press-release/2021/01/25/turkeys-organized-industrial-zones-to-become-more-effient-environmentally-sustainable-with-help-from-world-bank* (accessed 1 September 2022).

Yasukawa K., Nishikawa, N., Sasada, M. and Okumura, T. (2021), "Country update of Japan", *Proceedings of the World Geothermal Congress 2020+1*, Reykjavik, Iceland, April-October 2021, *www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01037.pdf*.

Yu, P., Dempsey, D. and Archer, R. (2022), "Techno-economic feasibility of enhanced geothermal systems (EGS) with partially bridging multi-stage fractures for district heating applications", *Energy Conversion and Management*, Vol. 257/April, Article 115405, *https://doi.org/10.1016/j.enconman.2022.115405*.

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