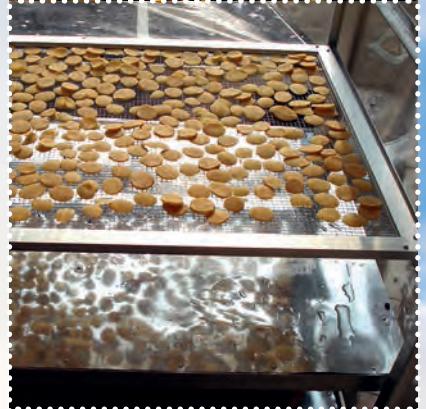




Food and Agriculture
Organization of the
United Nations



Uses of geothermal energy in food and agriculture

**Opportunities
for developing
countries**

Minh Van Nguyen
Sigurjón Arason
Margeir Gissurarson
Páll Gunnar Pálsson

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FOOD AND AGRICULTURE ORGANIZATION
OF THE UNITED NATIONS
Rome, 2015

Recommended citation

Van Nguyen, M., Arason, S., Gissurason M. and Pálsson, P.G. 2015. *Uses of geothermal energy in food and agriculture – Opportunities for developing countries*. Rome, FAO.

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ISBN 978-92-5-108656-8

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Foreword

As Planet Earth moves towards the challenge of feeding 10 billion people, we can seek guidance from the pioneering developments in Iceland and some other parts of the world in using the heat stored inside our planet to enhance the food security of nations on every continent.

The challenge has two dimensions: how to store successfully the food already produced, and how to enhance production without harming the environment.

The solutions to both are outlined in this ground breaking report, drawing on existing technologies and profitable business practices.

The drying of food products using geothermal heat or other clean energy resources, based on four decades of Icelandic experience, could enable people all over the world to utilize commercially food that is currently either thrown away or spoiled due to lack of suitable storage facilities. If applied extensively on a global scale, drying could increase the availability of food by up to 20 percent. No other single method holds such potential.

The development of greenhouse agriculture and geothermal-based aquaculture in my country also demonstrates how sustainable energy can increase food production considerably, giving farmers and fishermen new ways to earn a living.

By commissioning this report, FAO has significantly strengthened the emerging global coalition of international institutions and national leaders determined to explore fully how the rich geothermal resources of Planet Earth can make a substantial contribution to improving food security all over the world in the decades to come.



Ólafur Ragnar Grímsson
President of Iceland

Preface

Access to reliable supplies of energy is one of the main preconditions for the development of agrifood industries and is a key determinant of their competitiveness. With growing concern about climate change and the need to reduce the use of fossil fuels, there is increasing interest in the use of renewable energy. In this regard, geothermal energy is one of the options that can be exploited in countries that are endowed with this resource.

Traditionally, geothermal energy has been utilized for the most part in power generation. However, there are examples of successful applications in other, non-power generation uses, particularly in the food and agriculture sector. Its potential uses in the agrifood domain were highlighted by H.E. Ólafur Ragnar Grímsson, President of the Republic of Iceland, who during a visit to FAO Headquarters in Rome, Italy, in March 2011, underscored the experience of his country in the use of geothermal energy for agricultural and food processing purposes and the benefits that Iceland had gained in this regard. This was seen as a unique experience that FAO could help promote in other countries that are endowed with geothermal resources, especially in the developing world, as a way of promoting food security and economic development.

As a follow-up to the visit, FAO undertook a mission to Iceland in October 2011 to obtain first-hand knowledge of geothermal uses in the agrifood sector and to explore approaches to extending this technology to the developing world. The mission, comprising agroprocessing and agribusiness experts, visited public sector agencies, research institutes, university programmes, private consulting companies involved in geothermal resource exploitation and utilization, and private sector enterprises utilizing this energy source for non-power generation applications. The mission was exposed not only to technical installations for generation and utilization, but also to the institutional, policy and regulatory framework required for successful exploitation of geothermal energy in the agrifood sector.

As an outcome of the mission and its follow-up appraisals and consultations, FAO has strengthened its conviction that there is very good potential for numerous developing countries to harness geothermal resources with a view to promoting the development of their food and agriculture sector. These countries are located primarily in Central America, the Pacific coast of South America, the Rift Valley in Africa and the islands of southeastern Asia. All can benefit from the utilization of geothermal energy in attaining sustainable food and nutrition security through increased crop and fisheries production, better food preservation and storage, and reduction of losses and waste along the food chain.

This publication was commissioned by FAO with a view to furthering the process of awareness raising, information dissemination and advocacy to promote geothermal energy uses in food and agriculture. The document provides guidance on potential approaches, lessons, constraints and factors to be considered in devel-

oping geothermal energy applications for agrifood industry development, paying particular attention to technical, policy and economic considerations.

It is hoped that the publication will be valuable to professionals from the public and private sectors, development agencies and financial institutions with an interest in promoting renewable energy uses in food and agriculture.



José Graziano da Silva
Director-General, FAO

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Acknowledgements

This publication has been prepared by a team of professionals associated with Matís ltd.-Icelandic Food and Biotech R&D, following the conceptualization and editorial oversight of Carlos A. da Silva (Senior Agribusiness Economist, FAO Rural Infrastructure and Agro-Industries Division, [AGS]) and Divine Njie (Deputy Director, FAO AGS).

The editors wish to express their special gratitude to the representatives of the Government of the Republic of Iceland who collaborated on this project. We are grateful to H.E. Ólafur Ragnar Grímsson, President of the Republic of Iceland, for drawing our attention to, and sharing his deep knowledge of, geothermal energy and its potential uses as drivers of economic and social development. We also thank Guðni Bragason, former Minister Plenipotentiary/Permanent Representative of the Republic of Iceland to FAO, WFP and IFAD, for his engagement in the project and for facilitating our access to the many Icelandic institutions and professionals with expertise in the areas covered by this publication.

We are grateful to Modibo Traoré, former Assistant Director-General of FAO's Department of Agriculture and Consumer Protection, for steadfastly supporting the follow-up to the visit of H.E Grímsson to FAO, as well as to Gavin Wall and Eugenia Serova, former and current Directors of FAO AGS, for their support to this initiative.

Appreciation is extended to Danilo Mejía-Lorio, Joseph Mpagalile, Yvette Diei and Olivier Dubois of FAO, who kindly peer-reviewed the manuscript, and to Larissa D'Aquilio (FAO AGS) for production coordination, Jim Collis and Jane Shaw for copy editing, Monica Umena for the design, and Lynette Chalk for the proofreading.

The Editors

Chapter 1

Introduction

Two billion people – one in every three of the world’s population – lack access to modern energy services (Fridleifsson, 2001). Between 1990 and 2050, primary energy consumption is expected to increase by at least 50 percent, and by as much as 275 percent under the highest growth scenario (World Energy Council, 2002). The generation of energy from naturally replenished sources such as wind, rain, sunlight, tides, waves and geothermal water and steam is therefore set to become increasingly important (Fatona, 2011). Access to clean, affordable energy is seen as key to improving the living standards of the world’s poor people (Fridleifsson, 2001). By 2100, renewable sources are expected to be providing 30–80 percent of total energy consumption (Fridleifsson, 2001, 2013).

Geothermal energy is one of the most important energy resources for electricity generation and is also used directly in heating, food and agriculture, aquaculture and some industrial processes (Dickson and Fanelli, 2004). It is stored as heat in the magma, or molten rock, of the earth’s interior, where temperatures are extremely high; in hot water and rocks several kilometres below the earth’s surface; and – in some parts of the world – in shallow ground (Barbier, 2002).

The earliest reported use of geothermal energy dates from the pre-pottery period, before 11000 BC, when people in Japan were using hot springs for bathing and washing clothes (Sekioka, 1999). There is also archaeological evidence of geothermal energy being used in North America more than 10 000 years ago (Solcomhouse, no date), and its use in China has been recorded for more than 2 000 years (Fridleifsson, 2001). Industrial use started in the late eighteenth century, when steam from under the ground was used to extract boric acid from volcanic mud near what is now the town of Larderello in Tuscany, Italy. Just over a century later, in 1904, the world’s first geothermal power generator was tested at Larderello by Italian scientist Piero Ginori Conti, using steam to generate electricity (Conserve Energy Future, no date). Since then, geothermal energy has been put to a wide range of uses in space heating and cooling, industry, horticulture, fish farming, food processing and health spas (Fridleifsson, 2001).

Agriculture and agro-industry are still major economic sectors in most developing countries, where they are the main source of livelihoods for 75 percent of the poor (FAO, 2009). However, the people in these countries face famine and poverty, mainly as a result of post-harvest losses and the lack of affordable energy for aquaculture and food processing. Estimates of post-harvest losses (in weight and quality) in developing and less developed countries range from 1 to more than 50 percent (National Academy of Sciences, 1978; Hodges, Buzby and Bennett, 2011). A recent FAO study (FAO, 2011) calculates that the agriculture and food sector’s share in total energy consumption is 30 percent, of which more than 70 percent is consumed

beyond the farmgate. The sector also accounts for about 22 percent of total greenhouse gas emissions, including landfill gas produced from food wastes, and about 38 percent of all the energy consumed along the food chain is embedded in annual global food losses (FAO, 2011). The unsatisfied demand for a sustainable supply of affordable energy is therefore a major constraint to development of the agriculture and agro-industry sectors in developing countries.

This publication summarizes the current status of geothermal energy use in agriculture and agro-industry sectors around the world and seeks to provide developing countries with guidance on how to utilize geothermal energy to develop their agriculture and agro-industry sectors. The book is organized according to a simple format with illustrations, graphs and models of geothermal energy use for easy reference to help non-technical readers to increase their understanding of geothermal energy and its possible future applications.

Chapter 2

Geothermal energy: an overview

2.1 BASIC CONCEPTS

What is geothermal energy?

Geothermal energy is a clean, sustainable and renewable resource that provides energy using heat derived from the earth. Radioactive elements within the earth release heat at very high temperatures, which increase depending on the distance from the earth's surface (Figure 1). The temperature of the earth's core is estimated to be about 5 000 °C, and the outer core is about 4 000 °C – a similar temperature to that on the surface of the sun (Figure 1). The constant flow of heat energy from the earth's interior, equivalent to an estimated 42 million megawatts (MW) of power, is expected to continue for billions of years (Íslandsbanki, 2011).

Where is geothermal energy found?

Geothermal activity is concentrated around the Pacific Ocean and the Pacific Plate (Figure 2), in the “Ring of Fire” that reaches from Indonesia, the Philippines and Japan, to Alaska, Central America, Mexico, the Andes and on to New Zealand. Geothermal energy usually remains deep underground, but sometimes reaches the surface as hot springs and geysers, or volcanoes and fumaroles (holes created

FIGURE 1
Temperatures of the earth's crust, mantle, outer core and inner core layers

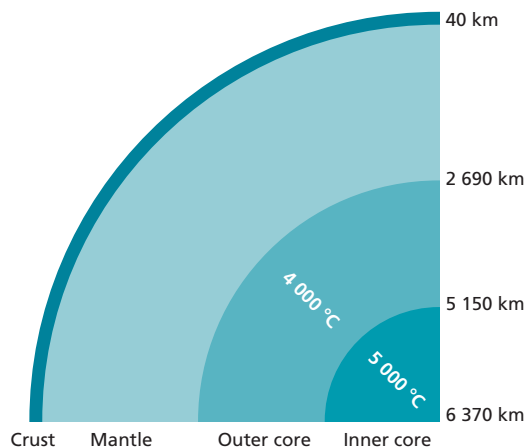
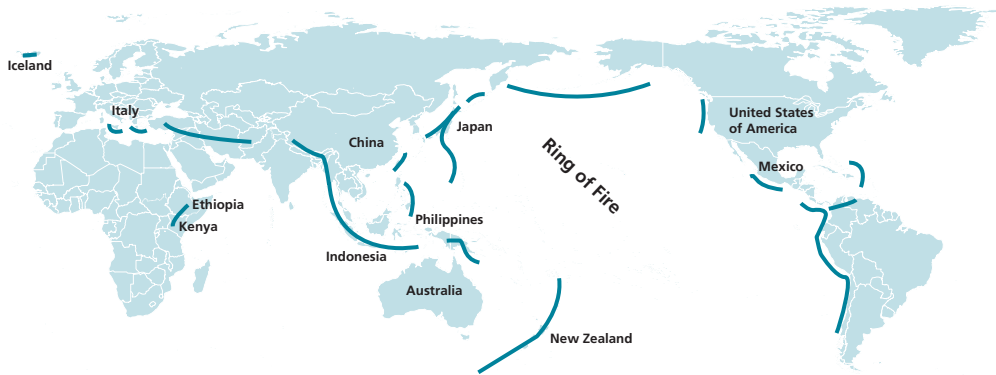
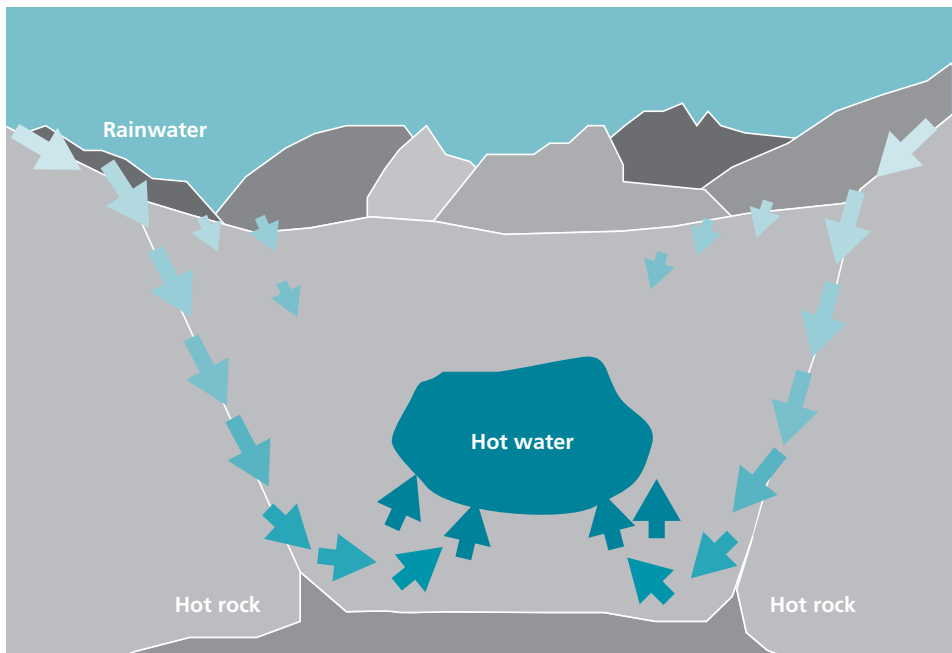


FIGURE 2
Major locations of geothermal activity around the world



Source: P.G. Pálsson, 2013. (Based on UN map No. 4170 Rev. 13, April 2012. Department of Field Support, Cartographic Section).

FIGURE 3
Formation of a geothermal reservoir



Source: P.G. Pálsson, 2013.

when volcanic gases are released), particularly in the high-temperature geothermal fields located along the major plate boundaries (Serpen, Aksoy and Ongur, 2010; Fridleifsson *et al.* 2008).

An important exploitable source of geothermal energy are the reservoirs that form underground when groundwater trapped along fault lines, fractures in rock and porous rock is heated by magma that has been pushed up from the earth's core (Figure 3). Geologists looking for these hydrothermal resources usually have to drill deep wells to find them (Serpen, Aksoy and Ongur, 2010).

2.2 USES AROUND THE WORLD

All over the world, naturally occurring steam and hot water are being used to generate electricity, provide heating and hot water for domestic and other uses, and drive industrial processes such as drying and concentrating (Burgess, 1989; Ghomshei, 2010; Gunerhan, Kocar and Hepbasli, 2001; Lund, 2010). Geothermal heat pumps, which use geothermal energy to heat and cool buildings, form the largest category of direct applications, followed by domestic hot water, swimming pools and space heating (Lund, Freeston and Boyd, 2010). Most of Iceland's electricity and heating needs are supplied from its abundant geothermal energy resources. Other countries deriving more than 10 percent of their electricity from geothermal sources include Costa Rica, El Salvador, Kenya, New Zealand and the Philippines.

At present, 24 countries use geothermal power to generate electricity, and another 11 are developing and testing geothermal systems, including Australia, France, Germany, Japan, Switzerland and the United Kingdom of Great Britain

FIGURE 4
Locations of geothermal operations around the world



Source: P.G. Pálsson, 2013. (Based on UN map No. 4170 Rev. 13, April 2012. Department of Field Support, Cartographic Section).

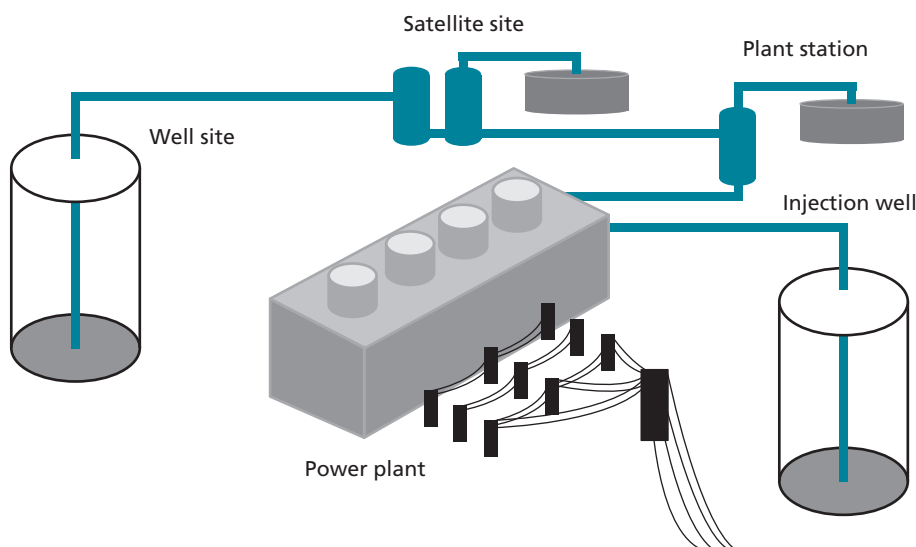
and Northern Ireland (Figure 4) (British Geological Survey, no date). Worldwide, an estimated 67 000 gigawatt hours (GWh) of electricity is generated from a total installed geothermal power capacity of about 10 700 MW. The United States of America accounts for about 30 percent of this installed capacity, with 3 100 MW, followed by the Philippines, Indonesia and Mexico (Table 1) (Íslandsbanki, 2011).

TABLE 1
Top ten countries for use of geothermal energy in power generation, 1990–2010 and 2015 forecast

Year	Installed capacity in megawatts									
	<i>El Salvador</i>	<i>Iceland</i>	<i>Indonesia</i>	<i>Italy</i>	<i>Japan</i>	<i>Kenya</i>	<i>Mexico</i>	<i>New Zealand</i>	<i>Philippines</i>	<i>United States</i>
1990	95	45	145	545	215	45	700	283	891	2 775
1995	105	50	310	632	414	45	753	286	1 227	2 817
2000	161	170	590	785	547	45	755	437	1 909	2 228
2005	151	202	797	791	535	129	953	435	1 930	2 564
2007	204	421	992	811	535	129	953	472	1 970	2 924
2010	204	575	1 197	863	536	167	958	628	1 904	3 087
2015	290	800	3 500	920	535	530	1 140	1 240	2 500	5 400

Source: Íslandsbanki, 2011.

FIGURE 5
A geothermal power plant cycle



Source: P.G. Pálsson, 2013.

There are three main categories of geothermal power plant, depending on the chemistry, fluid temperature and pressure involved: i) condensing power plants, with dry steam and single- or double-flash systems; ii) back-pressure turbines, which release into the atmosphere; and iii) binary plants, which use lower-temperature water or separated brine (Mburu, 2009). Figure 5 illustrates a typical geothermal power plant cycle.

The direct utilization of geothermal energy is well documented; people have been using hot springs for cooking and therapeutic purposes for thousands of years. Today, low- to moderate-temperature (20–150 °C) geothermal reservoirs provide a relatively cheap and pollution-free source of energy for direct uses (NREL, 1998).

TABLE 2
Categories of direct use worldwide, 1995–2010

Utilization category	1995	2000	2005	2010
Capacity (megawatt thermal)				
Geothermal heat pumps	1 853	5 275	15 384	33 134
Space heating	2 579	3 263	4 366	5 394
Greenhouse heating	1 085	1 246	1 404	1 544
Aquaculture pond heating	1 097	605	616	653
Agricultural drying	67	74	157	125
Industrial uses	544	474	484	533
Bathing and swimming	1 085	3 957	5 401	6 700
Cooling/snow melting	115	114	371	368
Others	238	137	86	42
Total	8 664	15 145	28 269	48 493
Utilization (terajoules/year)				
Geothermal heat pumps	14 617	23 275	87 503	200 149
Space heating	38 230	42 926	55 256	63 025
Greenhouse heating	15 742	17 864	20 661	23 264
Aquaculture pond heating	13 493	11 733	10 976	11 521
Agricultural drying	1 124	1 038	2 013	1 635
Industrial uses	10 120	10 220	10 868	11 745
Bathing and swimming	15 742	79 546	83 018	109 410
Cooling/snow melting	1 124	1 063	2 032	2 126
Others	2 249	3 034	1 045	955
Total	112 441	190 699	273 372	423 830

Source: Lund, Freeston and Boyd, 2011.

TABLE 3
Top ten countries for direct use of geothermal energy

Country	Annual use (terajoules/year)
China	75 348
United States of America	56 552
Sweden	45 301
Turkey	36 886
Norway	25 200
Iceland	24 361
Japan	15 698
France	12 926
Germany	12 765
Netherlands	10 699

Source: Lund, Freeston and Boyd, 2011.

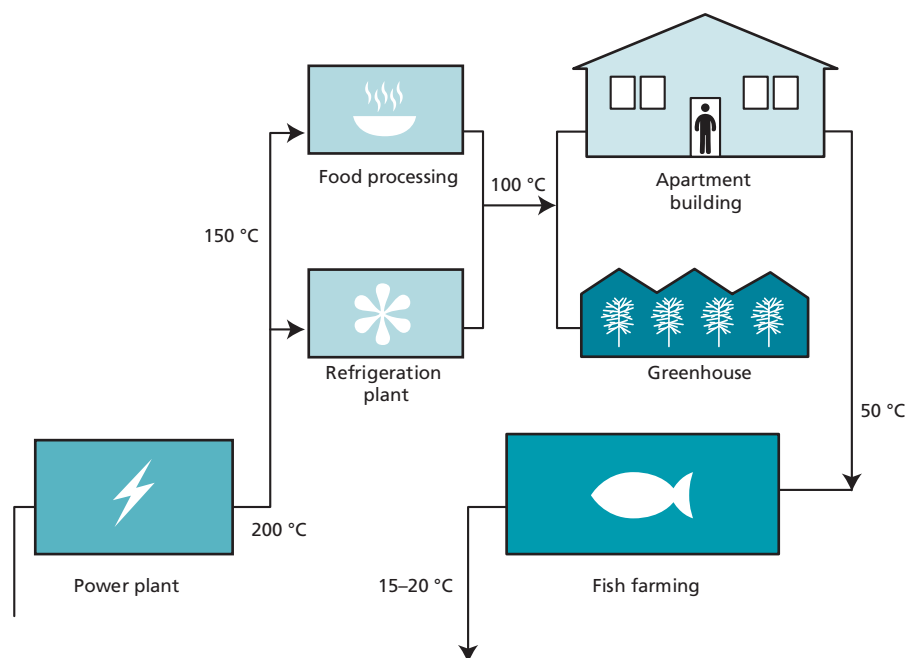
These geothermal reservoirs are reached via 1 000–3 000-m deep wells. Currently, about 73 countries around the world make direct use of a total geothermal energy output of 75.9 terawatt hours (TWh) per year, and the number of countries using geothermal energy for direct applications is increasing steadily (Mburu, 2009). The categories of direct utilization of geothermal energy in the period from 1995 to 2010 are presented in Table 2, and the top ten countries for the direct use of geothermal energy in Table 3.

2.3 GEOTHERMAL ENERGY UTILIZATION

Lindal diagram

The potential uses of geothermal energy in the agriculture and agro-industry sectors are summarized in Figure 6, which is an adapted Lindal diagram. In direct applications, geothermal reservoirs of low to intermediate temperature (20–150 °C) are exploited, mainly in heat pumps for heating and cooling, space heating, pools and spas, greenhouses, aquaculture and industrial processes. High-temperature geothermal reservoirs (150–300 °C) are exploited for indirect use applications, including steam and electricity production (conventional electric generation) (Islandsbanki, 2011). Electricity is also generated using intermediate-temperature (70–149 °C) geothermal resources (and binary electric generation). The electricity from conventional or binary power plants is used in industrial processes, and hot water from binary power plants can be used for direct applications (Ogola, Davidsdottir and Fridleifsson, 2012). Steam and superheated water are normally used in certain agro-industrial processes that require high temperatures, although lower temperatures can sometimes be used, especially for drying agricultural products (Lund, 1996).

FIGURE 7
Cascading from a geothermal power plant



Source: Geo-Heat Center, Klamath Falls, Oregon (USA). Adapted with permission.

2.4 GEOTHERMAL ENERGY EXPLOITATION

The preparation of geothermal energy exploration is divided into five phases:

1. *First-phase surface exploration.* Commonly used and relatively low-cost exploration methods are geothermal and geological mapping, geophysical surveying and geochemical surveying, including sampling and analysis of natural outflows.
2. *First-phase exploration drilling.* If the first-phase surface exploration produces positive results, the next step is to prove the existence of a geothermal reservoir by drilling and testing. Although the cost of this phase is higher than that of the surface exploration, more information about the geothermal field and the pressure, temperature and chemical composition of the geothermal resources is obtained. Normally, three to six wells are drilled during this phase.
3. *Second-phase surface exploration – environmental impact assessment.* A new reservoir model and further plans for surface exploration are designed based on the information obtained during drilling of the exploration wells. At this stage, the size of the reservoir and the potential power production capacity are estimated.
4. *Second-phase exploration drilling.* More wells are drilled to gather further information prior to a financial investment decision.
5. *Appraisal and operational phase.* During operation, the geothermal resource needs to be re-evaluated using data collected from existing wells. The sustainable production capacity is also estimated to enable better planning for the future.

Potential impacts of geothermal energy development

The potential impacts of geothermal energy development depend on many factors, such as the amount of land used for drilling, the construction activities implemented, and the number of well pads and the power plant technology applied. Among the most important impacts of geothermal energy development are environmental impacts, which include the following:

- *Gaseous emissions resulting from the discharge of non-condensable gases.* The most common gases are carbon dioxide (CO₂), hydrogen sulphide (H₂S) and other low-concentration gases such as methane, hydrogen, sulphur dioxide and ammonia.
- *Water pollution.* Dissolved minerals (e.g., boron, mercury and arsenic) contained in the liquid streams generated during the exploration, stimulation and production phases may poison surface or groundwater and harm local vegetation (Tester *et al.*, 2006). It is therefore important to monitor wells during drilling and subsequent operations so that any leakage can be detected and managed rapidly.
- *Noise pollution.* Primary sources of noise are associated with exploration activities such as the well drilling, stimulation and testing phases, when noise levels are in the range of 80–115 decibels at the site boundary. Noise levels drop rapidly with increased distance from the source (Tester *et al.*, 2006).

Geothermal energy development can also have impacts on agricultural resources, mainly through land disturbance related to the construction of power plants and transmission lines. It has impacts on ecological resources when construction activities destroy or injure wildlife, disturb breeding and migration patterns, and reduce habitat quality and species diversity.

2.5 AVAILABILITY AND USE IN DEVELOPED AND DEVELOPING COUNTRIES

Agricultural uses are a very important part of overall geothermal energy application. The potential for this type of use has stimulated the direct application of geothermal energy in many southeastern European countries (Figure 8) such as Greece, Hungary, Romania, Turkey and The former Yugoslav Republic of Macedonia (Popovski, 2009). Although geothermal energy resources also have high potential in developing countries, they have been used mostly for space heating, bathing and swimming in these countries. A few countries apply geothermal energy in the agriculture and agro-industry sectors, including Algeria and Kenya in Africa, Costa Rica and El Salvador in Central America, and China, India and Indonesia in Asia (Table 4).

Drying of agricultural products

Drying of agricultural products is a very important process in avoiding wastage and ensuring that nutritious food is available all year round, and during droughts. Low- to medium-enthalpy geothermal resources with temperatures less than 150 °C (Muffler and Cataldi, 1978) are used because they have the highest potential for agricultural drying applications (Ogola, 2013). The heat for drying can be obtained from the hot water or steam of geothermal wells or by recovering waste heat from a geothermal plant (Vasquez, Bernardo and Cornelio, 1992). The many advantages of using geothermal energy rather than oil and electricity in food processing (Araon, 2003) include the far lower costs of using hot water or steam. The thermal energy required for rice drying in The former Yugoslav Republic of Macedonia is

FIGURE 8
Agricultural and agro-industrial uses of geothermal energy in Europe



Source: P.G. Pálsson, 2013. (Based on UN map No. 4170 Rev. 13, April 2012. Department of Field Support, Cartographic Section).

136 kilowatt hours (kWh)/tonne of wet weight (Popovski *et al.* 1992), while tomato drying in Greece requires 1 450 kWh/tonne of wet weight (Andritsos, Dalampakis and Kolios, 2003). Geothermal energy has been used to dry a wide range of agricultural products, such as rice, wheat, tomatoes, onions, cotton, chillies and garlic.

Tomato and cotton drying in Greece

A small-scale tomato drying plant located in Nea Kessani, Xanthi started operating in 2001. Tomatoes are dried using geothermal hot water at 59 °C in a 14-m long rectangular tunnel dryer (1 m wide and 2 m high). The tomatoes are sorted and washed to remove dust, dirt, plant parts, etc. They are then cut in half and placed on to stainless steel trays (of 100 cm² × 50 cm² mesh). Each batch of 25 trays is dried for 45 minutes, with about 7 kg of raw tomatoes on each tray (Photo 1). The dried tomatoes are then immersed in olive oil and ready for transport and sale. During the first year of operation, 4 tonnes of high-quality dried-tomato products were produced.

A pilot-scale geothermal drying system for the pre-drying of cotton was designed and tested in Nea Kessani, Xanthi in 1991 and 1992. The test results demonstrated that cotton can be dried in a specially designed tower drier using geothermal water (Photo 2).

TABLE 4
Direct uses of geothermal energy in developing countries

Country	Capacity (MWt)*	Utilization (TJ/yr)	Fields of application	References
<i>Africa</i>				
Algeria	66.84	2 098.68	Space heating, fish farming, bathing and swimming, heat pumps	Fekraoui, 2010
Egypt	1.0	15.0	Spas and bathing	Lund, Freeston and Boyd, 2005
Ethiopia	2.2	41.6	Bathing and swimming	Lund, Freeston and Boyd, 2011
Kenya	16	126.62	Heating water and soil, drying agricultural products	Simiyu, 2010
Morocco	5.02	79.14	Bathing and swimming	Lund, Freeston and Boyd, 2011
South Africa	6.01	114.75	Bathing and swimming	Lund, Freeston and Boyd, 2011
Tunisia	43.8	364	Greenhouses, bathing and swimming	Lund, Freeston and Boyd, 2011
<i>Latin America and the Caribbean</i>				
Caribbean Island Countries	0.103	2.775	Bathing and swimming	Huttrer, 2010
Costa Rica	1.0	21.0	Drying agricultural products	Lund, Freeston and Boyd, 2005
El Salvador	2.0	40.0	Greenhouses and fish farming	Herrera, Montalva and Herrera, 2010
Honduras	1.933	45.0	Swimming pools	Lund, Freeston and Boyd, 2011
Chile	9.11	131.82	Bathing and swimming	Lahsen, Muños and Parada, 2010
Colombia	14.4	287.0	Bathing and swimming	Lund, Freeston and Boyd, 2005
Ecuador	5 157	102 401.0	Bathing and swimming	Beate and Salgado, 2010
Peru	2.4	49.0	Spas	Lund, Freeston and Boyd, 2005
<i>Asia</i>				
China	8 898	75 348.3	Space heating, greenhouse, heat pump, fish farming, agricultural drying	Zheng, Han and Zhang, 2010
India	265	2 545	Bathing and swimming, food processing	Chandrasekharam and Chandrasekhar, 2010

TABLE 4 (Continued)

Country	Capacity (MWt)*	Utilization (TJ/yr)	Fields of application	References
Islamic Republic of Iran	41.605	1 064.18	Bathing, heat pumps	Saffarzedeh, Porkhial and Taghaddosi 2010
Philippines	1.67	12.65	Bathing and swimming	Ogena <i>et al.</i> , 2010
Nepal	2.717	73.743	Bathing and swimming	Ranjit, 2010
Thailand	2.54	79.1	Crop drying, bathing and swimming	Lund, Freeston and Boyd, 2010
Viet Nam	31.2	92.33	Drying, medical treatment, iodized salt production	Cuong, Giang and Thang, 2005; Lund, Freeston and Boyd, 2005
Asia/Europe				
Turkey	2 084	36 885.9	Heat pump, space heating, greenhouse, bathing and swimming	Mertoglu <i>et al.</i> 2010

*MWt: Megawatt thermal

PHOTO 1
Tomatoes loaded on drying racks in Greece

© Nikos Andritsos

Chilli and garlic drying in Thailand

Chillies and garlic are important to the economy of Thailand, where people eat them both fresh and dried. Chillies and garlic are dried in cabinet driers 2.1 m wide, 2.4 m

PHOTO 2

Pilot-scale cotton dryer using geothermal energy in Greece

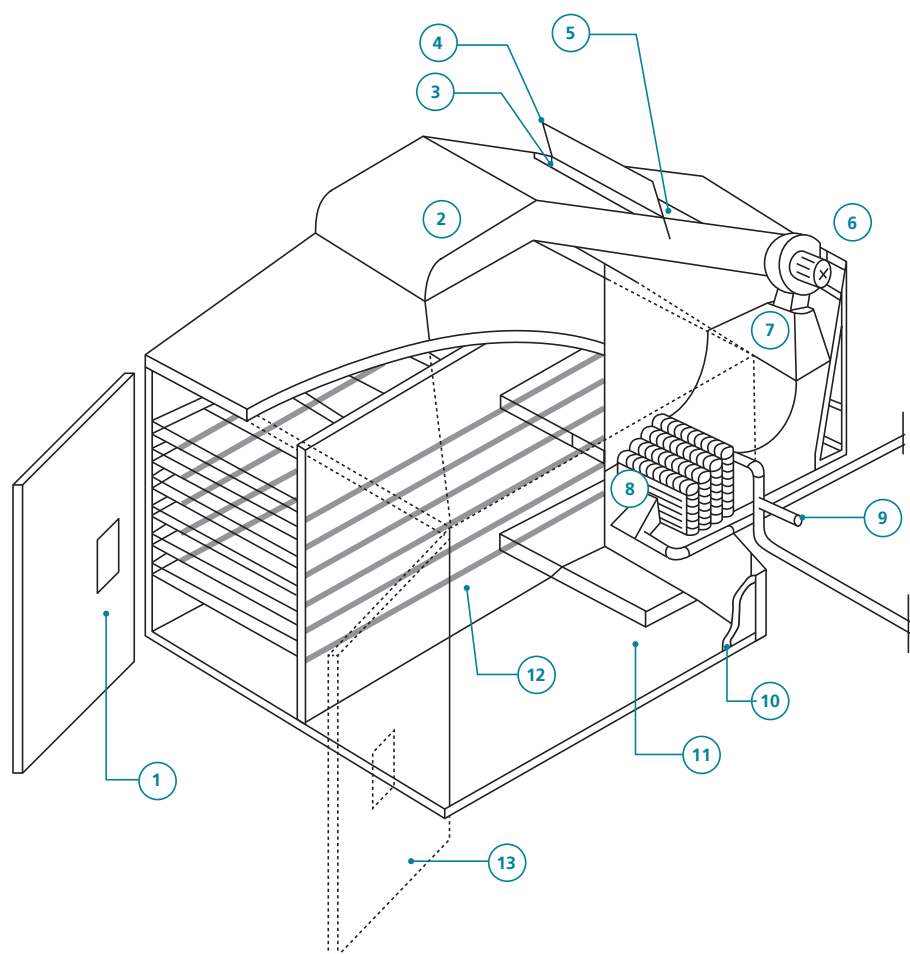
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long and 2.1 m high. Each dryer has 36 trays placed in two compartments with a total capacity of 450 kg of chillies or 220 kg of garlic (Figure 9). Waste heat recovered from a geothermal power plant is used for the drying process. Geothermal hot water at about 80 °C circulates through a cross-flow heat exchanger 100 mm wide, 500 mm long and 300 mm high, enabling a constant air flow of 1 kg/second to pass through the 10.5 m³ drying chamber. The required air temperatures are 70 °C for chillies and 50 °C for garlic, with drying times and hot water flow rates of about 46 hours at 1 kg/second for chillies, and 94 hours at 0.04 kg/second for garlic. The total energy consumed is 13.3 megajoules per kilogram of water (MJ/kg H₂O) evaporated for chillies and 1.5 MJ/kg H₂O evaporated for garlic. This type of dryer has relatively low running costs and can be used in any weather conditions (Hirunlabh, Thiebrat and Khedari, 2004; Thiebrat, 1997).

Rice drying in The former Yugoslav Republic of Macedonia

Water from a geothermal well is used for the direct heating of a rice drying plant in the Kotchany geothermal field (Figure 10). The capacity of the dryer is 10 tonnes/hour with a heating capacity of 1 360 kW. Air from outside, which has a temperature of 15 °C and relative humidity of 60 percent, is heated to about 35 °C in a water-to-air heat exchanger. The temperatures of the inlet and outlet geothermal water are 75 °C and 50 °C respectively. The heated air is blown into the drying zone to dry

FIGURE 9
Cabinet dryer for drying chillies and garlic

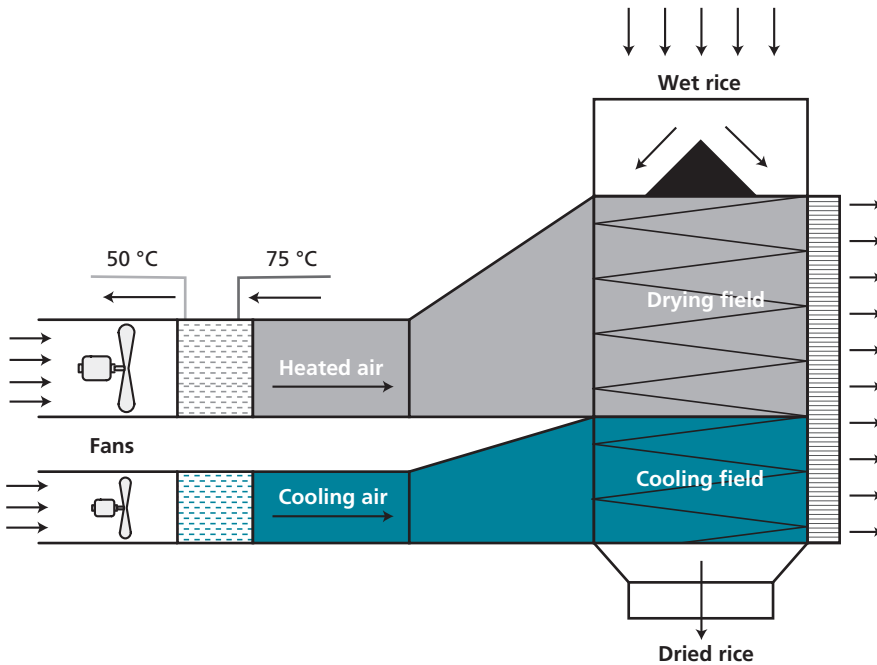


- | | | |
|--------------------|-----------------------------------|-----------------------------|
| 1. Window | 6. Centrifugal fan | 10. Insulated walls |
| 2. Return air duct | 7. Air duct | 11. Grills |
| 3. Exhaust opening | 8. Heat exchanger using hot water | 12. Shelf for putting grill |
| 4. Valve | 9. Hot water tap | 13. Door |
| 5. Inlet | | |

Source: Geo-Heat Center, Klamath Falls, Oregon (USA). Adapted with permission.

the rice, which moves downwards through the drier at constant velocity. There is gravitation mixing as the grain column moves downwards. The temperature of the heated air is kept below 40 °C to prevent cracking of the rice. The rice is dried to decrease the moisture content from 20 to 14 percent and then air-cooled. With the proper combination of other heat consumers – greenhouses, industry (drying), heating, etc. – the cost of using geothermal energy for rice drying is competitive with that of using liquid fuels (Popovski *et al.* 1992).

FIGURE 10
Convective geothermal rice dryer



Source: Geo-Heat Center, Klamath Falls, Oregon (USA). Adapted with permission.

Pyrethrum, tobacco and maize drying in Kenya

In Eburru, the local community uses a traditional system to harness and condense geothermal steam for drying agricultural products such as pyrethrum, tobacco and maize (Mangi, 2012).

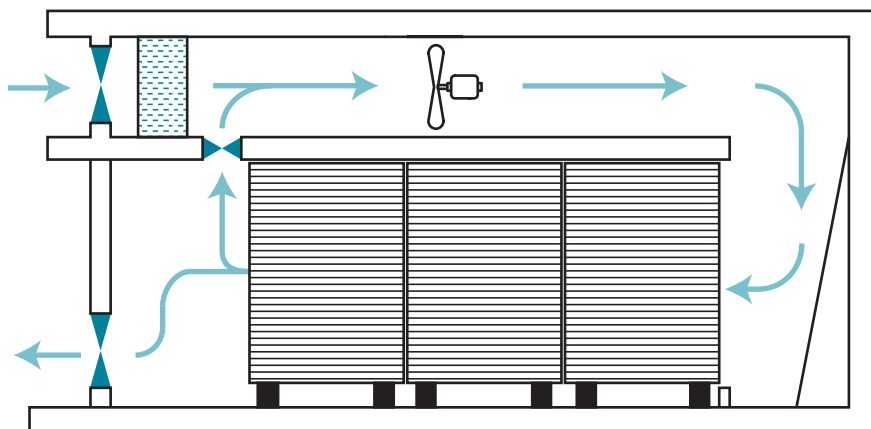
Fruit drying in Mexico

A fruit dryer using geothermal energy was designed by Lund and Rangel (1995) and installed in the Los Azufres geothermal field in Mexico. The dryer is 4.0 m long, 1.35 m wide and 2.3 m high (Figure 11), with concrete walls, a timber ceiling and roof, and a reinforced concrete floor. It contains two containers with 30 trays each and has a capacity of about 1 tonne of fruit per drying cycle. Energy consumption is 10 kilojoules (kJ)/second at a geothermal water flow rate of 0.03 kg/second. The drying chamber is kept at a temperature of 60 °C and reduces the moisture content of fruit from 80 to 20 percent in 24 hours. Cascading can be used to boost efficiency and reduce the cost of producing and utilizing the geothermal resource.

Bean and grain drying in Indonesia

Indonesia has the greatest potential geothermal resources in the world. Geothermal energy can be used to dry several of the crops available in the area, such as coffee

FIGURE 11
Fruit dryer using geothermal energy in Los Azufres, Mexico



Source: Geo-Heat Center, Klamath Falls, Oregon (USA). Adapted with permission.

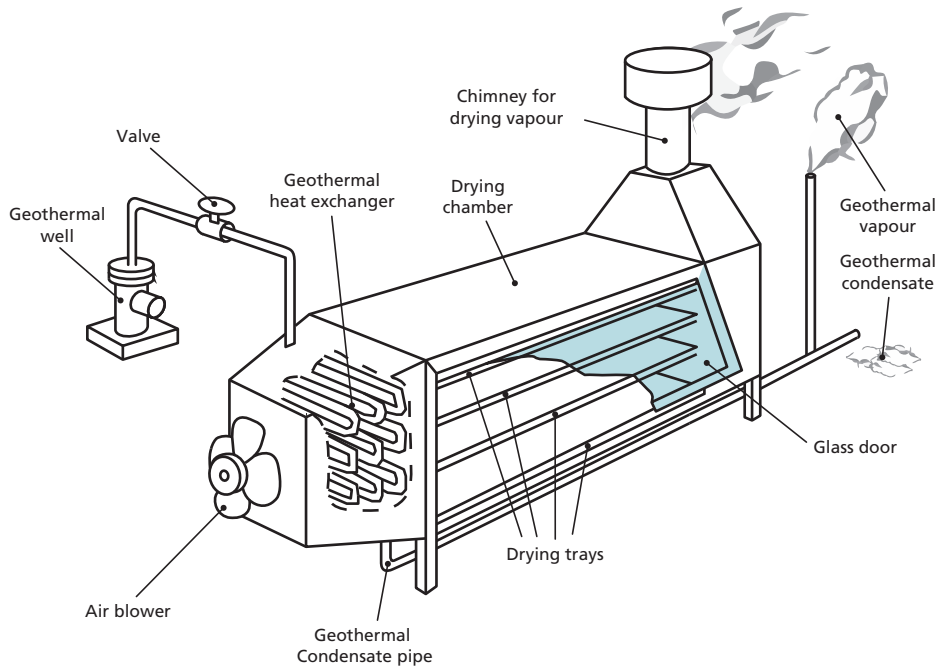
berries, tea, rough rice, beans and fishery products (Abdullah and Gunadnya, 2010). A specially designed geothermal dryer is being used to dry beans and grain in the Kamojang geothermal field of West Java. Geothermal steam from a well, at about 160 °C, is used to heat air for the drying process. The air is blown through a geothermal tube-bank heat exchanger where it is heated before being blown into the drying chamber, consisting of four trays (Figure 12). The heat transfer rate in the geothermal exchanger is 1 000 W. The air flow velocity ranges from 4 to 9 m/second and the drying temperature from 45 °C to 60 °C. The drying time depends on the moisture content of the raw material.

Food drying in developed countries

In western Nevada, United States of America, a large-scale onion and garlic drying facility employs 75 workers. Continuous conveyor belt dryers approximately 3.8 m wide and 60 m long (Figure 13) are fed 3 000–4 300 kg/hour of wet onions. The capacity of the dryers varies from 500 to 700 kg/hour of dried onions, reducing the moisture content of the onions from 85 to about 4 percent after 24 hours of drying (Lund, 2006).

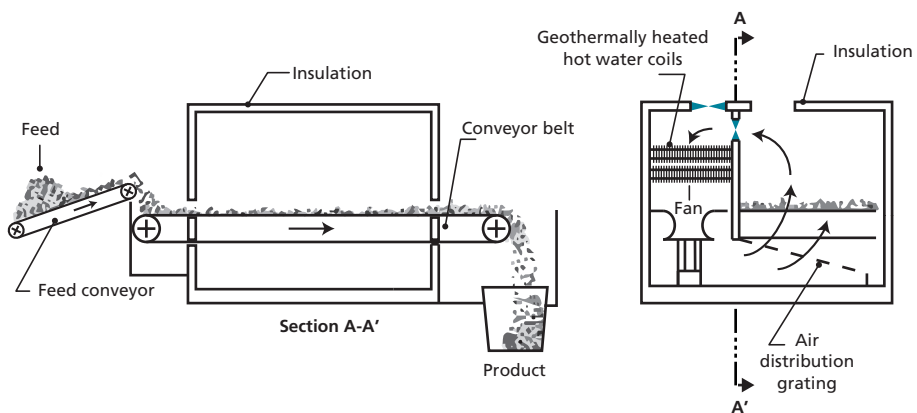
It is well known that grain drying consumes a significant amount of energy annually. These drying processes can easily be adapted to geothermal energy (Lienau, 1991). A deep-bed dryer (batch dryer) commonly used for drying grains (Figure 14) consists of a fan that blows air through a geothermal heat exchanger, where it is heated. The hot air is then distributed uniformly to the product through the perforated floor. The temperature of the hot air is controlled by adjusting the flow rate of geothermal hot water. The drying temperature of some grains can approach 90 °C, but moderate temperatures of 50–60 °C with relative humidity of about 40 percent is adequate for

FIGURE 12
Geothermal dryer for drying beans and grains



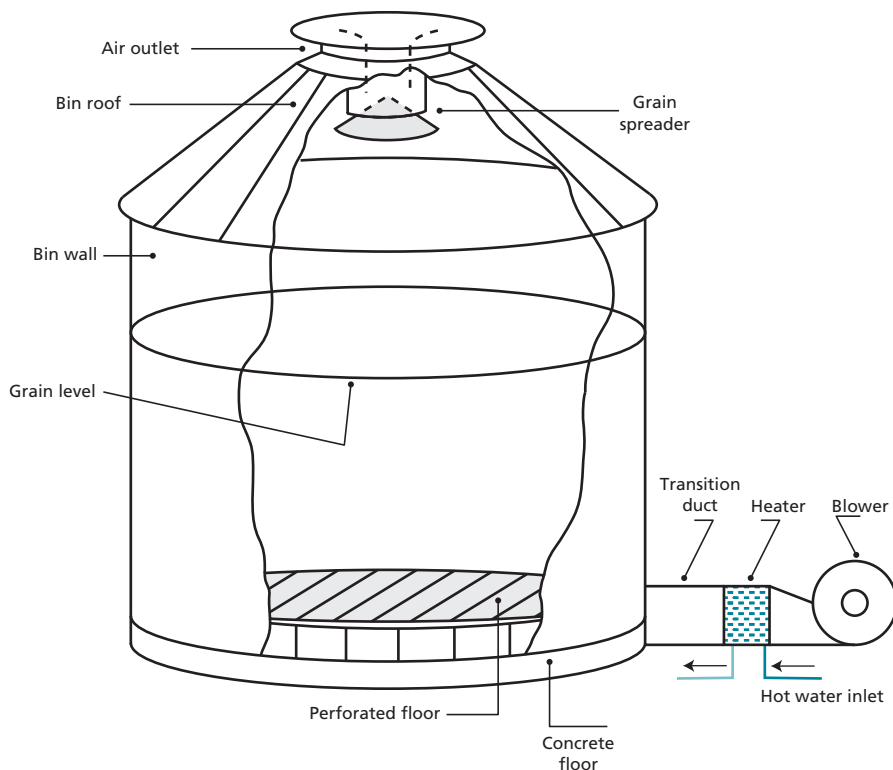
Source: Geo-Heat Center, Klamath Falls, Oregon (USA). Adapted with permission.

FIGURE 13
Conveyor dryer using geothermal energy



Source: Geo-Heat Center, Klamath Falls, Oregon (USA). Adapted with permission.

FIGURE 14
Batch grain dryer using geothermal energy

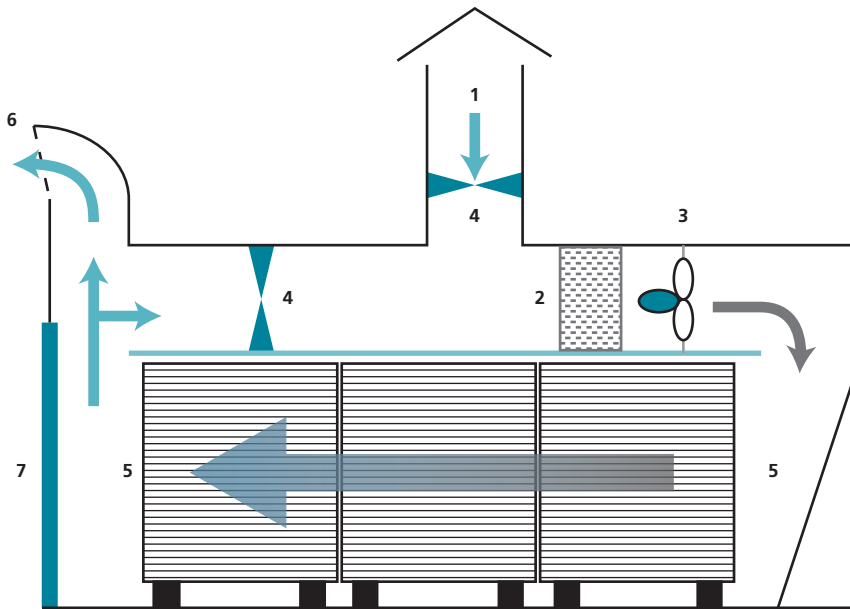


Source: Geo-Heat Center, Klamath Falls, Oregon (USA). Adapted with permission.

drying other produce. For example, the drying temperature of coffee berries is about 50–60 °C, that for rice must be maintained below 40 °C to prevent cracking (Abdullah and Gunadnya, 2010). The moisture content of dried grains should be in the range of 12–13 percent to prevent mould growth and spoilage (Lienau, 1991).

An example of a large-scale industrial operation that uses geothermal energy is seaweed and fish drying in Iceland. Indoor drying has been applied for more than 35 years in regions where geothermal energy is available. Salted fish, cod heads, cod backbones, small fish and stockfish are among the products most commonly dried in this way. About 20 companies across Iceland dry fish using geothermal hot water and steam. One company drying seaweed has an annual capacity of 2 000–4 000 tonnes using geothermal hot water, and the drying of pet food is an emerging industry, with annual production currently about 500 tonnes (Arason, 2003; Bjornsson, 2006). Fish is dried in a two-step process: i) primary drying in a rack tunnel dryer (Figure 15 and Photo 3) or conveyor dryer (Figure 16 and Photo 4) for 24–40 hours at a drying temperature of 20–26 °C, to reduce the

FIGURE 15
Rack tunnel dryer using geothermal energy for fish drying



- | | |
|------------------------------|-----------------------|
| 1. Air inlet | 4. Adjustable valves |
| 2. Geothermal heat exchanger | 5. Pallets with trays |
| 3. Fan | 6. Air outlet |
| | 7. Door |

Source: S. Arason, 2013.

PHOTO 3
Fish drying in a geothermal tunnel dryer in Iceland



© Larus Karl Ingason

moisture content from 80 to 55 percent; and ii) secondary drying in containers for three days at a temperature of 22–26 °C, resulting in a moisture content of about 15 percent (Photo 5) (Arason, 2003).

Greenhouse heating

Lund, Freeston and Boyd, (2010) report that 34 countries use geothermal resources to heat greenhouses, led by Turkey, Hungary, the Russian Federation, China and Italy. Vegetables, flowers and fruit are the main crops grown in these greenhouses. Duffield and Sass (2003) found that the use of geothermal resources instead of traditional energy cuts fuel costs by about 80 percent and total operating costs by 5–8 percent. Other advantages of geothermal heating for greenhouses include better hygiene, with cleaner air and water, and the ability to maintain a stable workforce and often to benefit from tax incentives.

In Turkey, geothermal greenhouse heating has recently become very popular, especially for growing tomatoes and Californian peppers. The total area of geothermal-heated greenhouses in Turkey is about 210.44 ha, with a heat capacity of 207.44 megawatts thermal (MWt). The main greenhouse area is located in western Anatolia and is expanding rapidly (Serpen, Aksoy and Ongur, 2010).

FIGURE 16
Conveyor dryer using geothermal energy for fish drying

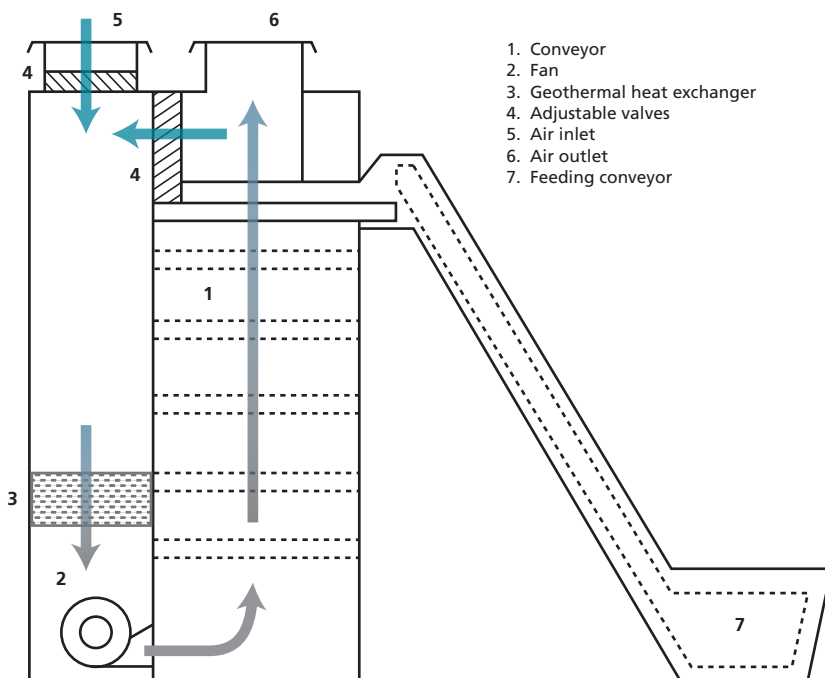


PHOTO 4

Fish backbones dried in a conveyor dryer using geothermal energy in Iceland



© Larus Karl Ingason

PHOTO 5

Secondary drying of fish in containers in Iceland



© Larus Karl Ingason

In Greece, geothermal greenhouses were first constructed in the early 1980s in the northern part of the country. By winter 2008/2009, about 13.1 ha of glass-covered and 5.1 ha of plastic-covered (polyethylene and polycarbonate) greenhouses were heated with geothermal hot water. The main vegetables grown in these greenhouses are tomatoes, sweet peppers and cucumbers (Photo 6). Lettuce, green beans, strawberries and certain herbs are also sometimes grown (Andritsos, Fytikas and Kolios, 2009).

PHOTO 6

Polyethylene heating tubes in a plastic-covered greenhouse for vegetable cultivation (left), and polypropylene heating tubes laid on the soil in a glass-covered greenhouse (right) in Greece



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In China, the total area of geothermal greenhouse heating was 0.8 million m² in 2007, mainly in the country's north. Geothermal greenhouses produce a range of high-quality vegetables in all seasons (Keyan, 2008).

In Kenya, the only commercial use of geothermal energy to heat greenhouses is at Oserian, Naivasha. The Oserian Development Company has been utilizing geothermal energy to heat rose greenhouses since 2003, starting on 3 ha and expanding to 50 ha. Geothermal heating reduces humidity in the greenhouses, which eliminates fungal infection and results in lower production costs. The use of geothermal greenhouses leads to better-quality flowers and increased production (Mburu, 2012). The company exports more than 400 million stems of roses annually, mainly to the United States of America and Europe.

In Iceland, geothermal energy was first used to heat greenhouses in 1924, and greenhouse heating is one of the oldest and most important uses of geothermal resources. The total surface area of greenhouses in Iceland is estimated to be about 175 000 m², of which 55 percent is used for growing vegetables and 45 percent for flowers. Most geothermal greenhouses are in southern Iceland and are glass-covered (Ragnarsson, 2008). The main crops grown in greenhouses include vegetables such as tomatoes, carrots, cucumbers and paprika (Photos 7 and 8), and potted plants and flowers for the domestic market.

Fish farming and spirulina cultivation

According to Lund, Freeston and Boyd (2011), 22 countries use geothermal resources in fish farming, led by the United States of America, China, Iceland, Italy and Israel. The most common species farmed in this way are tilapia, salmon and trout, but tropical fish, lobsters, shrimp, prawns and even alligators are also being

PHOTO 7

Tomato cultivation in a greenhouse in Iceland

© Haraldur Jónasson

PHOTO 8

Cucumber cultivation in a greenhouse in Iceland

© Haraldur Jónasson

farmed. In 2010, the total energy used in fish farming was 11 521 TJ/year, equivalent to 47 600 tonnes of annual production (Lund, Freeston and Boyd, 2011).

In Algeria, the government is promoting a project for utilizing geothermal energy, and providing financial support of up to 80 percent of the total project cost. So far, three fish farms have been built – in Ain Skhouna, Ouargla and Ghardaia. The Saida tilapia farm in Ain Skhouna consists of 33 ponds covering a total surface area of 49 500 m². Hot water at 30 °C is supplied from a drill hole with a capacity of 60 litres/second. In 2008, 200 tonnes of tilapia were produced and production is expected to increase to 500 tonnes over the coming years. Drill holes provide 44 litres/second of water at 21 °C at Ouargla and 150 litres/second of water at 28 °C at Ghardaia. About 1 500 tonnes of tilapia are produced each year from both sites (Fekraoui, 2010).

In Israel, the use of geothermal water for fish farming began in 1979 when geothermal water resources at about 40 °C were discovered in the desert and arid lands of the south. The use of geothermal hot water in intensive aquaculture enables maximum growth of the fish throughout the year. The main species cultured include common carp and tilapia, followed by silver carp, grass carp, grey mullet, North African catfish and gilthead seabream (Hulata and Simon, 2011). Common carp and tilapia together account for about 75 percent of Israeli inland aquaculture. Shapiro reports that in 2009 Israel had 45 fish farms with a total area of 2 693 ha and total production of 18 442 tonnes of fish (Shapiro, 2011 cited in Hulata and Simon, 2011).

In Greece, a spirulina cultivation project using geothermal energy started in the late 1990s in Nigrita. Geothermal hot water at a temperature of 51 °C and a flow of 10 kg/second is used to heat the water to 33–36 °C. Geothermal CO₂ is also used in spirulina cultivation, to increase production and reduce production costs. The spirulina cultivation season runs from April to November. The project uses eight shallow raceway ponds made of concrete in which the cultivation water is mixed using paddle wheels. Each raceway pond has a surface area of about 225 m² and can hold about 40 m³ of water (Photo 9). The ponds are located in a greenhouse covered by polyethylene. In 2008, 4 500 kg of dried spirulina was produced (Andritsos, Fytikas and Kolios, 2009).

PHOTO 9

Raceway pond for cultivation of spirulina using geothermal energy in Nigrita, Greece



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Chapter 3

Geothermal uses in practice

3.1 GREENHOUSES

For the past 25 years, greenhouse heating has been the most common use of geothermal energy in agriculture. In many European countries, geothermal heat is used to produce vegetables, fruits and flowers on a commercial scale all year round.

The use of geothermal energy to heat greenhouses has several benefits (Popovski and Vasilevska, 2003):

- Geothermal energy often costs less than energy from other available sources.
- Geothermal heating systems are relatively simple to install and maintain.
- Greenhouses account for a large share of agriculture's total consumption of low-enthalpy energy.
- Greenhouse production areas are often close to low-enthalpy geothermal reservoirs.
- It improves the efficiency of food production by making use of locally available energy sources.

General design criteria

Greenhouses can be heated in several ways (Lund, 1996): i) using perforated plastic tubes running the length of the greenhouse to circulate air that has been passed over hot water in finned-coil heat exchangers, and to distribute heat uniformly; ii) circulating hot water in pipes or ducts on or under the floor; iii) circulating heat through finned units along the walls and under benches; iv) using hot water to heat the greenhouse surfaces; or v) applying a combination of these methods.

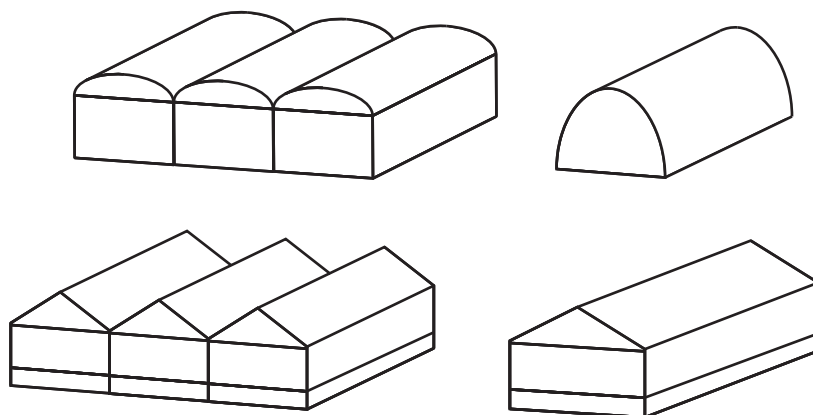
Construction materials

Greenhouses are built on steel or aluminium frames covered by glass, plastic film, fibreglass and/or other rigid plastics. Common greenhouse shapes are shown in Figure 17.

Glass is the most expensive covering material and also the heaviest, requiring a stronger frame, often with a peaked roof (Lund, 1996). Glass greenhouses also cost more to heat than others, because cold air infiltrates through the building joints and a single layer of glass provides low insulation. However, although glass greenhouses have the lowest energy efficiency, they also provide the highest light quality (Rafferty, 1996; von Zabeltitz, 1986).

Today, many greenhouses have plastic coverings and arched or hut-shaped frames. Recently, a double layer of plastic is sometimes used, with a small blower to maintain sufficient air pressure to keep the two layers separate. This provides insulation, reducing heat loss by up to 30–40 percent, thereby increasing the overall efficiency of the greenhouses (Rafferty, 1996; Dickson and Fanelli, 2004).

FIGURE 17
Common shapes of greenhouse



Source: M.K. Ingvarsson, 2013.

Fibreglass greenhouses are similar to glass ones but lighter. They cost less to construct than glass greenhouses, but the heat loss is about the same (Lund, 1996).

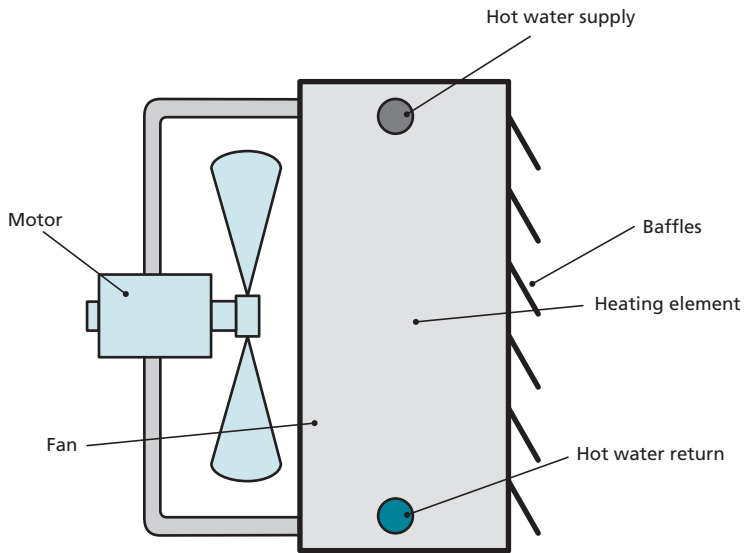
Heating systems

Greenhouses use a variety of geothermal heating systems, such as finned pipes, fan coil units, soil heating, plastic tubing, cascading, bare pipes, unit heaters, or a combination of these (Lund, 1996). Geothermal greenhouses are heated in two main ways: through natural air movement, and through forced air movement.

The water for heating greenhouses ranges from 40 to 100 °C, depending on the required temperature within the greenhouse (Popovski and Vasilevska, 2003). Water is driven through copper or steel pipes with aluminium or steel fins, which are placed under or on top of the soil between plants, on benches, or suspended from the roof (Panagiotou, 1996). Air is blown through a horizontal or vertical hot water unit heater (Figures 18 and 19) consisting of a finned coil and a small propeller fan. The air is heated by the hot water running inside the system of pipes and is discharged either into a perforated distribution tube or directly into the greenhouse (Lund, 1996).

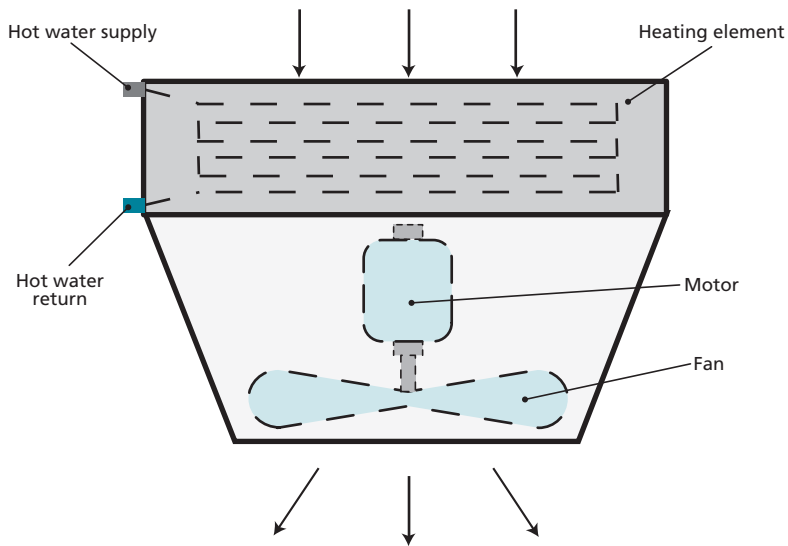
To heat the soil, pipes are usually buried in the floor of the greenhouse to create a huge radiator (Rafferty, 1996). Heat from the water circulating inside the pipes is transferred to the soil and air in the greenhouse. Two types of heating tube system are currently used for greenhouse soil heating: i) double-serpentine piping systems; and ii) single-serpentine piping systems (Figure 20).

FIGURE 18
Horizontal hot water unit heater



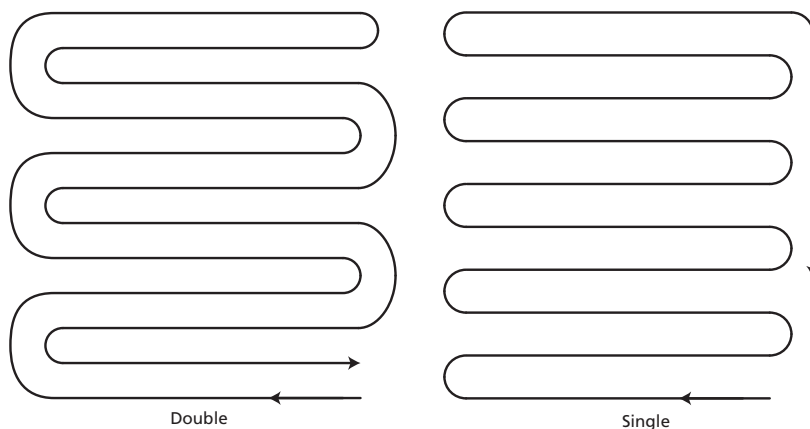
Source: S. Arason, 2013.

FIGURE 19
Vertical hot water unit heater



Source: M.K. Ingvarsson, 2013.

FIGURE 20
Soil heating systems for greenhouses



Source: Geo-Heat Center, Klamath Falls, Oregon (USA). Adapted with permission.

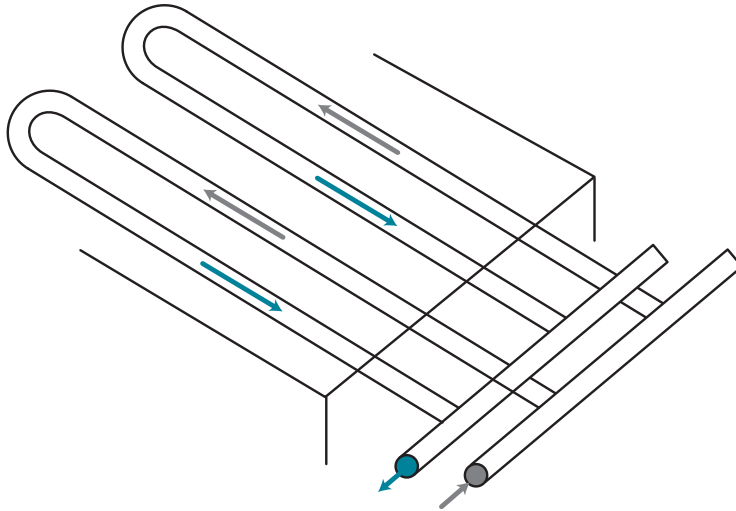
3.2 SEA/BRACKISH WATER GREENHOUSES

A recently developed process makes it possible to combine greenhouse heating with the desalination of sea/brackish water using geothermal energy. This innovation has particular potential for agriculture in cool arid regions with ready supplies of brackish and/or seawater (Mahmoudi *et al.* 2009, 2010). Currently there are two geothermal desalination plants, one in France and one in the south of Tunisia (Bourouni, Chaibi and Tadriss, 2001). The advantages of using geothermal energy in such systems are: i) geothermal energy supplies are generally more stable and accessible than those of other renewable resources such as wind and solar energy (Sablani *et al.* 2003); and ii) geothermal resources can be used to heat greenhouses while simultaneously providing freshwater to irrigate the greenhouse crops (Goosen, Mahmoudi and Ghaffour, 2010). Greenhouse desalination of sea/brackish water is discussed by Mahmoudi *et al.*, 2010. Geothermal energy is used to heat the sea/brackish water while the resulting hot vapour is used to warm the greenhouse. At the same time, ambient-temperature air is heated and humidified by being passed through a first evaporator before moving through the greenhouse, helping to heat the greenhouse. The air is then passed through a second evaporator where it is further humidified to near saturation point. The saturated air passes over a condenser where the freshwater it contains is condensed and stored in a tank to be used for irrigation.

3.3 SOIL HEATING

Soil heating makes it possible to extend the growing season and maintain a constant soil temperature to increase yields. Soil heating is used mainly to cultivate carrots and cabbages, but leeks also need it for normal growth (Kumoro and Kristanto, 2003).

FIGURE 21

Heating pipe distribution for a soil warming system inside a greenhouse

Source: P.G. Pálsson, 2013.

The soil is heated by passing geothermal water through a grid of corrugated polypropylene pipes (Figure 21) spaced at 1–2 m intervals and usually about 65–85 cm from the soil surface (Johannesdottir, Graber and Gudmundsson, 1986). The inlet water temperature in the polypropylene pipe system is about 60 °C and the used water is ejected at a temperature of 25 °C (Andritsos, Fytikas and Kolios, 2009). The flow rate of the inlet water is controlled to maintain a soil temperature of 20–30 °C. Wastewater from greenhouses is sometimes used to heat soil, but it is more common to have a separate supply (Kumoro and Kristanto, 2003).

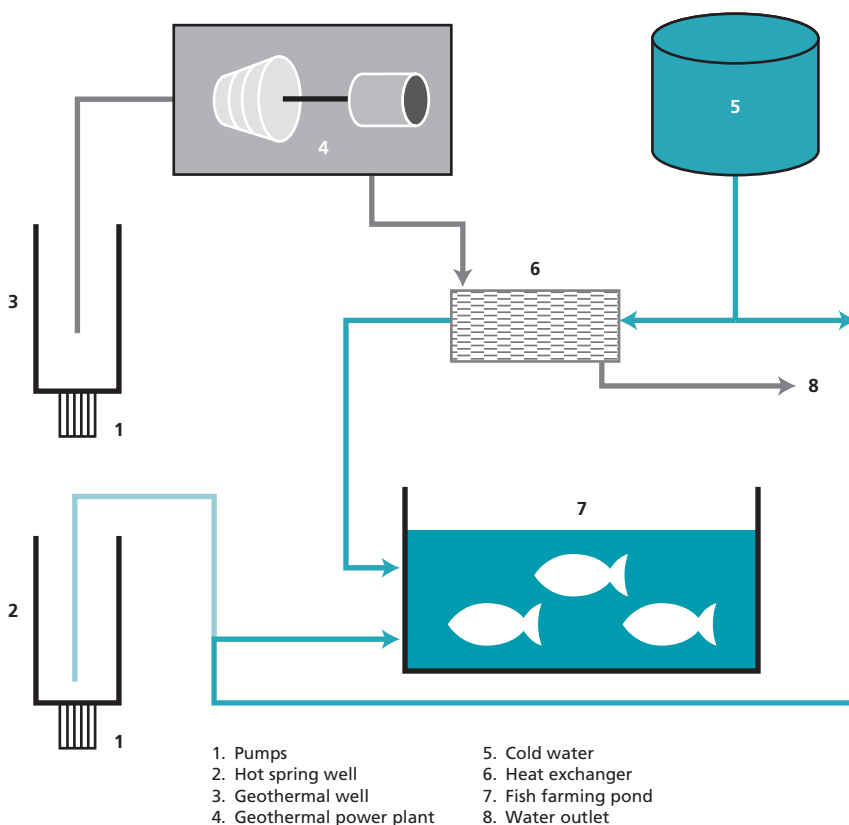
The factors affecting the temperature distribution in a cross-section of soil above the pipes are air temperature, inlet and outlet water temperatures, the surface heat transfer coefficient of the soil, the effective thermal conductivity of the soil, and the depth of and distance between the pipes.

3.4 AQUACULTURE

Geothermal hot water is used to heat freshwater in heat exchangers or is mixed with fresh water to obtain suitable temperatures for fish farming. Aquaculture pond and raceway heating are among the most common applications of geothermal energy. They make it possible to carry out aquaculture operations in colder climates or close to markets where alternative heating sources are not economical (Boyd and Lund, 2003). The use of geothermal energy in fish farming protects the fish stock against cold weather and increases fish production (Gelegenis, Dalabakis and Ilias, 2006). It is used mainly at the fish hatchery stage (Ragnarsson, 2003). The breeding of different species of fish in water heated with geothermal energy makes production cheap and profitable all year round. The main species raised are carp, catfish, tilapia, frogs,

mullet, eels, salmon, sturgeon, shrimps, lobsters, crayfish, crabs, oysters, clams, scallops, alligators, mussels and abalone (Boyd and Lund, 2003). The use of geothermal energy in fish farming is expanding rapidly in France, Greece, Hungary, Iceland, New Zealand and the United States of America. In Iceland, geothermal energy is used for farming such species as Arctic char, turbot, tilapia and Atlantic halibut. The use of geothermal energy in fish farming is illustrated in Figure 22. Cold water is heated in a heat exchanger using hot wastewater from a geothermal power plant, or is mixed with water from a hot spring. Once it has reached a suitable temperature – generally about 20–30 °C – the water is pumped into the fish pond. The size of the pond depends on the temperature of the geothermal source, the temperature required for the fish species, and the heat losses incurred during operation (Dickson and Fanelli, 2004).

FIGURE 22
Fish farming using geothermal energy



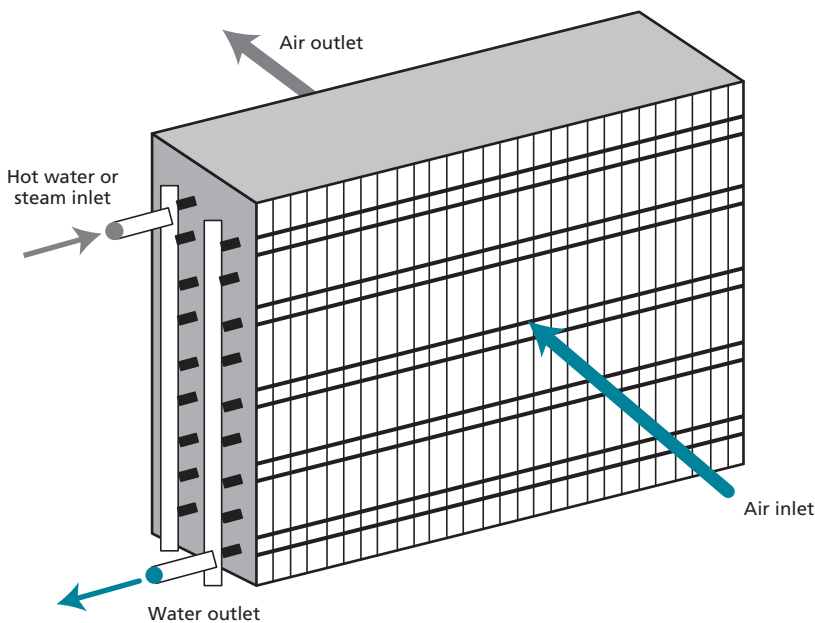
3.5 ALGAE CULTIVATION

Spirulina and other algae are sold as health foods and medical cures in many countries around the world. Spirulina is “a photosynthesizing cyanophyte (blue-green algae) that grows vigorously in strong sunshine under high temperatures and highly alkaline conditions” (FAO, 2008). When conditions are good, production is constant and of high quality. Spirulina is usually cultivated in shallow ponds, with paddle wheels mixing the culture. Optimum temperatures are between 35 and 37 °C (Andritsos, Fytikas and Kolios, 2009).

3.6 FOOD DRYING

Many food and agricultural industries make use of thermal drying processes to preserve a growing range of foods (Senadeera et al. 2005). In industrialized countries, drying processes use 7–15 percent of total industrial energy consumption, but their thermal efficiency remains relatively low, at 25–50 percent. In some highly industrialized countries, drying operations account for more than a third of prime energy consumption (Chou and Chua, 2001). It is therefore necessary to reduce energy consumption by using efficient energy resources for agricultural drying, and low- to medium-enthalpy geothermal resources are the best option (Ogola, 2013). Drying can use heat from the hot water or steam of geothermal wells or the waste heat recovered from a geothermal plant (Vasquez, Bernardo and Cornelio, 1992).

FIGURE 23
Geothermal heat exchanger

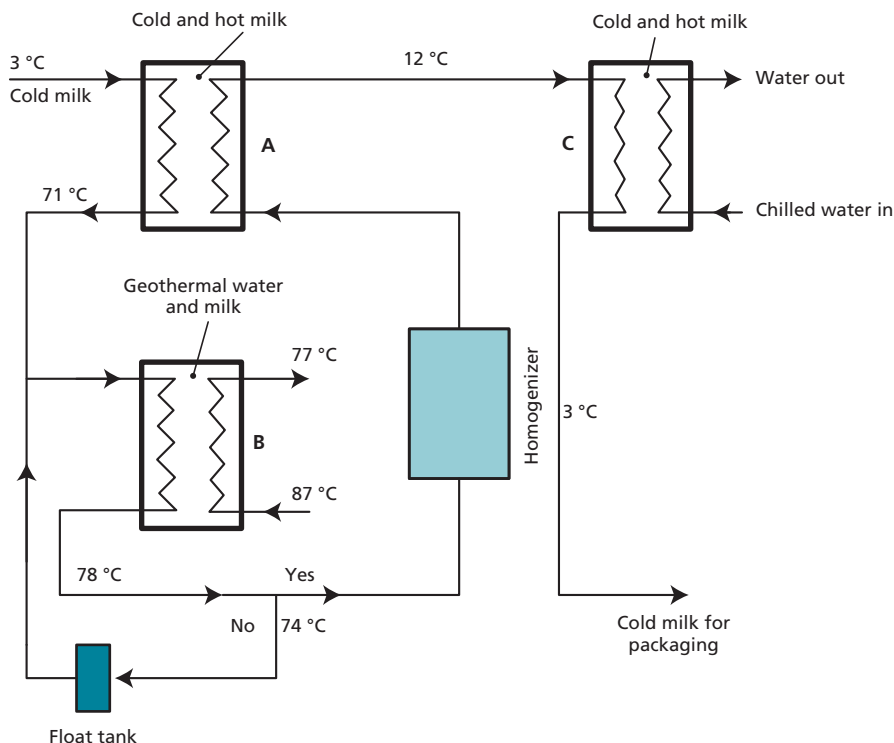


One of the most important devices in a dryer system using geothermal energy is the geothermal heat exchanger. This consists of steel or copper pipes equipped with copper or aluminium fins to increase the heat transfer surface (Figure 23). Geothermal hot water or steam is circulated inside the pipes and air is blown through the heat exchanger using a propeller fan. The air is heated by the geothermal hot water or steam and is then blown into the drying chamber for the drying process.

3.7 MILK PASTEURIZATION

Milk is a nutritious food and an important part of the diet of pastoralist communities. The quality of milk deteriorates rapidly after collection, mainly as a result of enzyme activity and the growth of microorganisms, particularly under unhygienic production and storage conditions at ambient temperatures. To prevent enzyme activity and microbial growth, milk must be processed using high-temperature treatments such as pasteurization or the ultra-high temperature (UHT) process (Perko, 2011; Torkar and Golc Teger, 2008).

FIGURE 24
Milk pasteurization using geothermal hot water

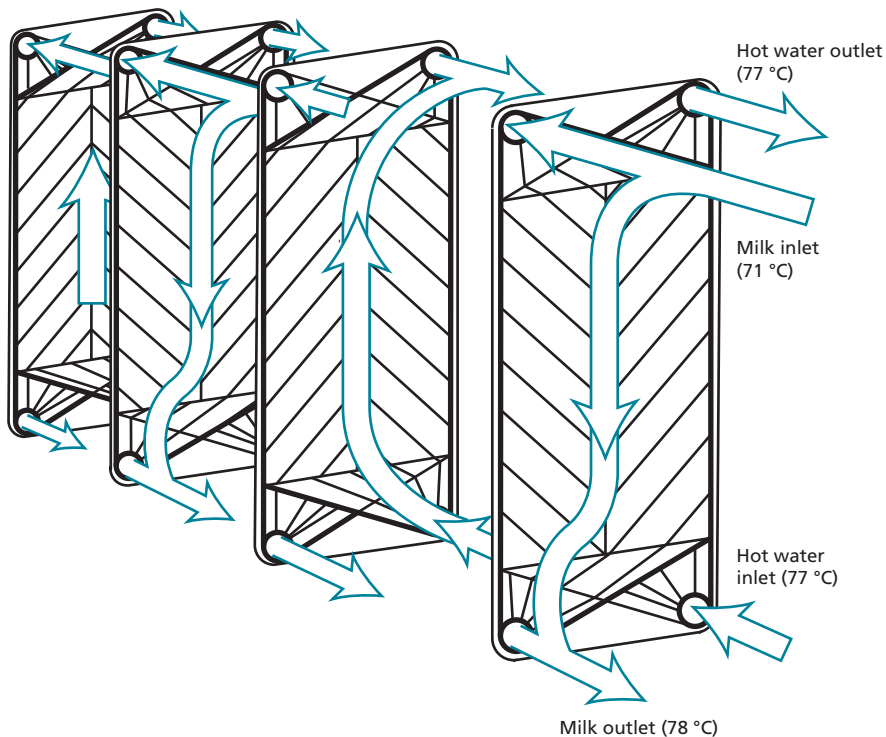


Source: Geo-Heat Center, Klamath Falls, Oregon (USA). Adapted with permission.

Geothermal hot water can be used for milk pasteurization and drying processes, while geothermal steam can be used for milk evaporation and the UHT process. A flow chart of the milk pasteurization process is shown in Figure 24. Fresh cold milk at a temperature of 3 °C is preheated to 71 °C in plate heat exchanger A by the hot milk from the homogenizer. The heated milk is then passed through geothermal plate heat exchanger B for pasteurization, where it is heated to at least 78 °C for 15 seconds. After pasteurization, the hot milk is passed through the homogenizer and then back through plate heat exchanger A where it is cooled to 12 °C. It is finally chilled to 3 °C by cold water in plate heat exchanger C before packaging and storage. The temperature of the inlet geothermal hot water is about 87 °C and the outlet is 77 °C (Lund, 1997).

The hot water and milk fluid flow through the plate heat exchanger as depicted in Figure 25, moving in opposite directions on either side of the plates. Water flow and circulation are controlled by the placement of the plate gaskets, which are installed to prevent mixing of the milk and hot water.

FIGURE 25
Fluid flows through a plate heat exchanger



3.8 PREHEATING AND HEATING PROCESSES

Geothermal energy can be used effectively for preheating and heating processes in the food processing industry. Both geothermal steam and geothermal hot water at temperatures in the range of 90 to 150 °C are commonly used. Two types of heating tank are used for heating: i) a twin-shell heating tank with spiral tubes between the shells (Figure 26); and ii) a heating tank with internal spiral or zigzag tubes (Figure 27).

In the twin-shell heating tank, geothermal hot water or steam is circulated in spiral tubes fitted in the space between the inner and outer shells. The heat from geothermal hot water or steam is transferred through the inner shell to the food inside the tank. The outlet water is discharged through a float valve (Figure 26).

In a heating tank with internal spiral or zigzag tubes, the geothermal hot water or steam is circulated inside the tubes. The heat is transferred through the tubes to the surrounding food. The outlet water is discharged through a float valve (Figure 27).

3.9 EVAPORATION AND DISTILLATION PROCESSES

Evaporation and distillation processes are applied in many food processing industries, such as sugar processing, mint distillation and liquor processes, to aid the concentration of food products (Lund, 1996). Evaporation can be performed either as a batch process or in a continuous system. The temperature required for evaporation and distillation varies depending on the product being processed, but common operating temperatures range from 80 °C to 120 °C.

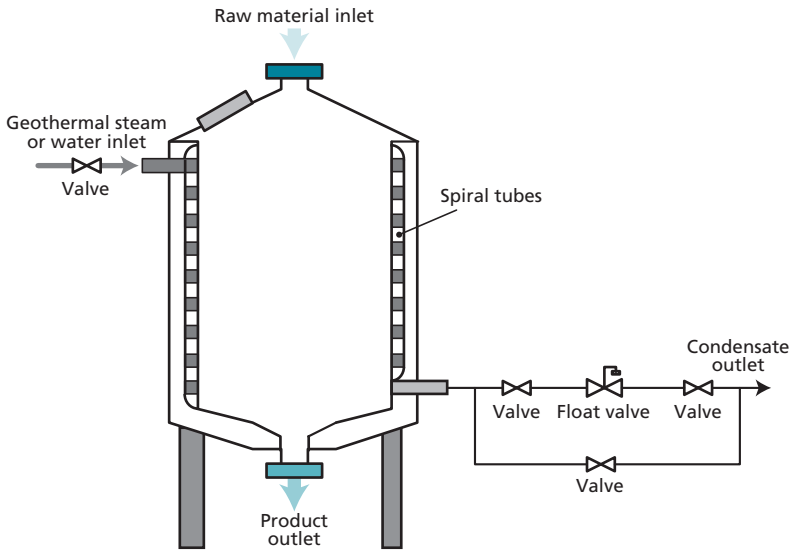
Geothermal hot water and steam are potential energy sources that can be used in evaporation and distillation processes. Geothermal fluids are supplied to the heat exchanger, where they discharge heat to the diluted liquid. A typical long-tube evaporator consists of a vertical chamber with a tubular heat exchanger and a separation chamber (Figure 28). Geothermal steam is circulated outside the tubes and the liquid is moved up into the tubes. Once inside the tubes, the liquid begins to boil and the expansion caused by vaporization forms vapour bubbles that carry the liquid upwards. The liquid-vapour mixture is then separated in a separation chamber by impingement baffles. The concentrated liquid can be extracted directly or mixed with diluted liquid and recirculated or fed into another evaporator (Ibarz and Barbosa-Cánovas, 2003).

Two or three evaporators can be linked together to increase the heat efficiency (Figure 29). Geothermal steam is supplied to the first evaporator. Vapour from the first evaporator becomes steam for the second evaporator, which in turn provides steam for the third evaporator. The vapour from the last evaporator is then discharged into the air or used for other purposes. The liquid flows into the system through the first evaporator and the concentrated liquid (product) is collected from the last evaporator.

3.10 PEELING AND BLANCHING PROCESSES

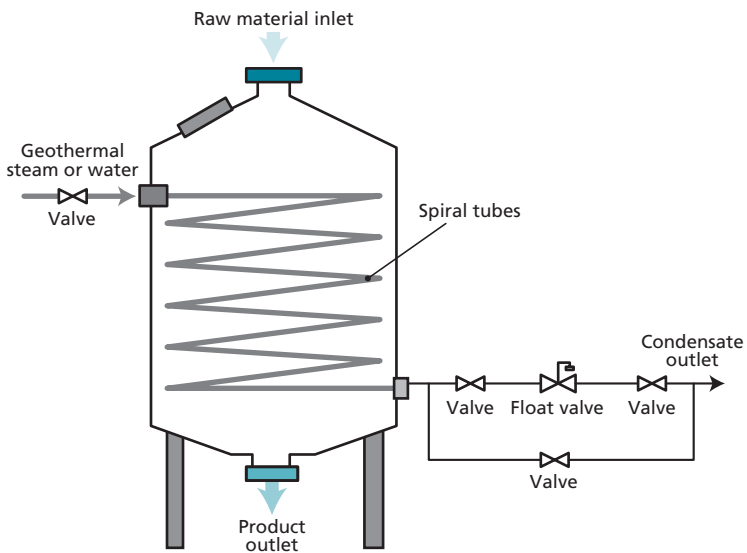
Peeling and blanching are important pre-processing steps in many food processing industries, such as those for fruits and vegetables. In the peeling process, the food is introduced into a hot water bath where the skin or outer layer is softened before being mechanically scrubbed or washed off. Peeling equipment is usually of a continuous-flow type in which geothermal hot water or steam is applied directly to the produce stream, or indirectly by heating the produce bath (Lund, 1996).

FIGURE 26
Twin-shell heating tank with spiral tubes



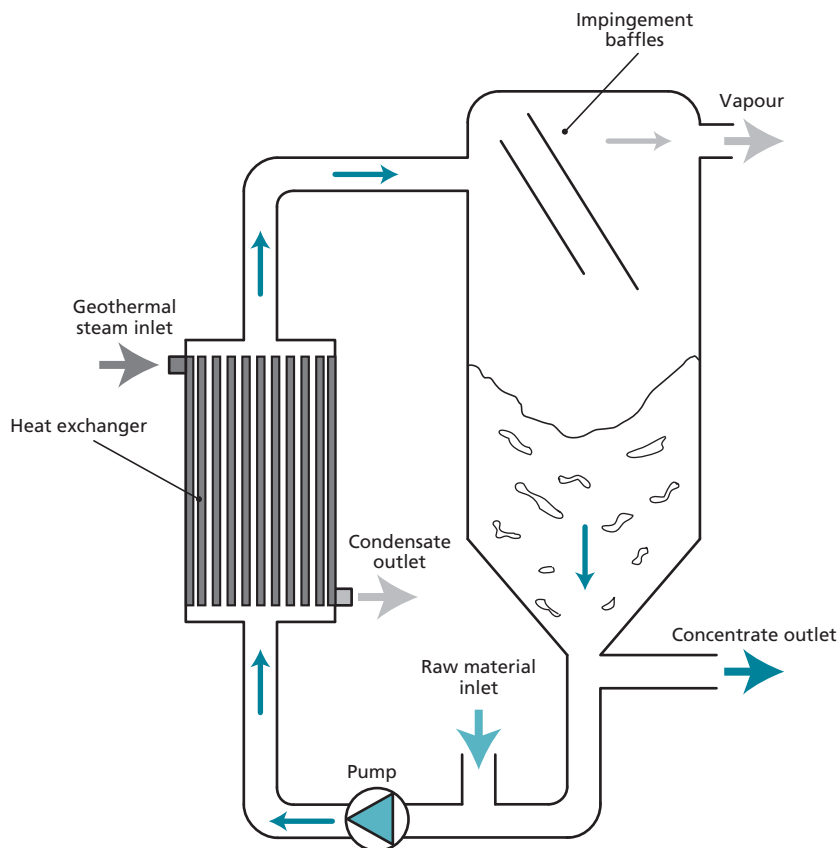
Source: M.V. Nguyen, 2013.

FIGURE 27
Heating tank with internal spiral or zigzag tubes



Source: M.V. Nguyen, 2013.

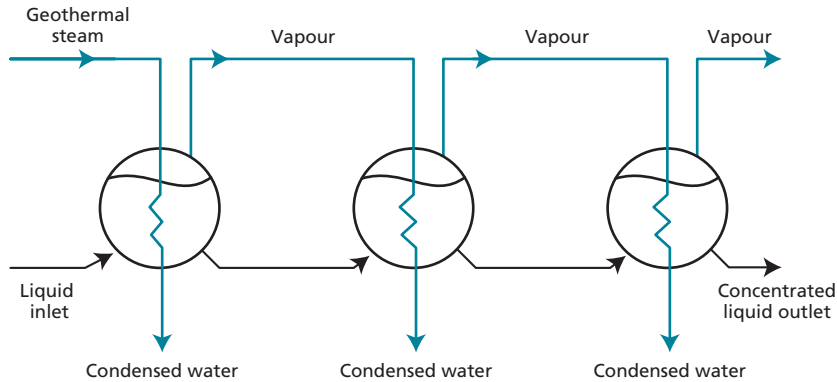
FIGURE 28
Forced circulation evaporator



Source: S. Arason, 2013.

Before some processing operations, such as canning, freezing or dehydration, vegetables or fruits are often blanched to inhibit enzyme activity and microbial growth, remove gas from the plant tissue, shrink and soften the tissue, and maintain some natural properties of the food. In blanching, food is heated rapidly to a predetermined temperature, maintained at that temperature for a set time, and then either cooled rapidly or passed on immediately to the next processing stage. As the properties of the blanching fluid usually need to be closely controlled, geothermal fluids are used to provide the required energy through heat exchangers. Common temperatures for peeling and blanching processes range from 77 °C to 104 °C (Lund, 1996).

FIGURE 29

Multi-evaporator using geothermal energy

Source: M.V. Nguyen, 2013.

3.11 STERILIZATION PROCESSES

Sterilization is an important step in a wide range of industries such as meat and fish canning, to stop the growth of bacteria, particularly *Clostridium botulinum*. The recommended temperature and time for killing *C. botulinum* bacteria are 121 °C for three minutes. The reference temperature for food sterilization processes is therefore 121 °C. Geothermal steam is normally used for food sterilization processes, but either geothermal hot water or steam at a temperature of 105–120 °C can be used to sterilize equipment in the food processing, canning and bottling industries (Lund, 1996).

3.12 IRRIGATION USING GEOTHERMAL WATER

Geothermal water at temperatures in the range of 40 to 75 °C can be used for heating of winter crops in open-field agriculture and greenhouses. It is also used directly for the irrigation of oases. Geothermal water is supplied through a surface irrigation piping system and/or a pipeline heating device buried under the soil. When using geothermal water in irrigation, the chemical composition and salinity of the water must be carefully monitored to prevent damage to the plants (Dickson and Fanelli, 2004). In Tunisia, for example, the use of geothermal water to both heat and irrigate greenhouses is proving to be a promising and economically viable option. After heating the greenhouses, the geothermal water is collected in large concrete ponds where it is cooled and stored until needed for irrigation, usually on nearby fields. Small, simple ponds with plastic linings provide a practical and cheaper alternative for individual farmers (Mohamed, 2005).

Chapter 4

Role of the public sector

The role of the public sector in geothermal energy development is to promulgate the necessary policy coordination and legislation and provide fiscal incentives to attract investors. Governments allocate geothermal resources and coordinate donor funding and bilateral borrowing. Other government roles are in facilitating exploration for geothermal resources and promoting research into potential uses of geothermal energy. Governments can also extend guaranteed concessionary funding to investors to increase investments in geothermal energy development.

In some countries, regional bodies may be responsible primarily for the integrated management of natural and physical resources and the regulation of food protection and biosecurity within each region.

Other ways in which the public sector can support the development and use of geothermal resources include (Clean Energy Council, 2011):

- providing loan guarantees for pilot projects, so that unsuccessful projects do not have to repay loans in full;
- funding feasibility studies, to encourage private insurance companies to cover the risks of developing geothermal resources and commercial banks to invest in geothermal development projects at earlier stages of their implementation;
- promoting structured soft loan programmes that provide developers with support throughout a project.

Kenya is one of the most successful countries in using geothermal energy for both electric power generation and direct uses. The Government of Kenya has approved several acts of parliament that work together to regulate and guide geothermal use in a sustainable manner (Table 5). Such legislation plays an important role in ensuring the sustainable development of geothermal resources (Mwangi-Gachau, 2009).

In addition to passing national legislation, the Government of Kenya has also signed important international treaties and conventions such as the United Nations Framework Convention on Climate Change, the Convention on Biological Diversity and the Ramsar Convention on Wetlands of International Importance. Those could have implications for geothermal development in the country (Mwangi-Gachau, 2009).

The Government of Kenya has invited private investors to participate in the exploitation of geothermal resources and promotes investments in renewable energy research and development through policy developments such as support to public-private partnerships, feed-in tariffs and the backing of loans. Major incentives backed by legal policies are needed to make geothermal development more attractive to the private sector. To encourage foreign investors, the Government of Kenya allows both Kenyans and non-Kenyans to hold foreign currency and

TABLE 5

Legislation concerning geothermal development approved by the Government of Kenya

Legislation	Area regulated
Geothermal Resources Act No. 12 of 1982	Licences for geothermal resource exploration
Geothermal Resources Regulation of 1990	(Refer to Geothermal Resources Act)
Electricity Power Act No. 11 of 1997	
Environmental Management and Coordination Act of 1999	Environmental impact audit for new projects Annual audits for existing projects
Factories Act (CAP 514)	Safety and protection of people working in factories
Water Act (CAP 372)	Extraction of water
Public Health Act (CAP 242) of 1921, revised in 1986	Sanitation in public places
Wildlife Conservation and Management Act (CAP 376)	Conservation of wildlife resources
Forests Act (CAP 385)	Consultation with government on research and development within a public forest
Fisheries Act (CAP 378)	Water discharge licences
Lakes and Rivers Act (1983 revision)	Conservation of catchment areas and licensing of activities around lakes and rivers
Use of Poisonous Substances Act	Threshold limits
Agriculture Act (CAP 372)	Sustainable development
Energy Act 2005	Energy audits

Source: Mwangi-Gachau, 2009.

foreign currency bank accounts, does not restrict the repatriation of income, and provides tax incentives for foreign investors along with other conducive tax policies (Ngugi, 2012). Kenyan experience shows that multilateral, bilateral, private and other entities are less willing to finance resource exploration and assessments than other phases of geothermal development. Government investment therefore plays a crucial role in opening up and preparing geothermal projects. If these initiatives are successful, other entities step in with funds for subsequent phases (Ngugi, 2012). Establishment of the Geothermal Development Company as a government body has given Kenya access to support from and collaboration with international financial institutions and financiers. The participation of stakeholders in early stages of a project can help build support from communities in the areas where geothermal development activities are being implemented.

Chapter 5

Constraints and challenges

The main constraints and challenges to the use of geothermal energy in the agricultural and food industries of developing countries are: i) policy and regulatory barriers; ii) technical barriers; and iii) financial barriers.

5.1 POLICY AND REGULATORY BARRIERS

- Government policies and legislation are important factors in creating an enabling environment for geothermal investment and resource mobilization and in encouraging investments from the domestic and foreign private sector. However, few governments have clear policies that promote the use of geothermal energy, and budgetary allocations to geothermal energy research and development tend to be low in developing countries.
- Most developing countries lack the financial resources to make the necessary investments in geothermal exploration and utilization. The legislative framework is inadequate for attracting private or foreign investment in geothermal projects. Governments can play a very important role in initiating geothermal projects by financing the early phases (i.e., exploration and appraisal). However, this requires the right policy environment, which is lacking in most cases.
- A successful geothermal system requires the right institutional framework, and coordination and consultation among relevant stakeholders. These are lacking in most developing countries, preventing the development of synergies and complementarity.

5.2 TECHNICAL BARRIERS

- Technical expertise is crucial for developing geothermal systems. A critical mass of policy analysts, economic managers, engineers and other professionals is required. However, there is a continuing shortage of qualified personnel in most developing countries.
- Infrastructure to support geothermal systems is often lacking or inadequate, including transport systems and communication networks.

5.3 FINANCIAL BARRIERS

- The high upfront cost of geothermal energy technologies is one of the main barriers to geothermal energy investments in resource-constrained economies. As noted in the section on Policy and regulatory barriers, most developing countries lack the financial resources to enable investments in the development of geothermal systems. The shortage of funding for certain phases of geothermal energy deployment discourages investors from undertaking the crucial first steps, such as energy resource assessments or feasibility studies for geothermal energy

projects. The limited availability of public funds often leads to competition for financial resources among different sectors, which may restrict the availability and allocation of funds to the geothermal energy sector.

- Financing plays an important role in geothermal programmes. The challenge often faced in the financing of geothermal energy projects is in developing models that can provide technologies and services to consumers at affordable prices while ensuring that the industry remains sustainable.
- The conditions laid down by financial institutions are often not suitable for – and may even act as a deterrent to – potential investors.

Chapter 6

Conclusions

It is evident from the report that geothermal energy has the potential to provide long-term and secure base-load energy for the agricultural and food industries. Geothermal energy is already used in these industries in many countries, but geothermal development has been slow in most. The main constraints and challenges impeding the use of geothermal energy in the agricultural and food industries are policy, regulatory, technical and financial barriers. Governments of developing countries have to take into consideration these constraints and challenges. Once the constraints have been addressed, a moderate increase in direct utilization can be expected in the future. Geothermal energy has both the technical and economic potential to facilitate the development of a range of added-value agricultural products (Andritsos, Fytkikas and Kolios, 2009).

References

- Abdullah, K. & Gunadnya, I.B.P. 2010. Use of geothermal energy for drying and cooling purposes. In *Proceedings of the 2010 World Geothermal Congress*, 25–29 April 2010, Bali, Indonesia.
- Andritsos, N., Dalampakis, P. & Kolios, N. 2003. Use of geothermal energy for tomato drying. *Geo-Heat Center Quarterly Bulletin*, 24: 9–13.
- Andritsos, N., Fytikas, M. & Kolios, N. 2009. Greek experience with geothermal energy use in agriculture and food processing industry. In *Proceedings of the International Geothermal Days Slovakia 2009 – Conference and Summer School*, 26–29 May 2009, Častá-Papiernička, Slovakia, Session III. 3.
- Arason, S. 2003. The drying of fish and utilization of geothermal energy; the Icelandic experience. In *Proceedings of the International Geothermal Conference*, 14–17 September 2003, Reykjavik, pp. 21–31.
- Barbier, E. 2002. Geothermal energy technology and current status: an overview. *Renewable and Sustainable Energy Reviews*, 6(1–2): 3–65.
- Beall, S.E. & Samuels, G. 1971. *The use of warm water for heating and cooling plant and animal enclosures*. Report No. ORNL-TM-3381. Oak Ridge, Tennessee, USA, Oak Ridge National Laboratory. (56 pp.)
- Beate, B. & Salgado, R. 2010. Geothermal country update for Ecuador, 2005–2010. In *Proceedings of the 2010 World Geothermal Congress*, April 25–29 2010, Bali, Indonesia, Paper No. 0160.
- Bjornsson, S., ed. 2006. *Geothermal development and research in Iceland*. Reykjavik, National Energy Authority and Ministries of Industry and Commerce.
- Bourouni, K., Chaibi, M.T. & Tadrist, L. 2001. Water desalination by humidification and dehumidification of air: state of the art. *Desalination*, 137(1–3): 167–176.
- Boyd, T.L. & Lund, J.W. 2003. Geothermal heating of greenhouses and aquaculture facilities. In *Proceedings of the International Geothermal Conference*, 14–17 September 2003, Reykjavik, pp. 14–19.
- British Geological Survey. no date. Geothermal energy – what is it? Available at: <http://www.bgs.ac.uk/research/energy/geothermal/> (accessed 1 May 2014)
- Burgess, W.G. 1989. Geothermal energy. *Geology Today*, 5(3): 88–92.
- Chandrasekharam, D. & Chandrasekhar, V. 2010. Geothermal energy resources, India: country update. In *Proceedings of the 2010 World Geothermal Congress*, 25–29 April 2010, Bali, Indonesia, Paper No. 0105.
- Chou, S.K. & Chua, K.J. 2001. New hybrid drying technologies for heat sensitive foodstuffs. *Trends in Food Science and Technology*, 12(1): 359–369.
- Clean Energy Council. 2011. *Why support geothermal energy?* Position Paper. Melbourne, Australia.
- Conserve Energy Future. no date. History of geothermal energy. Available at: <http://www.conserve-energy-future.com/GeothermalEnergyHistory.php> (accessed 17 April 2014)

- Cuong, N.T., Giang, C.D. & Thang, T.T. 2005. General evaluation of the geothermal potential in Vietnam and the prospect of development in the future. In *Proceedings of the 2005 World Geothermal Congress*, 24–29 April 2005, Antalya, Turkey, Paper No. 0101.
- Dickson, M.H. & Fanelli, M. 2004. *What is geothermal energy?* International Geothermal Association. Available at: http://www.geothermal-energy.org/geothermal_energy/what_is_geothermal_energy.html (accessed 16 April 2014)
- Duffield, W.A. & Sass, J.H. 2003. *Geothermal energy – clean power from the earth's heat*. United States Geological Survey Circular No. 1249. Washington, DC, United States Department of the Interior. (36 pp.)
- FAO. 2008. *A review on culture, production and use of spirulina as food for humans and feeds for domestic animals and fish*. FAO Fisheries and Aquaculture Circular No. 1034. Rome.
- FAO. 2009. *Food security and agricultural mitigation in developing countries: options for capturing synergies*. Rome.
- FAO. 2011. “Energy-smart” food for people and climate. Issue Paper. Rome.
- Fatona, P. 2011. Renewable energy use and energy efficiency – a critical tool for sustainable development. In M. Nayeripour and M. Kheshti, eds. *Sustainable growth and applications in renewable energy sources*, pp. 49–60. Rijeka, Croatia, InTech.
- Fekraoui, A. 2010. Geothermal activities in Algeria. In *Proceedings of the 2010 World Geothermal Congress*, 25–29 April 2010, Bali, Indonesia, Paper No. 0117.
- Fridleifsson, I.B. 2001. Geothermal energy for the benefit of the people. *Renewable and Sustainable Energy Reviews*, 5(2): 299–312.
- Fridleifsson, I.B. 2013. Geothermal – Prospective energy source for developing countries. *Technika Poszukiwań Geologicznych Geotermia, Zrównoważony Rozwój*, 1: 143–158.
- Fridleifsson, I.B., Bertani, R., Huenges, E., Lund, J.W., Ragnarsson, A. & Rybach, L. 2008. The possible role and contribution of geothermal energy to the mitigation of climate change. In *IPCC Scoping Meeting on Renewable Energy Sources Proceedings*, 20–25 January 2008, Lübeck, Germany, pp. 59–80.
- Gelegenis, J., Dalabakis, P. & Ilias, A. 2006. Heating of wintering ponds by means of low enthalpy geothermal energy. The case of Porto Lagos. *Geothermics*, 35: 87–103.
- Ghomshei, M.M. 2010. Canadian geothermal power prospects. In *Proceedings of the 2010 World Geothermal Congress*, 25–29 April 2010, Bali, Indonesia.
- Goosen, M., Mahmoudi, H. & Ghaffour, N. 2010. Water desalination using geothermal energy. *Energies*, 3(8): 1423–1442.
- Gunerhan, G.G., Kocar, G. & Hepbasli, A. 2001. Geothermal energy utilization in Turkey. *International Journal of Energy Research*, 25(9): 769–784.
- Herrera, R., Montalva, F. & Herrera, A. 2010. El Salvador country update. In *Proceedings of the 2010 World Geothermal Congress*, 25–29 April 2010, Bali, Indonesia, Paper No. 0141.
- Hirunlabh, J., Thiebrat, S. & Khedari, J. 2004. Chilli and garlic drying by using waste heat recovery from a geothermal power plant. *Geo-Heat Center Quarterly Bulletin*, 25: 25–27.
- Hodges, R.J., Buzby, J.C. & Bennett, B. 2011. Postharvest losses and waste in developed and less developed countries: opportunities to improve resource use. *Journal of Agricultural Science*, 149(S1): 37–45.

- Hulata, G. & Simon, Y. 2011. An overview on desert aquaculture in Israel. In FAO. *Aquaculture in desert and arid lands: development constraints and opportunities*, V. Crespi and A. Lovatelli, eds, pp. 85–112. FAO Fisheries and Aquaculture Proceedings No. 20. Rome.
- Huttrer, G.W. 2010. Country update for eastern Caribbean island nations. In *Proceedings of the 2010 World Geothermal Congress*, 25–29 April 2010, Bali, Indonesia, Paper No. 0113.
- Ibarz, A. & Barbosa-Canovas, G.V. 2003. *Unit operations in food engineering*, pp. 652–653. Boca Raton, Florida, USA, CRC Press.
- Íslandsbanki. 2011. *U.S. geothermal industry overview*. Reykjavik, Íslandsbanki Geothermal Research.
- Johannesdottir, B., Graber, J.A. & Gudmundsson, J.S. 1986. *Samantekt um jarðvegshitaða garða* [Compilation of soil heating for vegetable production]. OS-86058/JHD-21 B. Reykjavik, Orkustofnun. (17 pp.)
- Keyan, Z. 2008. Geothermal resources and use for heating in China. Presented at the Workshop for Decision Makers on Direct Heating Use of Geothermal Resources in Asia, organized by the United Nations University Geothermal Training Programme (UNU-GTP), TBLRREM and TBGMED, 11–18 May 2008, Tianjin, China.
- Kumoro, A.C. & Kristanto, D. 2003. Preliminary study on the utilization of geothermal energy for drying of agricultural product. In *Proceedings of the International Geothermal Conference*, 14–17 September 2003, Reykjavik, Session 14.
- Lahsen, A., Muños, N. & Parada, M.A. 2010. Geothermal development in Chile. In *Proceedings of the 2010 World Geothermal Congress*, 25–29 April 2010, Bali, Indonesia, Paper No. 0118.
- Levitte, D. & Greitzer, Y. 2005. Geothermal update report from Israel 2005. In *Proceedings of the 2005 World Geothermal Congress*, 24–29 April 2005, Antalya, Turkey, Paper No. 0125.
- Lienau, P.J. 1991. Industrial applications. In P.J. Lienau and B.C. Lunis, eds. *Geothermal direct use engineering and design guidebook*, pp. 325–348. Klamath Falls, Oregon, USA, Geo-Heat Center, Oregon Institute of Technology.
- Lund, J.W. 1996. *Lectures on direct utilization of geothermal energy*. Reports 1996 No. 1. Reykjavik, United Nations University Geothermal Training Programme.
- Lund, J.W. 1997. Milk pasteurization with geothermal energy. *Geo-Heat Center Quarterly Bulletin*, 18(3): 13–15.
- Lund, J.W. 2006. Direct heat utilization of geothermal resources worldwide 2005. *ASEG Extended Abstracts*, 1: 1–15.
- Lund, J.W. 2010. Direct utilization of geothermal energy. *Energies*, 3: 1443–1471.
- Lund, J.W., Freeston, D.H. & Boyd, T.L. 2005. Direct application of geothermal energy: 2005 worldwide review. *Geothermics*, 34(6): 691–727.
- Lund, J.W., Freeston, D.H. & Boyd, T.L. 2010. Direct utilization of geothermal energy 2010 worldwide review. In *Proceedings of the 2010 World Geothermal Congress*, 25–29 April 2010, Bali, Indonesia.
- Lund, J.W., Freeston, D.H. & Boyd, T.L. 2011. Direct utilization of geothermal energy 2010 worldwide review. *Geothermics*, 40(13): 159–180.
- Lund, J.W. & Rangel, M.A. 1995. Pilot fruit drier for the Los Azufres geothermal field, Mexico. In *Proceeding of the World Geothermal Congress*, 18–31 May 1995, Florence, Italy, Vol. 3, pp. 2335–2338.

- Mahmoudi, H., Spahis, N., Goosen, M.F., Sablani, S., Abdul-wahab, S.A., Ghaffour, N. & Drouiche, N.** 2009. Assessment of wind energy to power solar brackish water greenhouse desalination units: a case study from Algeria. *Renewable and Sustainable Energy Reviews*, 13(8): 2149–2155.
- Mahmoudi, H., Spahis, N., Goosen, M.F., Ghaffour, N., Drouiche, N. & Ouagued, A.** 2010. Application of geothermal energy for heating and fresh water production in a brackish water greenhouse desalination unit: a case study from Algeria. *Renewable and Sustainable Energy Reviews*, 14(1): 512–517.
- Mangi, P.** 2012. Geothermal resource optimization: a case of the geothermal health spa and demonstration centre at the Olkaria geothermal project. Presented at Short Course VII on Exploration for Geothermal Resources, organized by UNU-GTP, GDC and KenGen, October 27–18 November 2012, Lake Naivasha, Kenya. (10 pp.)
- Mburu, M.** 2009. Geothermal energy utilization. Presented at Short Course IV on Exploration for Geothermal Resources, organized by UNU-GTP, GDC and KenGen, 27 October–18 November 2012, Lake Naivasha, Kenya. (22 pp.)
- Mburu, M.** 2012. Cascaded use of geothermal energy: Eburru case study. *Geo-Heat Center Quarterly Bulletin*, 30(4): 21–26.
- Mertoglu, O., Simsek, S., Dagistan, H., Bakir, N. & Dogdu, N.** 2010. Geothermal country update report of Turkey (2005–2010). In *Proceedings of the 2010 World Geothermal Congress*, 25–29 April 2010, Bali, Indonesia, Paper No. 0119.
- Mohamed, M.B.** 2005. Low enthalpy geothermal resources application in the Kebbili region, Southern Tunisia. In *Proceedings of the 2005 World Geothermal Congress*, 24–29 April 2005, Antalya, Turkey.
- Muffler, P. & Cataldi, R.** 1978. Method for regional assessment of geothermal resources. *Geothermics*, 7(2–4): 53–89.
- Mwangi-Gachau, E.** 2009. Legal requirements for geothermal developments in Kenya. Presented at Short Course IV on Exploration for Geothermal Resources, organized by UNU-GTP, GDC and KenGen, 1–22 November 2009, Lake Naivasha, Kenya.
- National Academy of Sciences.** 1978. *Postharvest food losses in developing countries*. Washington, DC, National Research Council, Board of Science and Technology for International Development. (206 pp.)
- Ngugi, P.K.** 2012. Financing the Kenya geothermal vision. Presented at Short Course on Geothermal Development and Geothermal Wells, organized by UNU-GTP and LaGeo, 11–17 March 2012, Santa Tecla, El Salvador. (11 pp.)
- NREL.** 1998. *Geothermal technologies today and tomorrow: direct use of geothermal energy*. Factsheet No. DOE/GO-10098-536. Washington, DC, National Renewable Energy Laboratory, United States Department of Energy. (2 pp.)
- Ogena, M.S., Maria, R.B.S., Stark, M.A., Oca, R.A.V., Reyes, A.N., Fronda, A.D. & Bayon, F.E.B.** 2010. Philippines: country update: 2005–2010 geothermal energy development. In *Proceedings of the 2010 World Geothermal Congress*, 25–29 April 2010, Bali, Indonesia, Paper No. 0149.
- Ogola, P.F.A.** 2013. *The power to change: creating lifeline and mitigation-adaptation opportunities through geothermal energy utilization*. Reykjavik, University of Iceland, Faculty of Life and Environmental Sciences, School of Engineering and Natural Sciences. (Ph.D. dissertation)

- Ogola, P.F.A., Davidsdottir, B. & Fridleifsson, I.B. 2012. Potential contribution of geothermal energy to climate change adaptation: a case study of the arid and semi-arid eastern Baringo lowlands, Kenya. *Renewable and Sustainable Energy Reviews*, 16(6): 4222–4246.
- Panagiotou, C. 1996. *Geothermal greenhouse design*. Reports 1996 No. 11. Reykjavik, United Nations University Geothermal Training Programme (32 pp.)
- Perko, B. 2011. Effect of prolonged storage on microbiological quality of raw milk. *Mljekarstvo*, 61(2): 114–124.
- Popovski, K. 2009. Agricultural and industrial uses of geothermal energy in Europe. In *Proceedings of the International Geothermal Days Slovakia 2009 – Conference and Summer School*, 26–29 May 2009, Častá-Papiernička, Slovakia, Session III.1. (11 pp.)
- Popovski, K. & Vasilevska, S.P. 2003. Heating greenhouses with geothermal energy. In *Proceedings of the International Geothermal Workshop*, 6–10 October 2003, Sochi, Russian Federation. Paper No. W00037, 17 pp.
- Popovski, K., Dimitrov, K., Andrejevski, B. & Popovska, S. 1992. Geothermal rice drying unit in Kotchany, Macedonia. *Geothermics*, 21(5–6): 709–716.
- Rafferty, K.D. 1996. Greenhouses. In *Geothermal direct use engineering and design guidebook*, Chapter 14, pp. 307–326. Klamath Falls, Oregon, USA, Geo-Heat Center.
- Ragnarsson, A. 2003. Utilization of geothermal energy in Iceland. In *Proceedings of the International Geothermal Conference*, Reykjavik, 14–17 April 2003, pp. 39–45.
- Ragnarsson, A. 2008. Utilization of geothermal energy in Iceland. In *Proceedings of the 14th Building Services, Mechanical and Building Industry Days – International Conference*, 30–31 October 2008, Debrecen, Hungary.
- Ranjit, M. 2010. Geothermal energy update of Nepal. In *Proceedings of the 2010 World Geothermal Congress*, 25–29 April 2010, Bali, Indonesia, Paper No. 0146.
- Sablani, S., Goosen, M.F., Paton, C., Shayya, W.H. & Al-Hinai, H. 2003. Simulation of fresh water production using a humidification-dehumidification seawater greenhouse. *Desalination*, 159(3): 283–288.
- Saffarzadeh, A., Porkhial, S. & Taghaddosi, M. 2010. Geothermal energy developments in Iran. In *Proceedings of the 2010 World Geothermal Congress*, 25–29 April 2010, Bali, Indonesia, Paper No. 0126.
- Sekioka, M. 1999. Japanese geothermal waters through history. In R. Cataldi, S.F. Hodgson and J.W. Lund, eds. *Stories from a heated earth: our geothermal heritage*, pp. 393–406. Davis, California, USA, Geothermal Resources Council and International Geothermal Association.
- Senadeera, W., Bhandari, B.R., Young, G. & Wijesinghe, B. 2005. Modeling dimensional shrinkage of shaped foods in fluidized bed drying. *Journal of Food Processing and Preservation*, 29: 109–119.
- Serpen, U., Aksoy, N. & Ongur, T. 2010. 2010 present status of geothermal energy in Turkey. In *Proceedings of the Thirty-Fifth Workshop on Geothermal Reservoir Engineering*, 1–3 February 2010, Stanford University, Stanford, California, USA.
- Simiyu, S.M. 2010. Status of geothermal exploration in Kenya and future plans for its development. In *Proceedings of the 2010 World Geothermal Congress*, 25–29 April 2010, Bali, Indonesia, Paper No. 0169.
- Solcomhouse. no date. Geothermal energy. Available at: <http://solcomhouse.com/geothermal.htm> (accessed 17 April 2014)

- Song, Y., Kim, H. & Lee, T.J.** 2010. Geothermal development in Korea: country update 2005–2009. In *Proceedings of the 2010 World Geothermal Congress*, 25–29 April 2010, Bali, Indonesia, Paper No. 0121.
- Tester, J.W., Anderson, B.J., Batchelor, A.S., Blackwell, D.D., DiPippo, R., Drake, E.M., Garnish, J., Livesay, B., Moore, M.C., Nichols, K., Petty, S., Toksoz, M.N. & Veatch, R.W. Jr.** 2006. *The future of geothermal energy – impact of enhanced geothermal systems (EGS) on the United States in the 21st century*. An assessment by an MIT-led interdisciplinary panel. Cambridge, Massachusetts, USA, Massachusetts Institute of Technology.
- Thiebrat, S.** 1997. *Chili and garlic drying by using waste heat recovery from a geothermal power plant*. Bangkok, King Mongkut's Institute of Technology. (Master's thesis).
- Torkar, K.G. & Golc Teger, S.** 2008. The microbiological quality of raw milk after introducing the two days' milk collection system. *Acta agriculturae Slovenica*, 92(1): 61–74.
- Vasquez, N.C., Bernardo, R.O. & Cornelio, R.L.** 1992. Industrial uses of geothermal energy a framework for application in a developing country, *Geothermics*, 21(5–6): 733–743.
- von Zabeltitz, C.** 1986. Greenhouse heating with solar energy. *Energy in Agriculture*, 5(2): 111–120.
- World Energy Council.** 2002. *Survey of energy resources 2001*. London.
- Zheng, K., Han, Z. & Zhang, Z.** 2010. Steady industrialized development of geothermal energy in China: country update report 2005–2010. In *Proceedings of the 2010 World Geothermal Congress*, 25–29 April 2010, Bali, Indonesia, Paper No. 0136.



Uses of geothermal energy in food and agriculture

Opportunities for developing countries

Agriculture and agro-industry are important sectors in the economies of most developing countries, where they provide the main source of livelihoods for the majority of the poor. The lack of a sustainable supply of affordable energy is a major constraint to the development of these sectors in developing countries.

Traditionally, geothermal energy has been utilized mainly to generate electricity; however, it can be harnessed for other important uses in agriculture and agro-industry. Developing countries endowed with this renewable energy source have ample potential to use it in advancing their agriculture and agro-industry sectors.

This book reviews the use of geothermal energy in agriculture and agro-industry around the world. With a simple format and copious illustrations and models, the book is accessible to a wide range of interested readers, including those with no technical background. It shows that geothermal resources have the potential to provide long-term, secure energy for the agriculture and food industry in both developed and developing countries. Constraints and challenges that should be addressed before this potential can be fully achieved are also discussed.

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Viale delle Terme di Caracalla, 00153 Rome, Italy
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ISBN 978-92-5-108656-8



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I4233E/1/02.15