1

Geothermal Energy Project Considerations

1.1 Overview

The main focus of this book is geothermal heat pump applications for buildings. However, this first chapter first introduces readers to general considerations for renewable/clean energy project analysis. Then, specifics of geothermal energy projects are discussed through broad considerations of geothermal energy utilization, of which geothermal heat pumps is just one type. Elements of geothermal energy systems are discussed, laying the foundation for the organization of material in this book.

The chapter describes geothermal energy from the perspective of resource temperature in the context of high-, medium-, and low-temperature applications, emphasizing that the end use of the energy, at least in theory, can be any application where thermal energy is involved.

Learning objectives and goals:

1. Be aware of favorable conditions for alternative energy projects.
2. Understand general decision analysis of renewable/clean energy systems.
3. Draw analogies between geothermal and other renewable energy system analysis.
4. Appreciate the role of resource temperature in defining a geothermal energy project.
5. Appreciate the inherent risks in undertaking a renewable/clean energy project.
6. Realize the similarities in project development in all geothermal energy projects.

1.2 Renewable/Clean Energy System Analysis

Energy project stakeholders, investors, and decision-makers are mainly interested in project viability and feasibility. RetScreen® International (2004) provides a good discussion for general decision-making. For conventional and especially for renewable/clean energy projects

Geothermal Heat Pump and Heat Engine Systems: Theory and Practice, First Edition. Andrew D. Chiasson.

Companion website: www.wiley.com/go/chiasson/geoHPSTP

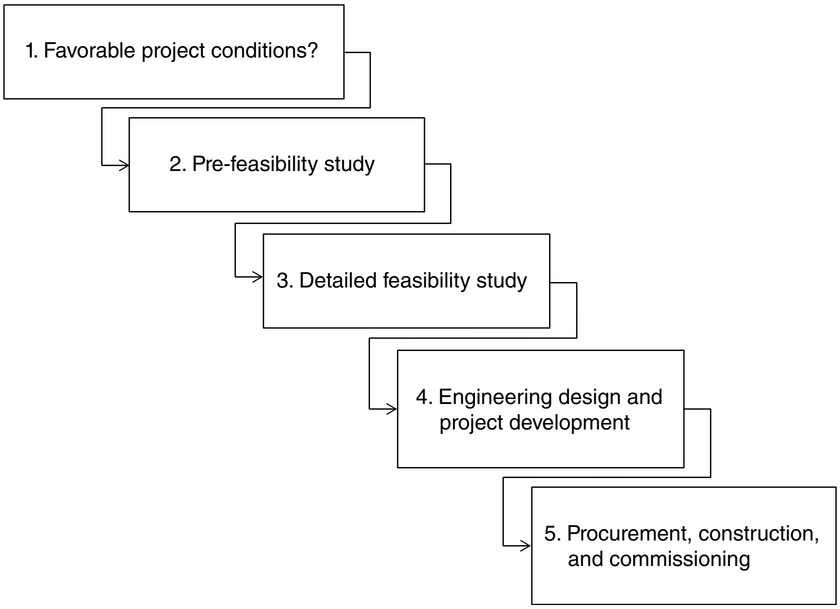

Figure 1.1 General flow of conventional and alternative energy projects

under consideration, Figure 1.1 shows general steps taken for advancing such projects to completion. At each step, a 'go/no-go' decision can be made by stakeholders as to whether or not to proceed to the next step of the development process. Thorough and accurate pre-feasibility and detailed feasibility studies are critical to helping the project owner reject projects or scenarios that do not make sense, either from a financial, regulatory, logistical, or other perspective. Accurate pre-feasibility and detailed feasibility analyses also facilitate development and engineering efforts prior to construction. The tools and techniques presented in this book are, in part, aimed toward that end.

The discussion that follows describes the boxes shown in Figure 1.1.

Favorable Project Conditions. In general, many decision-makers are not familiar with implementation of renewable/clean energy technologies and when they should be considered. The author has seen many misconceptions regarding the use of geothermal energy. One common misconception is, 'If you have a high temperature geothermal resource, you essentially have a gold mine'. The reality is: Does the capital exist to develop the resource? What is the revenue stream for the energy? Is there a business plan or a market for the energy? Who will operate and maintain any equipment? Another common misconception is, 'Geothermal heat pumps can be applied everywhere', but the reality is: How easy is your building to retrofit to a heat pump system? What's really underground at your site? How sustainable will the reservoir be? Are there qualified contractors in your area?

Renewable/clean energy systems are typically capital intensive, with low operating costs that are usually weighed against the operating cost of a conventional energy system. The following is a general set of conditions as to when a renewable/clean energy project might be considered:

1. **Need for an energy system.** An opportune time for considering a renewable/clean energy system is when an energy system is being planned or replaced. The capital cost of the

renewable/clean energy system can be offset by the avoided cost of the conventional system. In retrofit cases, for example in buildings, retrofitting the building to be compatible with a renewable/clean energy system may be prohibitive.

2. **High Conventional Energy Costs.** Obviously, when conventional energy costs are high, the relatively low energy cost of a renewable/clean energy system is attractive. Thus, interest in renewable/clean energy systems is typically proportional to conventional energy costs.
3. **Available Funding and Financing.** The relatively higher capital cost of renewable/clean energy projects is often a substantial barrier. Some jurisdictions promote clean energy projects with financial incentives, such as grants and tax rebates. Some companies offer third-party ownership of renewable/clean energy projects, where they bear the cost of the project and sell lower-cost energy to the project proponent.
4. **Qualified Contractors, Installers, and Maintenance Personnel.** Renewable/clean energy systems (particularly geothermal heat pump systems) typically involve specialized, non-traditional training and certification. If qualified personnel are not local, installation costs can become prohibitive. At early stages of a project, complexity of the system should also be considered; local availability of qualified personnel for system maintenance may eliminate a project from consideration.
5. **Persistent Project Stakeholders.** Seeing a renewable/clean energy project through to completion, especially a complex one, can be a daunting task. Diligent project management is required, involving coordination of numerous trades, monitoring budgets, navigation through complicated regulations, and, perhaps most of all, persistence.
6. **Simple Legal and Permitting Processes.** Development costs and schedule delays are minimized when laws and regulations are understood by the project team, and when these laws and regulations do not unfairly disadvantage a renewable/clean energy project.
7. **Adequate, Sustainable Resource.** An adequate resource is necessary for any renewable/clean energy project. However, special considerations are needed for geothermal resources, which are discussed in Chapter 3. In particular, a geothermal venture involves risk because the resource cannot be completely observed with depth. Further, the resource is finite, and proper resource management is necessary.

Pre-Feasibility Study. The pre-feasibility analysis determines whether the proposed project has a good chance of satisfying the owner's requirements for profitability and/or cost-effectiveness. It is characterized as a 'desktop' study, involving the use of readily available site and resource data, ±30–50% cost estimates, and simple calculations and professional judgement often involving experience with other projects. For geothermal projects, a site visit is very important to observe surface features, access, and potential site barriers. A conceptual model of the resource is generally produced.

Detailed Feasibility Study. As the name implies, this is more in-depth analysis of the project's viability. A detailed feasibility study must provide information about the physical characteristics, financial viability, and environmental, social, or other impacts of the project, such that the owner can come to a decision about whether or not to proceed. It is characterized by the collection of refined site, resource, cost, and equipment data. For geothermal projects, the resource is fully defined, which typically involves drilling and measuring of thermal exchange properties. A conceptual model of the resource is refined and completed. In some cases, detailed computer simulation is undertaken. Project costs are refined through solicitation of price information from equipment suppliers.

Engineering and Development. If, based on the feasibility study, the project owner decides to proceed with the project, then engineering and development are the next step. Engineering includes the planning and technical design of the physical aspects of the project. Development involves the planning, arrangement, and negotiation of financial, regulatory, contractual, and other non-physical or 'soft' aspects of the project. Some development activities, such as training, customer relations, and community consultations, extend through the subsequent project stages of construction and operation. Even following significant investments in engineering and development, the project may be postponed or abandoned prior to construction because financing cannot be arranged, environmental approvals cannot be obtained, the pre-feasibility and feasibility studies overlooked important cost items, qualified contractors are not available, or for other reasons.

Procurement, Construction, and Commissioning. Finally, the project is built and put into operation. Prior to turning the project over to the owner, a proper commissioning process is key. The commissioning process involves a set of procedures to verify that all components of the system are operational, and that the system functions as it was intended and designed.

1.3 Elements of Renewable/Clean Energy Systems

The study of renewable energy systems can, in general, be subdivided into the following five elements: (i) energy loads and resource characteristics, (ii) harnessing the energy, (iii) energy conversion (to useful energy), (iv) optional energy storage, and (v) energy distribution.

Figure 1.2 shows these elements specific to geothermal energy systems. It should be emphasized that these elements are not mutually exclusive, but rather they are useful for

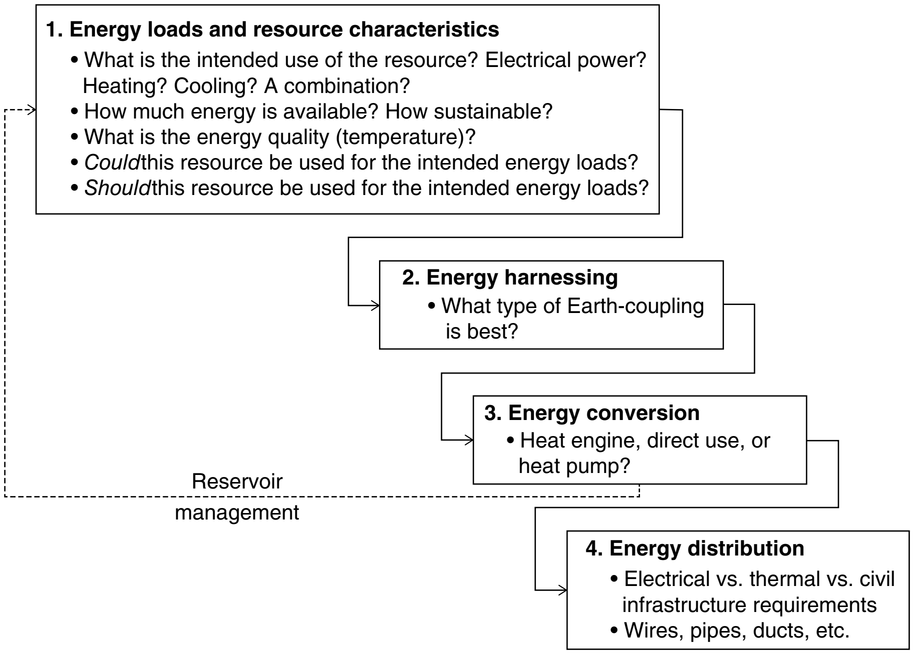

Figure 1.2 Elements of geothermal energy systems

understanding energy system components. Regarding geothermal projects, these elements can, however, and often do, represent the various specialty areas. For example, consulting scientists and engineers may be involved in resource characterization and/or resource harnessing, but not in the conversion or energy distribution stages.

Thus, the study of geothermal energy systems as presented in this book follows the aforementioned four elements of the system. Following this introductory chapter, Part I addresses energy loads and the geothermal resource. Part II covers the numerous Earth-coupling types used to harness stored thermal energy for geothermal heat pump applications. Part III discusses the various methods for converting geothermal energy to useful energy. Finally, Part IV discusses methods for distributing the energy. The focus of each part is on geothermal heat pumps, but higher-temperature geothermal applications are intermixed to give readers a broader perspective of the similarities of geothermal projects.

1.4 Geothermal Energy Utilization and Resource Temperature

We will see in Chapter 3 that there are a number of factors that dictate the end use of a geothermal resource, but the end use ultimately depends on the resource temperature. Thus, there have been a number of classification methods aimed at categorizing geothermal resources by temperature. Here, we will use the following gross temperature categories:

(a) high-temperature uses: $T_{resource} > 150\ ^\circ C$
(b) medium-temperature uses: $90\ ^\circ C < T_{resource} < 150\ ^\circ C$
(c) low-temperature uses: $30\ ^\circ C < T_{resource} < 90\ ^\circ C$
(d) ambient temperatures (heat pump uses): $\sim 0\ ^\circ C < T_{resource}$

Note that there is no distinct break between categories. The geothermal power industry typically uses only the top three temperature categories (a, b, and c), based on cut-off temperatures of economical electric power generation, which has historically not been economical for resources with temperatures below about 150 °C. However, binary organic Rankine cycle power plants, under favorable circumstances, have demonstrated that it is possible to generate electricity economically above 90 °C. A fourth category (d) is added here to distinguish the geothermal heat pump applications.

Figure 1.3 shows some of the many past and/or current uses of geothermal energy worldwide. As shown in this figure, there are many other ‘high-temperature’ resource use possibilities aside from electric power generation. Many of the medium-temperature uses are termed ‘direct uses’ because there is no energy conversion process, and the resource temperature matches or exceeds that required by the load. However, as noted in Figure 1.3, ambient groundwater can also be used for direct cooling applications.

1.5 Geothermal Energy Project History and Development

In the geothermal industry, projects are typically identified by their end use and associated resource temperature. Thus, power plant projects are associated with high-temperature reservoirs, direct-use projects are associated with low- to medium-temperature reservoirs, and geothermal heat pump projects are associated with ambient-temperature reservoirs. Note that,

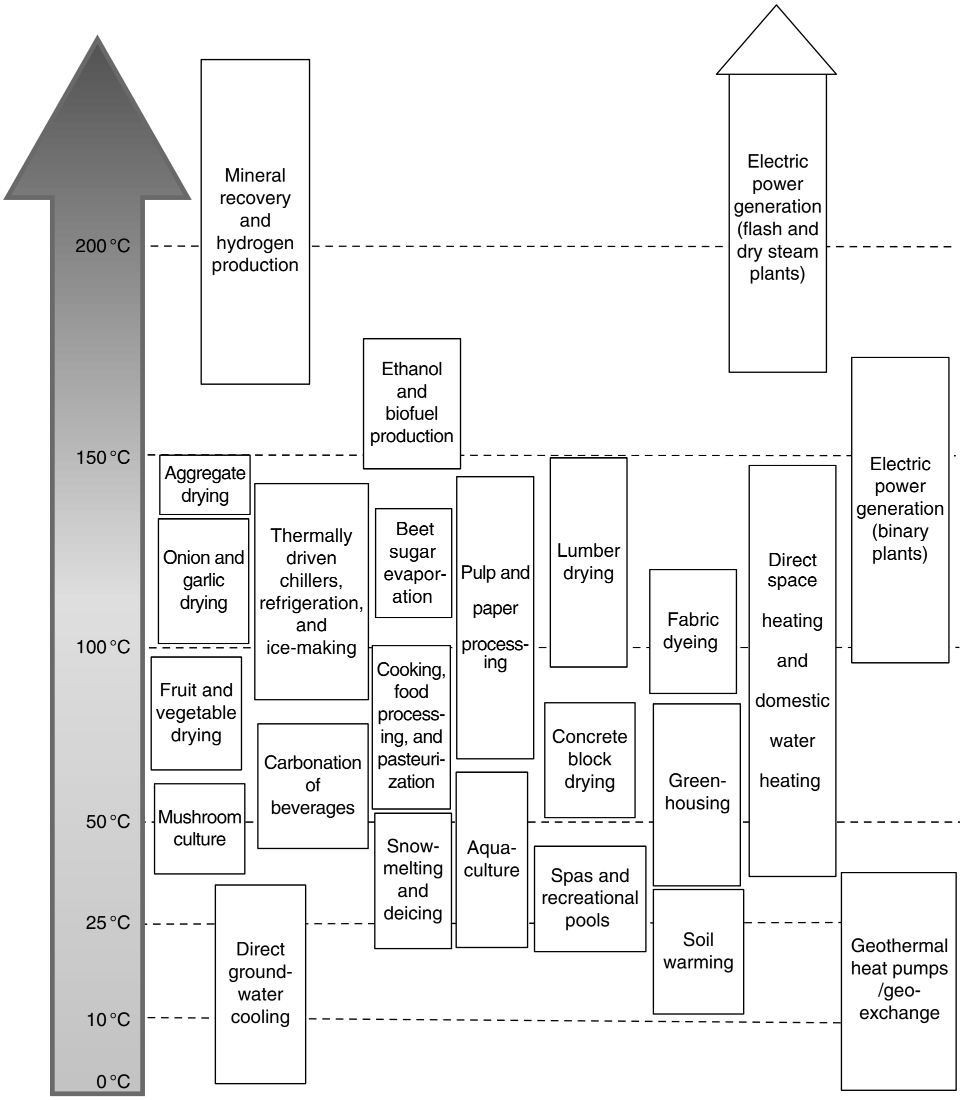

Figure 1.3 Worldwide past and present utilization of geothermal energy based on resource temperature

strictly speaking, such a classification scheme is ambiguous because the term 'direct use' means that the resource is used directly owing to its temperature match to the load, and thus a direct-use application can occur over a large temperature range. Further, thermally driven heat pump applications are utilized with moderate-temperature resources. Nevertheless, in the subsections that follow, we will use these descriptors to illustrate typical development of geothermal projects.

1.5.1 Geothermal Power Plants

1.5.1.1 Overview

The first geothermal power was generated at Larderello, Italy, in 1904. According to Lund (2007), the first commercial power plant (250 kW) was commissioned in 1913 at Larderello, Italy. Owing to the impurity of the geothermal fluids, steam was generated in a secondary loop isolated from the geothermal fluids by a heat exchanger. In the United States, an experimental 35 kW plant was installed at The Geyers geothermal field, California, in 1932, and provided power to the local resort. These developments were followed in New Zealand at Wairakei in 1958, an experimental plant at Pathe, Mexico, in 1959, and the first commercial plant at The Geysers in the United States in 1960. Japan followed with 23 MW at Matsukawa in 1966. All of these early plants used steam directly from the Earth (dry steam fields), except for New Zealand, which was the first to use flashed or separated steam.

According to Lund (2007), Iceland first produced power at Namafjall in northern Iceland, from a 3 MW non-condensing turbine. This was followed by plants in El Salvador, China, Indonesia, Kenya, Turkey, Philippines, Portugal (Azores), Greece, and Nicaragua in the 1970s and 1980s. Later plants were installed in Thailand, Argentina, Taiwan, Australia, Costa Rica, Austria, Guatemala, and Ethiopia, with the latest installations in Germany and Papua New Guinea.

The first medim-temperature geothermal binary power plant was put into operation at Paratunka near the city of Petropavlovsk on Russia's Kamchatka peninsula in 1967. It was rated at 670 kW and served a small village and some farms with both electricity and heat for use in greenhouses. It ran successfully for many years, proving the concept of binary plants as we know them today (DiPippo, 2012). Lund and Boyd (1999) list and describe the operation of 34 small geothermal power projects around the world, over 20 of which are binary. Many of these were installed in the 1980s and have (had) decades of successful operation. Notable installations since that time include Chena Hot Springs, Alaska (plant installed 2006), and the Oregon Institute of Technology, Klamath Falls, Oregon (plants installed 2009 and 2014), where ORC geothermal plants have been operating with resource temperatures of 74 and 90 °C respectively.

Bertani (2015) reports on worldwide geothermal power generation. As of 2015, approximately 25 countries have geothermal power plant installations, adding up to a total worldwide capacity of over 12 GW. The projected worldwide capacity is over 21 GW by 2020.

As we will discuss in Chapter 3, currently operating geothermal power plants make use of so-called hydrothermal resources. Other types of resource exist, but their utilization is still considered a developing and emerging use. The main types of geothermal power plant are summarized in Table 1.1: (i) binary, (ii) flash steam, and (iii) dry steam.

In binary power plants (discussed in detail in Chapter 14), the geothermal fluid remains liquid. The geothermal fluid exchanges heat with a lower-boiling-point working fluid, which is expanded through a turbine or other prime mover. The working fluid is then condensed back to liquid and operates in a closed cycle. On the other hand, in flash-steam plants (Figure 1.4), a two-phase geothermal fluid is extracted from wells and is separated near the well head into steam and water fractions. The steam fraction is expanded through a turbine, condensed, and returned to the geothermal reservoir in an open system. Dry steam plants are similar to flash plants, except that the geothermal fluid is in the superheated vapor state when extracted.

Table 1.1 Summary of Geothermal Power Plant Types

Power plant type	Geothermal resource	Working fluid	Occurrence
Binary cycle	Single-phase fluid (compressed liquid)	Engineered fluid (low-boiling-point refrigerant or hydrocarbon)	Most common type (generally considered feasible at resource temperatures up to ~175 °C)
Flash-type	Two-phase fluid	Geothermal fluid	Moderately common
Dry steam	Single-phase fluid (superheated vapor)	Geothermal fluid	Very rare (only a few plants worldwide)

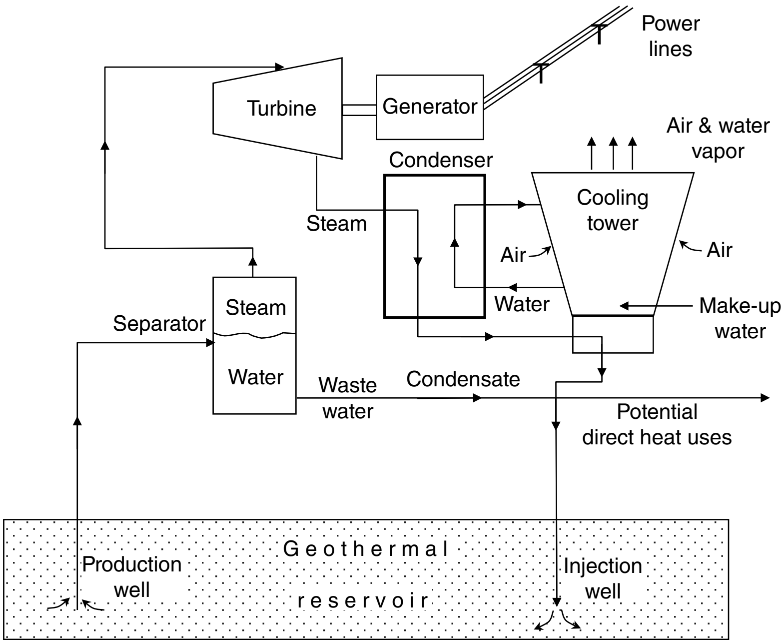

Figure 1.4 Schematic of a flash steam geothermal power plant

The development of a geothermal power plant can take up to several years, depending on what is known about the resource at the outset of a project. Resource prospectors must first determine where a viable resource might be, and then work toward acquiring access to the resource.

1.5.1.2 Geothermal Power Plant Project Development

Here, we define ‘project development’ as the process that takes a project from concept to construction and implementation. In reference to Figure 1.1, favorable project conditions for a high-temperature geothermal resource may begin with reconnaissance-type work. This phase is typically conducted by a geoscience consulting firm, and may take up to one year to complete, and account for about 3% of the total project costs. A regional study is conducted, typically examining thousands of square kilometers with the objective of selecting target areas for further examination. Available geoscience information is synthesized, and low-cost, rapid field studies may be conducted, such as basic geological mapping, geochemical sampling, aerial photography, and remote sensing. Construction of reservoir conceptual models is also begun.

The pre-feasibility phase consists of a more concentrated study of potential target areas, and is also typically conducted by a geoscience consulting firm. This phase may take up to two years to complete, and accounts for another 3% of the total project costs. This phase focuses on areas up to hundreds of square kilometers, with the primary objective of developing a preliminary geological model to form the basis of siting deep exploratory boreholes. Surface exploration studies to define subsurface structure, typically consisting of geophysical studies (i.e., gravity, magnetic, resistivity, seismic) and possibly additional geochemical work, are carried out. Temperature gradient holes to determine subsurface heat flow may also be drilled. A significant barrier to this phase is obtaining site access and regulatory approvals.

The detailed feasibility phase is aimed at resource confirmation. This phase may take up to two years to complete, and may account for about 5% of the total project cost. Personnel involved generally include a geoscience consulting firm, a reservoir engineering firm, and a drilling firm. This phase typically involves deep drilling and logging of exploratory wells to reach the geothermal reservoir, with the main objective of supporting and refining the geothermal model. Exploratory wells should also be used to make quantitative assessments of the available resource (one to five wells are typical). If a suitable resource is discovered, the exploratory wells are ideally used as production and injection wells for flow testing and reservoir engineering, with geochemical analysis of the geochemical fluids. A significant component of this phase also typically includes securing financing for the geothermal project. Potential barriers encountered during this phase include site access, environmental impact, and risk of not finding the resource expected.

The engineering and project development phase involves all remaining activities necessary to bring the geothermal field to full production. This phase may take up to two years to complete, and may account for about 30% of the total project cost. Personnel involved generally include a reservoir engineering firm and a drilling firm. In this phase, all final legal and regulatory permits and land acquisitions are secured. Impact studies of the project relating to the environment, ecology, and cultural issues are completed. All production and injection wells are drilled, tested, and completed, and surface piping and fluid handling systems are designed and constructed. As geothermal fields may encompass several square kilometers, the surface piping system can represent a significant portion of the total project cost (i.e., GEA (2005) reports 7%). Piping materials must be chosen that are compatible with the geothermal fluid chemistry. Potential barriers encountered during this phase include legal and regulatory permitting, cultural/community opposition to the project, and still some minor risk in not finding the resource expected.

The procurement, construction, and commissioning phase involves all remaining activities necessary to bring the geothermal power plant on line to supply electricity to the end user. This phase may take up to one year to complete, and may account for about 60% of the total project cost. Personnel involved generally include civil, mechanical, and electrical design firms. In this phase, the power plant is designed and constructed, and electrical transmission lines are designed and constructed. The final plant design (i.e., binary vs. flash steam) depends on the temperature and fluid production from the geothermal reservoir. Binary power plants are typically more cost effective at resource temperatures below about 177 °C (350 °F) (GEA, 2005). In flash plants, materials must be chosen that are compatible with the geothermal fluid chemistry. GEA (2005) reports transmission line cost estimates ranging from $168 000 to $282 000/km (in 2004 $US).

It should be noted that the project phases described above do not progress in a linear fashion. Some overlap of the phases is necessary for timely project completion. The above project development applies to large geothermal power plants, where a 'small' geothermal power plant is typically taken as less than 5 MW capacity. Geothermal project costs are highly variable and have significant economies of scale. Ormat Technologies, Inc. estimates the probable cost of a 20 MW geothermal project at $70 million (or $3500/kW). Small power plant costs can easily exceed $5000/kW. For perspective, geothermal power plants are known for providing stable, baseload power. Thus, a 1 MW geothermal power plant can supply the average electrical load to about 800–1000 homes.

1.5.2 Direct Uses of Geothermal Energy

1.5.2.1 Overview

Direct utilization of geothermal energy refers to its use for a thermal purpose, rather than to its conversion to some other form of energy such as electrical energy. In theory, then, geothermal energy can be directly used for any process or application that relies on heat, as long as the resource temperature matches the load temperatures (see Figure 1.3). The most popular direct uses of geothermal energy (excluding geothermal heat pump applications) include spas and swimming pools, space heating (including district applications), greenhouse heating, aquaculture, industrial uses, snow-melting, and agricultural drying. On a worldwide basis, of the order of 80 countries directly use geothermal energy for a thermal purpose, with spas and recreation being the most popular at approximately 50% of the total worldwide use, followed by space heating at approximately 30% of the total worldwide use.

Some authors include geothermal heat pump applications as a direct use, but that will not be the case here. The fact that a heat pump is needed for temperature amplification means that the resource temperature is too low to be used directly for heating, which contradicts the above definition of direct-use geothermal. Moderate to high geothermal fluids can be used in thermally driven (absorption or adsorption) heat pumps that produce a cooling effect for space cooling or industrial refrigeration. Thermally driven heat pumps are discussed in detail in Chapter 13.

According to Lund (2007), early humans probably used geothermal water that occurred in natural pools and hot springs for cooking, bathing, and warmth. Archeological evidence exists to suggest that the early native Americans occupied sites around these geothermal resources for over 10 000 years to recuperate from battle and to take refuge. Also according to Lund (2007), recorded history shows uses by Romans, Japanese, Turks, Icelanders, Central Europeans, and the Maori of New Zealand for bathing, cooking, and space heating. Baths in the Roman Empire and the middle kingdom of the Chinese and the Turkish baths of the Ottomans were some of the early uses of balneology. This custom has been extended to geothermal spas in Japan, Germany, Iceland, and countries of the former Austro-Hungarian Empire, the Americas and

New Zealand. Early industrial applications include chemical extraction from the natural manifestations of steam, pools, and mineral deposits in the Larderello region of Italy, with boric acid being extracted commercially from the early 1800s onwards. At Chaudes-Aigues in the heart of France, the world's first geothermal district heating system was started in the fourteenth century and is still in operation. The oldest geothermal district heating project in the United States is on Warm Springs Avenue in Boise, Idaho, going on line in 1892, which continues to provide space heating for up to 450 homes. Closed-loop, downhole heat exchangers for direct-use applications were first installed in residential wells in the late 1920s in Klamath Falls, Oregon, where some 550 direct-use geothermal wells exist today.

1.5.2.2 Direct-Use Geothermal Project Development

The development of direct-use geothermal projects is similar to that described above for power plants, with typically a much lower level of effort on resource exploration. Direct-use geothermal projects are intensely driven by economics, and thus cannot typically support an extensive exploration program. There are a number of factors that dictate direct-use project favorability, which have been summarized by Bloomquist (2006) and ASHRAE (2011). Similarly to power plant projects, these include: resource access and regulatory hurdles, level of effort needed for exploration, depth to the resource, distance between resource location and application site, well yield, allowable geothermal fluid temperature drop, resource temperature, thermal load and load factor, geothermal fluid chemical composition, and ease of geothermal fluid disposal.

Access and Regulatory Approvals. In many jurisdictions, groundwater is regulated as a resource, and thus permits and rights are required to utilize groundwater. In other jurisdictions, geothermal fluids are regulated as a mineral resource, thus requiring mineral rights. Therefore, proper water or mineral rights, in addition to land access approvals, must be obtained at the outset of a direct-use geothermal project. Local laws regarding subsurface injection requirements must also be ascertained. Competition with adjacent geothermal users and any potential royalty payments should also be understood. The cost and time to obtain such approvals may be substantial owing to the potential legal and environmental frameworks involved.

Level of Effort Needed for Exploration. Once access has been secured and all necessary regulatory approvals have been obtained, the developer may initiate a more detailed exploration program, refining whatever data were initially gathered in the reconnaissance or pre-lease phase of the development process. This phase usually consists of interdisciplinary activities of geology, geochemistry, geophysics, drilling, and reservoir engineering. These exploration activities are usually expensive, and often the economics of a direct-use activity will not support an extensive program. However, the minimum exploration and resource characteristics that are necessary include determining the depth to the resource, resource temperature, potential yield and specific capacity of wells, and chemistry of the geothermal fluid.

Depth to Resource. The cost of the wells to access the geothermal resource is typically one of the larger items in the overall cost of a direct-use geothermal system. Well cost generally increases non-linearly with resource depth. Compared with geothermal wells for electrical energy production or oil and gas wells, well depths for most direct-use geothermal projects are relatively shallow. For example, most larger direct-use geothermal systems in the United States operate with production wells at depths of less than 600 m, and many at less than 200 m (ASHRAE, 2011).

Distance Between Resource Location and Application Site. Direct use of geothermal energy must occur near the resource. This is not always the case for geothermal energy projects for electrical power generation, although these projects do have transmission costs; electrical energy can be sold to the power grid once transmitted from the resource to point of grid inter-tie. As there is no such thing as a *hot water* grid, direct-use projects must bear the transmission infrastructure costs of conveying the geothermal energy from the source to the load.

The cost of geothermal fluid transmission piping is commonly the largest cost item in the overall direct-use geothermal system (Bloomquist, 2006). Large conveyance distances generally require larger pipe diameters to offset friction losses in the pipe, in addition to increased pipe insulation to limit heat loss from the pipe. Therefore, there are economic trade-offs between the pipeline length (and cost) and the thermal load being met; long pipelines need large loads for a viable project. Geothermal fluids for direct-use projects can technically be transported relatively long distances (greater than 100 km) without great temperature loss, but such transmission is generally not economically feasible; most existing direct-use geothermal projects have transmission distances of less than about 1.5 km.

Well Yield. Thermal energy output from a geothermal production well is directly related to the fluid flow rate. However, higher fluid flow rates come at the energy expense of pumping. A typical good resource for direct-use purposes has a production rate of 25–50 L/s per production well, but some geothermal direct-use wells have been designed to produce up to 130 L/s (ASHRAE, 2011).

Allowable Temperature Drop of Geothermal Fluid. Thermal energy output from a geothermal production well is also directly related to the temperature decrease (ΔT) in the geothermal fluid as it exchanges heat with the thermal load. Therefore, the larger the allowable temperature drop of the fluid, the lower are the operating (pumping) and capital (well and production pump) costs. Cascading geothermal fluid from higher-temperature uses to lower-temperature uses can help to achieve large temperature differences in the geothermal fluid, thereby optimizing energy use of the resource. Most geothermal systems are designed for a ΔT between 15 and 30 °C, but care must be taken to avoid undesirable chemical changes or mineral precipitation in the geothermal fluid as a result of large temperature drops.

Resource Temperature. The resource temperature generally dictates the geothermal application, as previously mentioned.

Thermal Load and Load Factor. Geothermal direct-use projects can benefit significantly from economies of scale, particularly with the development cost of the resource. Therefore, it is economically desirable to match the load to the thermal output of a geothermal well.

The load factor is defined as the ratio of the average load to the design capacity of the system. Thus, the load factor effectively reflects the fraction of time for which the initial investment in the system is working. Again, as the life-cycle cost of a geothermal system is primarily attributed to its initial cost rather than its operating cost, the load factor significantly affects the viability of a geothermal system. As the load factor increases, so does the economy of using geothermal energy. There are generally two main ways to increase a geothermal direct-use load factor: (1) select applications where it is naturally high, and (2) design the system in a base-peaking arrangement, where the base load is handled by geothermal and the peak loads are met by supplemental equipment.

Geothermal Fluid Chemical Composition. The chemical quality of the geothermal fluid is site specific, and may vary from less than 1000 ppm (parts per million or mg/kg) total dissolved solids to heavily brined with total dissolved solids exceeding 100 000 ppm. Fluid chemical quality influences two aspects of the system design: (1) material selection to avoid corrosion and scaling effects, and (2) disposal or ultimate end use of the fluid. Each of these can have a significant impact on the system viability.

According to Ellis (1998), geothermal fluids commonly contain seven chemical species of concern for direct-use geothermal applications: pH, dissolved oxygen, chloride ion, sulfide species, carbon dioxide species, ammonia species, and sulfate ion. Low pH accelerates corrosion of carbon steel, while high pH indicates scaling potential. Total dissolved solids (TDS) concentrations in excess of 500 ppm indicate corrosion potential. Chloride ions (Cl^-) accelerate corrosion of steels; 304 stainless steel is acceptable to 140 ppm Cl^-, while 316 stainless steel is acceptable to 400 ppm Cl^-. Bicarbonate is linked to calcium carbonate scale above 100 ppm. Hydrogen sulfide attacks copper, and oxygen accelerates steel corrosion.

Ease of Fluid Disposal. The costs associated with disposal, particularly when injection is involved, can substantially affect geothermal direct-use development costs. Historically, most geothermal effluent was disposed of on the ground surface, including use in irrigation, or discharge to surface water bodies. This method of disposal is considerably less expensive than constructing injection wells, but can result in deleterious effects on the producing aquifer, mainly manifested as a decline in hydrostatic pressures. Discharge of geothermal fluids to the ground surface can also cause deleterious effects on and even contaminate the receiving body owing to undesirable concentrations of dissolved chemical constituents in the geothermal fluid.

Most new, large geothermal systems use injection for disposal to minimize environmental concerns and ensure long-term resource sustainability. If injection is chosen as the means of geothermal effluent disposal, the depth at which the fluid can be injected affects well cost substantially. Many jurisdictions, at least in the United States, require that the fluid be returned to the same or similar aquifers; thus, it may be necessary to complete the injection well at the same elevation as the production well.

1.5.2.3 Direct-Use Geothermal Equipment

Excluding wells, the primary equipment used in direct-use geothermal systems includes pumps, heat exchangers, and piping. Although aspects of these components are routine for many other applications, there are some special considerations with regard to direct-use geothermal applications, mainly related to the potentially aggressive nature of geothermal fluids. Thus, design and selection of equipment for direct-use geothermal applications mainly focuses on materials of construction that are capable of handling high temperatures and possible aggressive fluids. These aspects of direct-use geothermal projects are discussed in Chapter 4.

1.5.3 Geothermal Heat Pumps

1.5.3.1 Overview

Geothermal heat pump (GHP), Geoexchange®, or ground-source heat pump systems involve the coupling of low-grade thermal energy from Earth sources to a heat pump. A Swiss patent issued in 1912 to Heinrich Zoelly is the first known reference to geothermal heat pump systems (Spitler, 2005). In the United States, some ground-source and groundwater heat pump systems were installed just prior to World War II, and post-war, installations began to increase. At the same time, about a dozen research projects involving laboratory investigations and field monitoring were undertaken by US electric utilities. In addition, after some time, interest in further research seemed to wane until the 1970s after the oil crisis and initially followed much the same paths as the 1940s research, with an emphasis on experimental testing. This research did lead to solutions for several of the problems associated with the 1940s installations, particularly leakage problems, which were substantially resolved with the use of heat fusion of polybutylene and high-density polyethylene pipe. The 1980s saw the formation of the International Ground Source Heat Pump Association (IGSHPA), which worked to develop protocols for sizing closed-loop ground heat exchangers (GHX). Simultaneous research at Lund University in Sweden (e.g., Eskilson, 1987 and Hellström, 1991) made significant contributions, still in use to this day, in new GHX sizing algorithms and computer software tools. The 1990s saw the emergence and rapid growth of the GHP market in the United States and in Europe, combined with the growth and formation of various engineering trade organizations (e.g., ASHRAE Technical Committee 6.8 expanded in scope from direct use geothermal to GHPs).

Today, the term 'geothermal heat pump' system has become an all-inclusive term to describe a heat pump system that uses the Earth, groundwater, surface water, or other Earth-based heat exchange, such as sewer heat, as a heat source and/or sink. Other names exist, such as 'Geoexchange®' and 'ground-source heat pump'. Still others define the name based on the Earth coupling: groundwater heat pump (GWHP) systems, ground-coupled heat pump (GCHP) systems, surface water heat pump (SWHP) systems, and standing column well (SCW) systems. The types of Earth coupling used to harness shallow Earth energy are the focus of Part II of this book, Chapters 4 to 10. Common types of ground heat exchanger (GHX) couplings are shown in Figure 1.5.

In **groundwater heat exchange systems** (Figure 1.5a), conventional water wells and well pumps are used to supply groundwater to a heat pump or directly to some application. Corrosion protection of the heat pump may be necessary if groundwater chemical quality is poor. The 'used' groundwater is typically discharged to a suitable receptor, such as back to an aquifer, to the unsaturated zone (as shown in Figure 1.5a), to a surface water body, or to a sewer. Design considerations for groundwater heat exchange systems are considered in Chapter 4, and include groundwater availability, groundwater chemical quality, groundwater disposal method, well-drilling technologies, and well-testing methods. The main advantage of groundwater heat exchange systems is their potentially lower cost, simplicity, and small amount of ground area required relative to other Earth couplings and conventional systems. Disadvantages include limited availability, regulations, and poor chemical quality of groundwater in some regions. With growing environmental concerns over recent decades, many legal issues have arisen over groundwater withdrawal and injection in some localities.

A special type of Earth heat exchange is the so-called **standing column well system** as shown in Figure 1.5b. Sometimes referred to as an 'open–closed' system or a 'semi-open-loop' system, a standing column well has features of both open- and closed-loop systems. This type of system draws water to a heat pump from a standing column of water in a deep well bore, and returns the water to the same well. These systems, primarily installed in hard rock areas (e.g., granite), use uncased boreholes with typical diameters of about 15 cm and depths up to about 500 m. The uncased borehole allows the heat exchange fluid to be in direct contact with the Earth (unlike grouted closed-loop heat exchangers), and allows groundwater infiltration over the entire length of the borehole. Properly sited and designed, standing column systems have

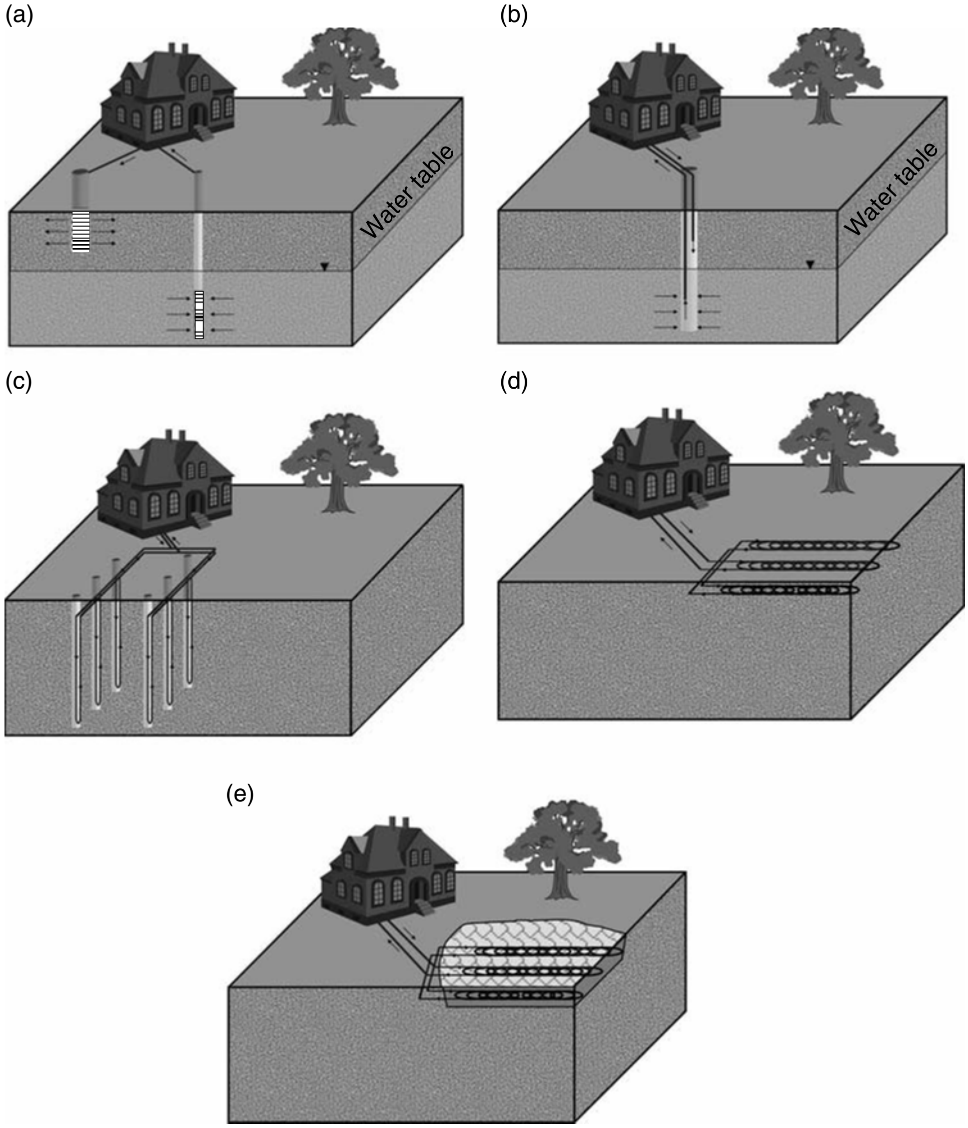

Figure 1.5 Schematic of various ground heat exchangers: (a) groundwater well, (b) standing column well, (c) vertical closed-loop borehole, (d) horizontal Slinky, and (e) surface water closed loop

been shown to have significant installation cost savings over closed-loop systems. Integrated into a drinking water system, the system has a natural 'bleed', as water is removed from the well, thereby allowing new groundwater into the well and moderating the well water temperature.

In **closed-loop, vertical bore heat exchange systems** (Figure 1.5c), heat rejection/extraction is accomplished by circulating a heat exchange fluid through a plastic piping system installed in an array of vertical boreholes, typically drilled to depths ranging from 50 to 100 m. Figure 1.5c shows a commonly-used u-pipe heat exchanger grouted in place. However, in some jurisdictions, groundwater-filled boreholes are acceptable. The key design aspects of closed-loop vertical bore heat exchange systems involve proper subsurface characterization, design of the borehole heat exchanger, and sizing and dimensioning of the ground heat exchanger (i.e., number of boreholes, depth, and spacing). In addition, optimal piping and pumping schemes need to be determined. These aspects are covered in Chapters 5, 6, and 10.

Horizontal closed-loop ground heat exchange systems (Figure 1.5d) are similar in principle to vertical ones, except, obviously, for their configuration. Horizontal GHX configurations typically consist of a series of parallel pipe arrangements laid out in dug trenches, excavations, or horizontal boreholes about 1–2 m deep. A number of piping arrangements are possible. 'Slinky' configurations (as shown in Figure 1.5d) are popular and simple to install in trenches and shallow excavations. In horizontal boreholes, straight pipe configurations are installed. Typical pipes have a diameter ranging from ¾ in (19 mm) to 1½ in (38 mm). Because of their proximity to the ground surface, horizontal GHXs are more affected by weather and air temperature fluctuations. Design aspects of horizontal GHXs are covered in Chapters 7 and 10.

Surface water heat exchange systems (Figure 1.5e) can be a closed-loop or an open-loop type. Typical closed-loop heat exchanger configurations are the loose bundle coil type, plate type, or Slinky coil type (as shown in Figure 1.5e). In closed-loop systems, heat rejection/extraction is accomplished by circulating a heat exchange fluid through a heat exchanger positioned at an adequate depth within a lake, pond, reservoir, or other suitable open channel. In open-loop systems, water is extracted from the surface water body through a screened intake area at an adequate depth and is discharged to a suitable receptor. Open-loop systems can be used for direct cooling (e.g., Cornell University). Heat transfer mechanisms and the thermal characteristics of surface water bodies are quite different from those of soils and rocks. Design aspects of surface water GHXs are covered in Chapters 8 and 10.

A photo of a geothermal heat pump in a residential building is shown in Figure 1.6. Note the fluid connections and associated circulating pumps, and the ductwork. This particular heat pump is equipped with a *desuperheater*, which is used to generate hot water in the adjacent storage tank, also coupled to a solar thermal system. Vapor compression heat pumps used in geothermal applications are discussed in detail in Chapter 12.

Worldwide, there are well over 1 million geothermal heat pump installations. Geothermal heat pumps are relatively well established as a means of significantly reducing energy consumption in space conditioning of buildings. This improvement in efficiency, however, generally comes at a higher first cost, as with most renewable/clean energy systems, which must be offset by lower operating and maintenance costs within an acceptable period of time to the building owner. As with most alternative energy systems, high capital cost is a significant barrier to market penetration.

Why are geothermal heat pumps labeled as an energy-efficient technology? First, any heat pump is more thermodynamically efficient than fossil fuel combustion because heat pumps 'move' heat from a lower-temperature source to a higher-temperature sink, and do not generate heat. You will hear arguments that heat pumps in a space heating application are less efficient than fossil fuel combustion owing to inefficiencies at the power plant. In most cases this is untrue, and will become progressively less true in the future as supply-side electricity generation becomes more efficient and as more renewable energy sources are used. Second,

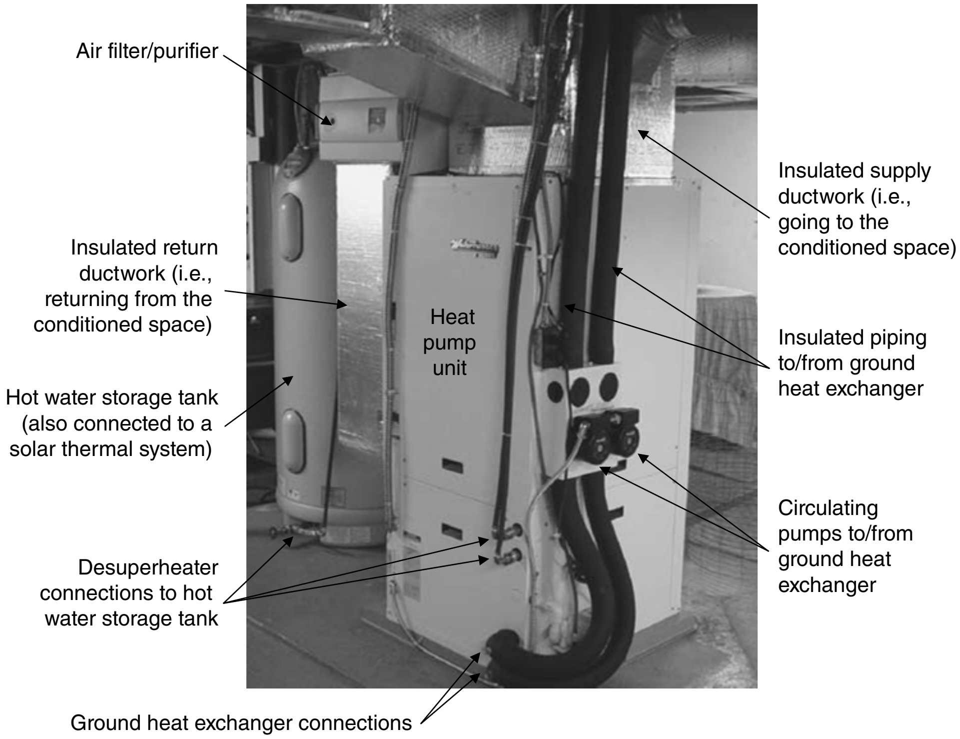

Figure 1.6 Photo of a geothermal heat pump in a residential building (photo by J. Bohrer; permission obtained)

geothermal heat pumps are more energy efficient than other heat pumps because the heat source/sink (the ground) is seasonally closer to room temperature than outdoor air. Additionally, heat is absorbed and rejected through water or an aqueous antifreeze solution, which is a more desirable heat transfer medium than air because of its relatively high heat capacity.

1.5.3.2 Geothermal Heat Pump Project Development

Again, we define 'project development' as the process that takes a project from concept to construction and implementation. In reference to Figure 1.1, favorable project conditions for a geothermal heat pump project may begin with the need for an HVAC system. Other favorable factors include: (i) owner preference for a sustainable building (life-cycle cost approach); (ii) applications where the total annual heating loads are balanced with total annual cooling loads; (iii) buildings with diverse floor plans and loads; (iv) contractor/designer experience and availability; (v) high alternative fuel costs.

The pre-feasibility phase should be conducted by qualified personnel, and is generally aimed at ultimately selecting the best GHX for the site conditions. Schillereff *et al.* (2008) describe a site suitability assessment method that we will further discuss in Chapter 3. In the pre-feasibility stage, all plausible options are first considered with an open mind, and then non-viable options are screened out. Thus, the energy intent of the project should be clear, and estimates of the thermal loads are needed in order to determine probable system costs. Detailed knowledge of every site is not always required if there are numerous other systems in the area and the local geology is uniform. The level of effort in site characterization is typically proportional to the size of the project; the economics of small residential systems cannot support a detailed study. This phase may take months to complete in complex projects. At the conclusion of this phase, GHX options are rejected if they: (i) are non-compliant with laws and regulations, (ii) have an unacceptable development schedule, (iii) require an unacceptable land area, (iv) have unacceptable thermal or hydraulic effects on neighbors or on the environment, or (v) do not meet owner's financial or sustainability criteria.

The detailed feasibility phase is aimed at resource confirmation and determining the most suitable GHX to work with the strengths of the site. Based on the recommendations of the pre-feasibility study, intrusive investigation for site-specific information is undertaken as needed (exploratory drilling, thermal response testing, aquifer testing, water chemistry sampling, etc.). Again, the economics of small projects generally cannot support a detailed feasibility study; favorable projects based on professional judgement typically proceed directly to the design and construction phase. A significant component of this phase may also include refining the load calculations of the application, further HVAC design work, refining costs, and securing financing for the geothermal project. Potential barriers encountered during this phase include site access, environmental impact, and risk of not finding the resource expected. This phase may take months to complete, depending on the project complexity.

The engineering and project development phase involves all activities necessary to complete the geothermal field and associated HVAC system design. This phase may take months to complete, depending on the project complexity. Personnel involved generally include certified designers and installers and licensed professional engineers. Also in this phase, all final legal and regulatory permits are secured. Impact studies of the project relating to the environment, ecology, and cultural issues are completed. Potential barriers encountered during this phase include legal and regulatory permitting, cultural/community opposition to the project, and still some minor risk in not finding the resource expected.

The procurement, construction, and commissioning phase involves all activities necessary to construct the geothermal field and associated HVAC systems. Personnel involved generally include civil, mechanical, and electrical design firms, in addition to certified installers and construction managers.

1.6 Chapter Summary

This chapter presented an overview of the utilization of geothermal energy based on resource temperature. Information flow of energy projects was discussed in some detail, and parallels were drawn with the development of the following types of geothermal energy project: (i) power plants, (ii) direct uses, and (iii) geothermal heat pumps. Site and resource characteristics of geothermal projects were emphasized because all other pieces of the project flow from them.

This chapter also introduced elements of renewable energy systems that are helpful in studying components of the overall system. With regard to geothermal energy systems, these elements represent the four subsections of this book: (i) energy loads and resource characteristics, (ii) harnessing the energy, (iii) energy conversion (to useful energy), and (iv) energy distribution.

Discussion Questions and Exercise Problems

1.1 Is geothermal energy renewable? Give reasons why or why not and cite some examples.

1.2 Identify locations of some low, medium, and high geothermal resource locations nearest to you, and in your country. Find an example utilization of each (if it exists) near you, and in your country.