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Introductory Chapter: Power Generation Using Geothermal Low-Enthalpy Resources and ORC Technology

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1. Introduction

The natural heat energy produced from the Earth is called “geothermal heat energy.” It is proved to be an environmentally friendly clean energy source that could significantly help to mitigate GHG emissions when used for power generation [1]. The source of geothermal energy is the continuous heat energy flux flowing from the interior of the Earth toward its ground surface. The geothermal resources of the Earth are vast. For instance, the amount of geothermal energy stored at a depth of approximately 3 km is estimated to be 1,194,444,444 TWh which is much larger compared to all fossil fuel resources combined, whose energy equivalent is estimated to be 1,010,361 TWh [1, 2]. Unlike other renewable energy resources, geothermal energy has distinct characteristics; namely, it is available and stable at all times throughout the year, has an inherent storage capability, and is independent of weather conditions [1]. It was estimated that the world net electricity demand is going to increase by approximately 85% from 2004 to 2030, increasing from 16,424 TWh (in 2004) to 30,364 TWh (in 2030), so that the utilization of geothermal energy for electric power production continues to be a promising solution, more particularly with the new discoveries of innovative technological methods of power generation cycles and drilling technologies. The utilization of geothermal energy resources can also be used for direct heating applications [1]. In general, the utilization of geothermal energy is divided into two parts: (a) electricity generation and (b) direct heating (non-electrical) applications. Recently, this form of renewable energy source has grown in 25 countries, with installed geothermal-electric capacity up to 11 GW_e in 2010 [1, 2], and is increasingly contributing to the electric power supply worldwide [1–3].

Geothermal energy resources vary from one geographic location to another, depending on the depth, temperature, and pressure of the geothermal resource, the abundance of ground water, and the underground chemical composition. Geothermal energy resources typically differ in temperature from about 50 to 350°C. The high-temperature geothermal resources (with temperature >200°C) are typically found in volcanic regions and island chains, whereas the medium-temperature (150–200°C) and low-temperature geothermal resources (<150°C) are usually found widely in most continental regions and by far the most commonly available geothermal resource [2, 3]. The increase in temperature with depth in the Earth’s crust can be expressed in terms of what is known as the geothermal temperature gradient. Down to the depths accessible by drilling with state-of-the-art technology

(over 10 km), the average geothermal gradient is about 2.5–3.0°C/100 m [2]. For example, at depth around 3 km below ground surface, the estimated temperature is approximately 90°C. There are, however, regions in which the geothermal temperature gradient is far from the average value. For instance, in some geothermal areas, the gradient is 10 times the average value due to composition of these areas and geothermal structure [2]. It was also reported that the emissions of GHG from geothermal power plants, in general, constitute less than 2% of the emission of these gases by fossil-fuelled power plants [2]. To comply with future energy demands, potential renewable energy sources should meet the following criteria: (1) the sources should be technically and economically accessible, (2) the sources should be large enough to sustain a long-lasting energy supply to generate the required electricity for the country, (3) the sources should be environmentally friendly and thus should be low GHG emitters in order to make significant contribution to global warming mitigation, and (4) the sources should have a wide geographic distribution [1–3]. Low-enthalpy geothermal energy (LEGE) resources extraordinarily satisfy all of these important criteria. This vast LEGE resource has already been utilized for electric power generation by some countries, such as the USA, Mexico, the Philippines, Indonesia, Austria, Germany, and Iceland [2]. The installations of several commercial LEGE electrical power systems in these countries have substantially proved the ability of low-temperature geothermal fluids to generate electricity [2]. In most developing countries, LEGE resources have not received much attention for electricity production. The key reason for not utilizing these resources by most developing countries and several industrialized countries for commercial exploitations is that they are not considered as cost-effective for generating electricity [2]. Recent increases in the cost and uncertainty of future conventional energy supplies for power generation are improving the attractiveness of LEGE resources. Generating electricity from medium- and low-enthalpy geothermal resources (water-dominated resources) can be effectively achieved using a binary cycle method which is also known as organic Rankine cycle (ORC) method [1, 2]. LEGE-ORC technology has virtually no GHG emissions to the atmosphere [1–3] and is a promising technology due to its simplicity and its limited number of components, all of them being very common and commercially available.

In this introductory chapter, the basic concept of LEGE-ORC binary power technology using LEGE heat sources is introduced, and its potential applications and limitations for small-scale geothermal power generation and its relevant environmental and economic considerations are presented and discussed.

2. Basic concept of LEGE-binary ORC technology for electrical power generation

A schematic diagram showing a LEGE-ORC binary-fluid system used for electric power generation is shown in **Figure 1**.

In this system, the first (primary) fluid being the geo-fluid (brine) is extracted from the LEGE resource through the production well. The geo-fluid carries the heat from the liquid-dominated resource and efficiently transfers this heat to the low boiling point (BP) organic working fluid (the secondary/binary fluid) using an effective heat exchanger. Shell-and-tube heat exchangers are widely used in these applications [1, 2]. The ORC is a thermodynamic Rankine cycle that uses the organic working fluid instead of steam (i.e., water). In this binary-fluid system, the low boiling point organic liquid absorbs the heat which is transferred by the geothermal fluid and boils at a relatively much lower temperature (compared to water) and as a result develops significant vapor pressure sufficient to drive the axial flow

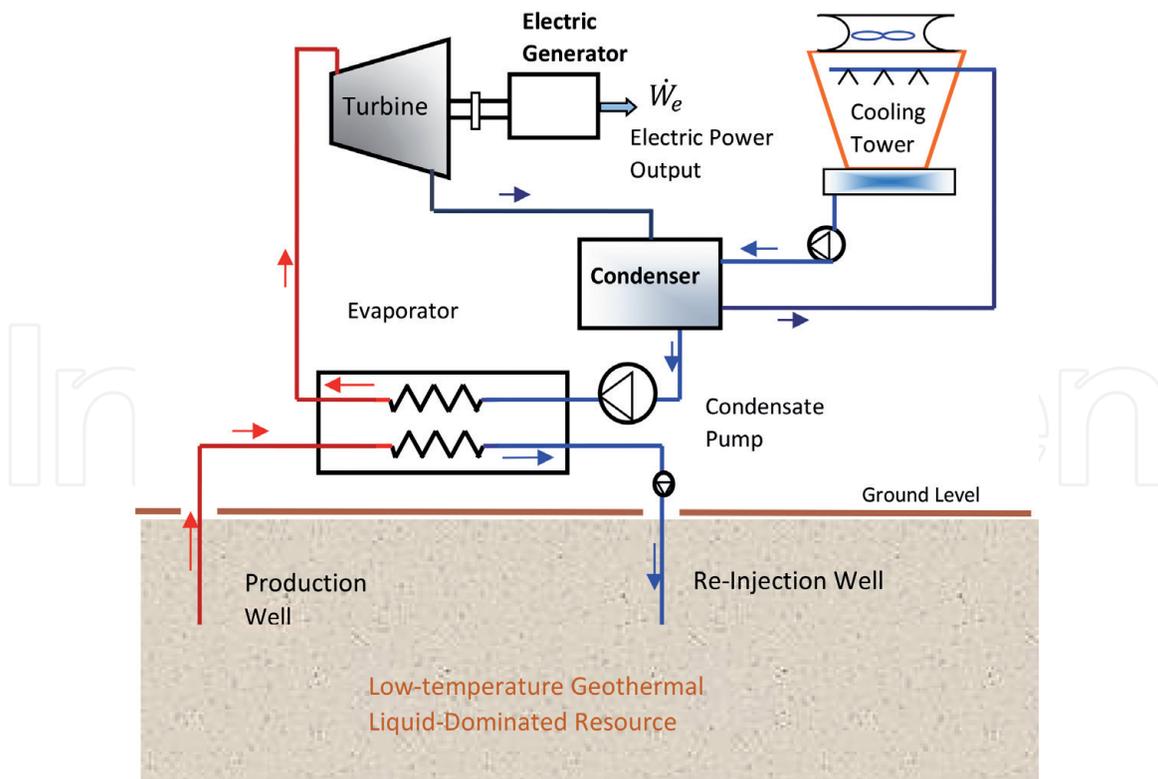


Figure 1.

A schematic showing the basic concept of LEGE-ORC technology for power generation [1].

or radial inflow turbine. The turbine is coupled to an electric generator which converts the turbine mechanical shaft power into electrical power. The organic working fluid expands across the turbine and then is cooled and condensed in the condenser before it is pumped back as a liquid to the heat exchanger using a condensate pump to be re-evaporated, and the power cycle repeats itself. One of the most important performance criteria in LEGE-ORC power generation technology requires the optimal selection of the ORC organic working fluid. Organic fluids used in binary ORC technology have inherent feature (compared to water) and that is they have low boiling temperature and high vapor pressure at relatively low temperatures, compared with steam (water) [1]. It was noted in [1] that typical ORC organic fluids may include pure hydrocarbons (e.g., pentane, butane, propane, etc.), refrigerants (e.g., R134a, R218, R123, R113, R125, etc.), or organic mixtures. The optimal energy conversion performance of a LEGE-ORC power generation system depends mainly on the type of organic fluid being used in the system. The selection of the type of organic fluid is typically based on the following criteria [1, 2]:

- The ORC organic fluid should result in high thermal efficiency by allowing maximum utilization of the available low-temperature geothermal heat source.
- It should be safe (non-flammable and nontoxic) and non-corrosive.
- It should not react or disassociate at the pressures and temperatures at which it is used.
- It should have suitable thermal stability and high thermal conductivity.
- It should have appropriate low critical temperature and pressure.
- It should result in low maintenance.

- It should have a low boiling temperature and should evaporate at atmospheric pressure.
- It should be environmentally friendly and less in ozone depletion potential (ODP) and global warming potential (GWP).
- It should have small specific volume and low viscosity and surface tension.
- It should lead to optimum design and cost-effectiveness of the ORC system.

It was also mentioned in [1] that many binary ORC fluids may not meet all these criteria but the selection of the organic fluid should be optimized, in terms of the above requirements, while meeting the demanded power generation. In general, binary ORC systems exhibit great flexibility, low maintenance, and high safety (installations are perfectly tight). It was also reported in [1] that the selection of suitable organic fluids for application in binary ORC systems for generating electricity still deserves extensive thermodynamic, technical, and feasibility studies.

3. Energy conversion efficiency of LEGE-ORC technology

In Ref. [1], the theoretical overall performance of LEGE-ORC binary systems can be evaluated using the fundamental thermal efficiency of a heat engine, given as:

$$\eta_{th} \equiv \frac{\dot{W}_{net,out}}{\dot{Q}_{geo,in}} \quad (1)$$

and also

$$\eta_{th} \equiv 1 - \frac{\dot{Q}_{cond}}{\dot{Q}_{geo,in}} \quad (2)$$

where $\dot{W}_{net,out}$ is the net power output delivered by the geothermal power system (in kW), $\dot{Q}_{geo,in}$ is the thermal power supplied by the geo-fluid from the available geothermal resource (in kW), and \dot{Q}_{cond} is the thermal energy rejected in the condenser (in kW). For quick estimate purposes, a correlation is proposed [1, 2] to calculate the actual net power output (with rough accuracy), given by

$$\dot{W}_{net,act} = \left(\frac{1}{278}\right) [(0.18T_{geo,in} - 10) \dot{Q}_{geo,in}] \quad (3)$$

Substituting Eq. (3) in Eq. (1), the estimated thermal efficiency of the low temperature-based geothermal power generation system, as a function of geo-fluid inlet temperature (in °C) at the production well, is given by

$$\eta_{th} \approx \left(\frac{1}{278}\right) (0.18T_{geo,in} - 10) \quad (4)$$

The thermal efficiency as a function of the low-temperature geothermal heat resource temperature, T_H (in K), and ambient temperature, T_a (in K), is given by

$$\eta_{th} \approx \left(\frac{58}{100}\right) \left(\frac{T_H - T_a}{T_H + T_a}\right) \quad (5)$$

The estimated net power output delivered by the geothermal power system can also be determined using [2]

$$\dot{W}_{net,out} \cong 2.47 \dot{m}_{geo} \left(\frac{T_H - T_o}{T_H + T_o} \right) (T_H - T_C) \quad (6)$$

4. Installations and land usage aspects for using LEGE-ORC technology

LEGE-ORC power generation systems are typically constructed and installed in small modular, compact (and in some cases mobile) units of a few hundred kW_e to a few MW_e capacities [2]. These units can then be integrated to form power plants of 10–50 MW_e which are considered to be small power plants. It was estimated that 1 MW_e power plant could serve about 20,000 households assuming that the demand for electricity per person at off-grid sites will be of the order of 500 W [1, 2]. The convenience of the small power plants is most evident for areas without ready access to conventional fuels, but with access to LEGE resources, and for communities that it would be very expensive to connect to the national electric grid [2–4]. Basic LEGE-ORC power generation systems typically include the following list of equipment [2]:

- Downwell pumps
- Geo-fluid (brine) supply system (sand removal system)
- Heat exchangers (evaporator/condenser, shell-and-tube type)
- Turbine generator and controls
- Condensate pump
- Piping system
- Heat rejection system (cooling tower)
- Backup electric power system
- Fire protection system (if the ORC working fluid is flammable)

The area required to support a geothermal power facility, including the well field, access roads, and auxiliary buildings, depends on the geothermal power plant power rating, the properties of the geothermal reservoir fluid, and the piping system selected for collecting the geo-fluid from the production wells and disposing the waste brine to the reinjection wells. The geothermal power facility should be installed close to the production wells to avoid thermal and hydraulic losses caused by long geo-fluid pipelines. The pipelines used to transport the geo-fluids are usually mounted on stanchions, run along service roads, and incorporate vertical and horizontal expansion loops [2]. It should be noted that a low-enthalpy geothermal power plant typically requires (per MW_e) 5% of the area needed for a solar thermal power plant and 2% for a solar PV power plant located in the best solar insolation area in the USA. It was reported also in [2] that a 20 MW_e geothermal binary power plant (excluding wells) requires a land area of 1415 m²/MW_e.

5. Environmental aspects of using LEGE-ORC technology

Geothermal energy is relatively free from pollution problems and considered to be a clean technology. It seems to have the largest technological potential compared to other renewable energy sources [1–4]. Emissions are typically zero when LEGE reservoirs are utilized using ORC binary technology, since all of the produced geo-fluid is injected back into the reservoir. Some chemical constituents of geothermal water (e.g., trace metals) may need to be monitored in case their concentrations exceed permitted pollution limits. One of the effective ways of getting rid of hazardous chemicals is reinjection. Low-enthalpy geothermal binary power generation systems are far less environmentally intrusive than alternative power generation systems in several respects, for example, they are essentially zero-GHG emission systems and have low land usage per installed megawatt [2]. As far as physical environmental effects, geothermal projects may cause some kind of disruption activities as other same size and complexity of civil engineering projects. Also, the locations of excavations and sitting of boreholes and roads will have to be taken into account; soil and vegetation erosion, which may cause changes in eco-systems, has to be watched. There is considerable noise involved during geothermal drilling, construction, and production phases of development, so that protection has to be ensured for residents, and some permanent noise-reduction measures may need to be considered. It should be noted that many geothermal developments are in remote areas where the natural level of noise is low and any additional noise is very noticeable [1, 2]. At the social-economic level, the construction of geothermal power installations involves a temporary increase in employment, and the building of new roads may open up areas and possibly increase tourism, especially if natural geothermal manifestations are left intact. Geothermal power facilities utilize low-source temperature to produce the primary thermal energy for conversion to power production, and therefore the waste heat per MW_e of electricity generated is much larger than others types of power generation [2]. Appropriate measures should be applied to prevent leakage of the binary working fluid from ORC power generation units to the environment [1, 2]; normally the installations of these units are made perfectly tight to meet high safety requirements.

6. Economic aspects of using LEGE-ORC technology

Generating electricity using geothermal ORC technology is very cost-effective and reliable [1, 2]. **Table 1** [2] compares the unit cost of electricity generated from low enthalpy-based small power plants. Moreover, the unit cost of electricity from small-scale geothermal plants (<5 MW_e) is much lower than the average cost of

Net power (kW _e)	Capital cost (US\$/net kW _e)			O and M cost (US\$/year)
	Resource temperature (°C)			
	100	120	140	
100	2786	2429	2215	21,010
200	2572	2242	2044	27,115
500	2357	2055	1874	33,446
1000	2143	1868	1704	48,400

Table 1.
Unit cost of electricity generated from LEGE-based small power plants [2].

0.25 US\$/kWh supplied through diesel generators [2]. The total investment for a geothermal power plant mainly includes the following: (1) cost of drilling, (2) cost of exploitation, (3) operating and maintenance costs, and (4) cost of power plant (capital cost of design and construction) [1, 2]. The first two types are referred to as subsurface costs, whereas the other two are referred to as surface costs. For small-scale geothermal power plants (<5 MW_e) utilizing LEGE resources, the subsurface cost typically accounts for approximately 30% of the total investment costs, whereas the surface cost accounts for the remaining 70%. For larger geothermal power plants (>5 MW_e) utilizing high-enthalpy resources, the surface cost is a small part of the total cost of the project. The major cost involved in larger plants seems to be the subsurface cost. Generating electricity using LEGE-ORC technology is very reliable due to its advanced technological aspects [2]. However, the maintenance costs and shutdowns could be reduced when the technical complexity of the plant is on a level that is accessible to local technical personnel or to experts who are readily available [2]. Also, reducing operations and maintenance costs can be achieved through advanced methods to control the geo-fluid (brine) chemistry and the use of more robust instruments for tighter controls [1, 2]. Geothermal ORC power generation plants are normally constructed and installed in small modular power generation units. These units can then be linked up to create power plants with larger power production rates. Their cost depends on a number of factors, but mainly on the temperature of the geothermal fluid produced, which influences the size of the ORC turbine, heat exchangers, and cooling system. The total size of the plant has little effect on the specific cost, as a series of standard modular units is linked together to obtain larger power capacities [2]. The modular units have a satisfying economic efficiency, because modular construction reduces installation time and costs. Ultimately, the economic viability of the geothermal power plant depends on its ability to generate revenue in the long term. This is because of relatively lower unit cost of electricity generated by geothermal plants and the future power-sale factor. This means that geothermal power plants, in general, are normally built and designed to serve for more years in order to get to the point where they could pay back for the investment cost and start to generate revenue and ultimately become highly cost-effective [2].

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