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# ORC-Based Geothermal Power Generation and CO<sub>2</sub>-Based EGS for Combined Green Power Generation and CO<sub>2</sub> Sequestration

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Additional information is available at the end of the chapter

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## 1. Introduction

Electrical power generation using innovative renewable and alternative geothermal energy technologies have shown merits and received renewed interest in recent years due to an increasing concern of greenhouse gas (GHG) emissions, being responsible for global warming & climate change, environmental pollution, and the limitations and conservation of natural energy resources. Organic Rankine Cycle (ORC) power generation using low-temperature geothermal resources is one of these innovative geothermal power generation technologies. The vast low-temperature geothermal resources found widely in most continental regions have not received much attention for electricity generation. Continuous development of ORC power generation and state-of-the-art drilling technologies and other factors make this renewable and nonconventional energy source one of the best future viable, alternate and available source to meet the required future electricity demand worldwide, significantly reducing GHG emissions and mitigating global warming effect. The first part of this chapter will introduce the ORC-based geothermal power generation technology. It will also present its fundamental concept for power generation and discusses its limitations, environmental & economic considerations, and energy conversion performance concept. Another novel “double-benefit” technology is enhanced (engineered) geothermal systems (EGS) using CO<sub>2</sub> as the working fluid for combined renewable power generation and CO<sub>2</sub> sequestration. CO<sub>2</sub> is of interest as a geothermal working fluid mainly because it transfers geothermal heat more efficiently than water. While power can be produced more efficiently using this technology, there is an additional benefit for carbon capture and sequestration (CCS) for reducing GHG emissions. Using CO<sub>2</sub> as the working fluid in geothermal power systems may permit utilization of lower-temperature geologic formations than those that are currently deemed eco-

nomically viable, leading to more widespread utilization of geothermal energy. The second part of this chapter will present and discuss the merits, limitations, environmental, economic and fundamental aspects of CO<sub>2</sub>-based EGS technology.

## 2. ORC-based geothermal power generation

### 2.1. Developments & utilization of low-temperature geothermal energy resources for power generation

The geothermal resources of the Earth are vast and abundant. For example, the part of geothermal energy stored at a depth of 3 km is estimated to be 43,000,000 EJ (equivalent to 1,194,444,444 TWh) which is much larger compared to all fossil fuel resources, whose energy equivalent is 36,373 EJ, combined (Chandrasekharam & Bundschuh, 2008). Conventional energy resources, such as oil, natural gas, coal, and uranium, being widely consumed in the world, originate from finite energy sources embedded in the crust of the Earth. Only one energy resource of the crust is renewable, namely geothermal energy. The word “geothermal” is originated from Greek words; “geo” meaning the Earth and “therme” meaning heat, so geothermal energy means the natural heat energy from the Earth. The source of geothermal energy is the continuous energy flux flowing from the interior of the Earth towards its surface. Unlike other conventional and renewable energy sources, geothermal energy has unique characteristics, namely it is abundantly available, stable at all times throughout the year, independent of weather conditions, and has an inherent storage capability (Hammons, 2004). Distinct from fossil-fuelled power generation, geothermal power generation is also considered to be a clean technology and environmentally friendly power source which could significantly contribute to the reduction of GHG emissions by replacing fossil fuels and other non-clean energy sources used for power generation (Chandrasekharam & Bundschuh, 2008).

Depending on the temperature and depth of the resource, the rock chemical composition and the abundance of ground water, geothermal heat energy resources vary widely from one location to another (Gupta & Roy, 2007). Geothermal heat sources are typically classified based on their available temperature, thus enthalpy energy level, from about 50 °C to 350 °C. The high-temperature (high-enthalpy) geothermal resources (with temperature > 200 °C) are typically found in volcanic regions and island chains, whereas the moderate-temperature (150-200 °C) and low-temperature (low-enthalpy) geothermal resources (<150 °C) are usually found broadly in most continental regions and by far the most commonly available heat resource (Chandrasekharam & Bundschuh, 2008; Gupta & Roy, 2007). 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 modern technology (e.g. over 10 km), the average geothermal gradient is about 2.5-3.0 °C/100 m (Dickson & Fanelli, 2005). For example, at depth around 3 km below ground level, the temperature is about 90 °C. There are, however, areas in which the geothermal gradient is far from the average value (e.g. in some geothermal areas the gradient is ten times the average

value) due to geothermal structure and composition of these areas (Dickson & Fanelli, 2005). The type of geothermal resource determines the type of system and method of its harvesting and utilization for electrical power generation. For example, high-temperature geothermal resources (vapour- and liquid-dominated) can be harvested and utilized to generate electricity using one of the following methods depending on the compositional and thermal characteristics of the resource: (1) single-flash steam power systems, (2) double-flash steam power systems, and (3) dry-steam power systems. Generating electricity from medium- and low-temperature geothermal resources (i.e. water-dominated resources) can be efficiently accomplished using a Binary-cycle technique, such as, ORC (Ismail, 2011a; Chandrasekharam & Bundschuh, 2008; Dickson & Fanelli, 2005; DiPippo, 2008).

Generating electricity from geothermal steam resources using an experimental 10 kW-electrical generator was made at Larderello of Italy in 1904 (Dickson & Fanelli, 2005; Panea et al., 2010). The commercial success of this attempt indicated the industrial value of geothermal energy and marked the beginning of a form of exploitation that was to develop significantly from the on. By 1942, the installed geothermal-electric capacity had reached approximately 128 MW<sub>e</sub> (Dickson & Fanelli, 2005). In the early 1950's, many countries were attracted by geothermal energy, considering it to be economically competitive with other forms of energy. It was estimated (Dickson & Fanelli, 2005; Ruggero, 2007) that the worldwide installed geothermal-electric capacity reached 1.300 GW<sub>e</sub> (in 1975), 4.764 GW<sub>e</sub> (in 1985), 6.833 GW<sub>e</sub> (in 1995), 7.974 GW<sub>e</sub> (in 2000), 8.806 GW<sub>e</sub> (in 2004), 8.933 GW<sub>e</sub> (in 2005), 9.732 GW<sub>e</sub> (in 2007). In 2010, it was reported (Holm et al., 2010) that 10.715 GW<sub>e</sub> is online generating 67,246 GWh which represents a 20% increase in geothermal power online between 2005 and 2010. While power on-line grew 20% between 2005 and 2010, countries with projects under development grew at a much faster pace. In 2007, Geothermal Energy Association (GEA) reported that there were 46 countries considering geothermal power development. In 2010, this report identified 70 countries with projects under development or active consideration, a 52% increase since 2007. It should be noted that projects under development grew the most intensely in two regions of the world; namely, Europe and Africa (Holm et al., 2010). Very recently, it was reported (GEA, 2012) that as of May 2012, approximately 11.224 GW<sub>e</sub> of installed geothermal-electric power capacity was online globally, and is increasingly contributing to the electric power supply worldwide. It was estimated (Ruggero Bertani, 2007) that geothermal energy provides approximately 0.4% of the world global power generation, with a stable long term growth rate of 5%; the largest markets being in USA, Mexico, Indonesia, Philippines, Iceland, and Italy. Security for long-term electricity supply and GHG emission from fossil fuelled power plants is becoming a cause of concern for the entire world today. It was estimated (Chandrasekharam & Bundschuh, 2008) that the world net electricity demand is going to increase by approximately 85% from 2004 to 2030, rising from 16,424 TWh (in 2004) to 30,364 TWh in the year 2030. It was also reported (Chandrasekharam & Bundschuh, 2008; Dickson & Fanelli, 2005) that the emissions of GHG from geothermal power plants constitute less than 2% of the emission of these gases by fossil-fuelled power plants. To meet future energy demands renewable energy sources should meet the following criteria (Chandrasekharam & Bundschuh, 2008): (1) the sources should be large enough to sustain a long-lasting energy supply to generate the required electricity for the country, (2) the sources

should be economically and technically accessible, (3) the sources should have a wide geographic distribution, and (4) the sources should be environmentally friendly and thus should be low GHG emitters in order to make significant contribution to global warming mitigation. Low-temperature (low-enthalpy) geothermal energy resources meet all the above criteria. It was reported in (Chandrasekharam & Bundschuh, 2008; Cui et al., 2009) that this huge low-temperature geothermal energy resource has already been used for power generation by typical countries, such as USA, Philippines, Mexico, Indonesia, Iceland, Germany, and Austria. The installations of several commercial low-temperature geothermal power systems in these countries have substantially proved the ability of low-temperature geothermal fluids to generate green electricity (Chandrasekharam & Bundschuh, 2008).

In most developing countries, low-temperature geothermal resources have not received much attention for electricity generation. The main reason for not utilizing these resources by most developing countries (and several industrialized countries) for commercial exploitation is that they are not considered as economically feasible for generating electricity (Chandrasekharam & Bundschuh, 2008). In contrast, in some industrialized countries, especially USA and in Europe, increasing energy demand and environmental awareness related to climate change have urged these countries to develop technologies which utilize low-temperature geothermal resources economically for power generation (Chandrasekharam & Bundschuh, 2008; Dickson & Fanelli, 2005). It was reported (Chandrasekharam & Bundschuh, 2008; Galanis et al., 2009) that developing countries, in general, need to benefit from these new and continually improving technologies for using low-temperature geothermal resources for generating electricity. It should be noted that for many developing countries, the use of low-temperature geothermal resources is not new. Many of developing countries have been using these resources for the past centuries for direct heating (but not power generation) applications (Chandrasekharam & Bundschuh, 2008). Recent increases in the cost and uncertainty of future conventional energy supplies for power generation are improving the attractiveness of low-temperature geothermal resources. Continuous development of innovative drilling and power generation technologies makes this nonconventional, renewable and clean energy source the best future viable, alternate and available source to meet the required future electricity demand worldwide, significantly reducing GHG emissions and mitigating global climate change (Chandrasekharam & Bundschuh, 2008).

As mentioned earlier, generating electricity from low-temperature geothermal resources (water-dominated resources) can be effectively achieved using a binary ORC technology. Low-temperature geothermal ORC technology has virtually no GHG emissions to the atmosphere (DiPippo, 2008; Hettiarachchi et al., 2007) and is an attractive energy-conversion technology due to its simplicity and its limited number of components, all of them being very common and commercially available. Nowadays, the ORC can be considered as the only proved technology that is commonly used in ranges of a few kW up to 1 MW (Schuster et al., 2009). Despite the fact that ORC technology is currently associated with low conversion efficiencies, new applications of this technology are commonly examined and implemented due to its possibility to utilize the low-grade heat from sources, such as low-temperature geothermal resources, for power generation (Ismail, 2011a). A number of successful &

innovative ORC binary power plants were installed in different locations (e.g. remote and rural sites) worldwide which demonstrate the ability of this promising alternative technology to utilize renewable low-temperature geothermal energy sources for generating electricity. For example, two plants were installed in Nevada, USA in 1984 and 1987 with electric power generation capacity of 750 and 800 kW<sub>e</sub>, respectively (Chandrasekharam & Bundschuh, 2008). The production wells supply geo-fluid (water) temperature at 104 °C with a flow rate of 60 l/s to these plants. The ORC binary fluid used was initially R-114 but due to non-availability of this working fluid the plant switched to iso-pentane in 1998. In another location near Empire, Nevada, approximately four 1 MW<sub>e</sub> units were installed and commissioned in 1987. Two geothermal production wells with geo-fluids temperature of 137 °C were used (Chandrasekharam & Bundschuh, 2008). In 1998, a third well with geo-fluid temperature of 152 °C was drilled to maintain the capacity of the plant at approximately 4 MW<sub>e</sub>. The modular approach was used so that high plant availability factors of 98% and more were achievable (Hammons, 2004). In 1987, another plant was installed and commissioned in Taiwan with an electric power generation of 300 kW<sub>e</sub>. The plant draws geo-fluids from a 500 m deep well at a temperature of 130 °C. It was reported that the power generated from this facility was sold to the national power grid at 0.04 US\$/kWh (Chandrasekharam & Bundschuh, 2008). In 1986, a low-temperature geothermal ORC unit (Mulka plant) with a power capacity of 15 kW<sub>e</sub> was commissioned in Australia. The unit was coupled to a geothermal production well which was drilled down to a depth of 1,300 m, and supplying geo-fluid at 86 °C. The unit was operated non-stop for about three and a half years, showing frequency stability and response to load changes (Rosca et al., 2010).

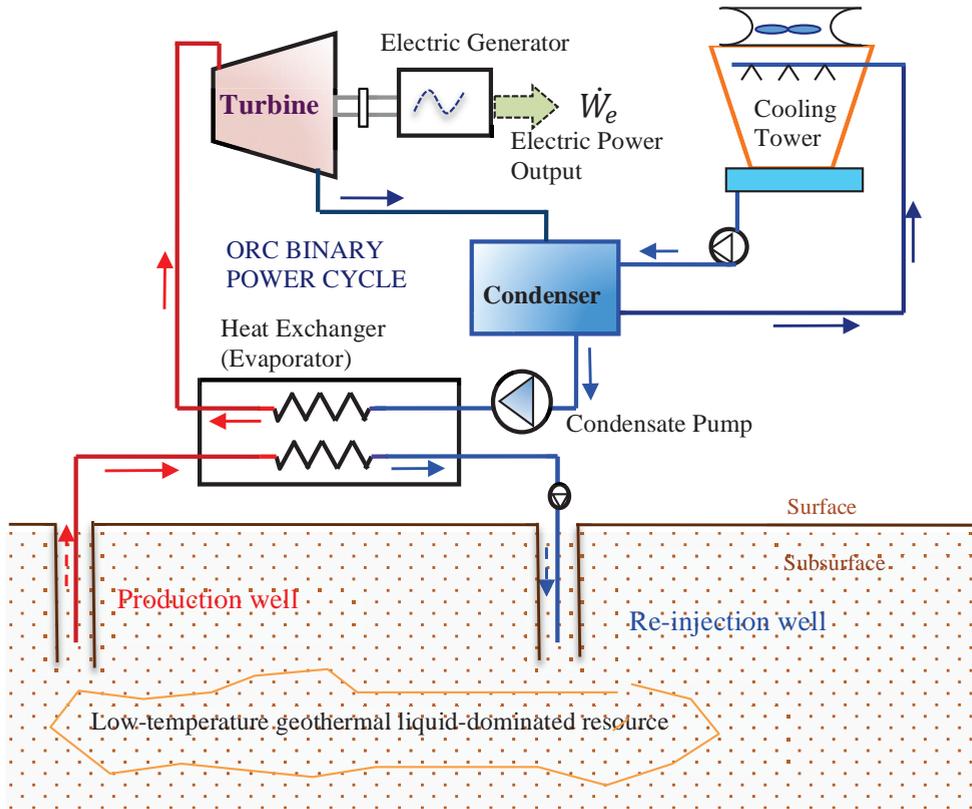
In 1992, a binary ORC power generation unit which utilized a low-temperature geothermal water resource with a temperature ranging from 90 to 115 °C was tested at a location near Arderello, Italy. The geothermal power plant generated between 800 and 1,300 kW<sub>e</sub> of electricity (Rosca et al., 2010). In Germany, the first low-temperature geothermal power plant using ORC technology was installed at Neustadt-Glewe, with a power capacity of approximately 230 kW<sub>e</sub> using a geo-fluid temperature of 98 °C (Ruggero Bertani, 2007). Another plant was commissioned in Thailand in 1989, with an installed capacity of 300 kW<sub>e</sub>. The actual production was reported to vary from 150 to 250 kW<sub>e</sub> and the geo-fluid temperature is 116 °C with a flow rate of approximately 8 l/s (Chandrasekharam & Bundschuh, 2008). In Japan, binary ORC technology was experimentally operated for 5 years starting in 1993 by NEDO (Yamada & Oyama, 2004). More recently, in 2006, the first binary ORC plant which utilizes a low-temperature geothermal resource at a temperature of 74°C reported by (Ruggero Bertani, 2007) to be the lowest low-temperature geothermal energy resource worldwide) was installed at Chena Hot Springs, Alaska, with a power generation capacity of 200 kW<sub>e</sub>. A photograph of Chena ORC-based geothermal power plant is shown in Figure 1. A second ORC unit was added, reaching the total installed capacity of 400 kW<sub>e</sub> net. The total project cost of this binary geothermal plant was \$2.2 million with a simple payback period of 4 years (Holdmann, 2007). In Altheim, Austria, a geo-fluid of temperature 106 °C is utilized both for district heating and electric power generation using a binary plant technology. The net electric output of this plant is 500 kW<sub>e</sub>, selling to the electric grid 1.1 GWh in 2006 (Ruggero Bertani, 2007).



**Figure 1.** Photograph of Chena ORC-based geothermal power plant at Chena, Alaska, USA (Holdmann, 2007).

## 2.2. Energy conversion and performance aspects of ORC-based low-temperature geothermal power generation

The ORC is a thermodynamic Rankine cycle that uses an organic working fluid instead of steam (water). A schematic diagram showing a low-temperature geothermal ORC binary-fluid system used for electric power generation is shown in Figure 2. In this system, the first (primary) fluid being the geo-fluid (brine) is extracted from the low-temperature geothermal resource through the production well. The geo-fluid carries the heat from the liquid-dominated resource (thus called the geo-fluid heat carrier) and efficiently transfers this heat to the low-boiling point (BP) organic working fluid (the secondary fluid) using an effective heat exchanger; shell-and-tube heat exchangers are widely used (Chandrasekharam & Bundschuh, 2008). 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 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



**Figure 2.** A schematic diagram showing the basic concept of a low-temperature geothermal binary ORC system for electrical power generation.

pump to be re-evaporated, and the power cycle repeats itself. One of the most important performance criteria in low-temperature geothermal 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) (Dickson & Fanelli, 2005).

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 (Panea et al., 2010; Saleh et al., 2007; Hung, 2001; Wei et al., 2007). The optimal energy conversion performance of a low-temperature geothermal ORC power generation system depends mainly on the type of organic fluid being used in the system (Ismail, 2011a). The selection of the type of organic fluid is normally based on the following criteria (Hettiarachchi et al., 2007; Saleh et al., 2007; Chandrasekharam & Bundschuh, 2008; Ismail, 2011b):

- The ORC organic fluid should be environmentally friendly; less in ozone depletion potential (ODP) and global warming potential (GWP).
- It 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 no-toxic) and non-corrosive.
- It should have a low-boiling temperature and should evaporate at atmospheric pressure.
- It should lead to optimum design and cost effectiveness of the ORC system.
- 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 have small specific volume, low viscosity and surface tension.
- It should result in low maintenance.

It should be noted that many binary ORC fluids may not meet all these criteria (Chandrasekharam & Bundschuh, 2008) 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, high safety (installations are perfectly tight), and low maintenance (Wei et al., 2007). It was reported that the selection of suitable organic fluids for application in binary ORC systems for generating electricity still deserves extensive thermodynamic and technical studies (Maizza, V., & Maizza, A., 2001).

The quality of heat energy which can be supplied by any heat source depends on its temperature level. For ORC-based geothermal power system, this is the temperature of the produced geo-fluid from the geothermal production well. The theoretical overall performance of low-temperature geothermal binary systems can be evaluated using the thermal efficiency of a heat engine, given by (Cengel & Boles, 2008)

$$\eta_{th} = \frac{\dot{W}_{out}}{\dot{Q}_{geo}} \quad (1)$$

In Eq. (1),  $\dot{W}_{out}$  is the net power output produced by the geothermal power system (in kW<sub>e</sub>); and  $\dot{Q}_{geo}$  is the thermal heat supplied by the geo-fluid from the available geothermal resource (in kW<sub>t</sub>). A correlation is proposed (Dickson & Fanelli, 2005) to calculate the actual net power output (used for a quick estimate with rough accuracy) as a function of the available thermal power from the geo-fluid flow and inlet temperature of the geo-fluid, given by

$$\dot{W}_{out} = 0.0036 \dot{Q}_{geo} (0.18 T_{geo,in} - 10) \quad (2)$$

Substituting Eq. (2) 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) available at the production well, is given by

$$\eta_{th} = 0.000648 T_{geo,in} - 0.036 \quad (3)$$

For example, using Eq. (3) it can be estimated that a thermal efficiency of approximately 4.8% could be achieved for power generation with a geo-fluid extracted from a low-temperature geothermal resource available at 130 °C. The thermal efficiency as a function of the geothermal heat resource temperature,  $T_{geo,in}$  (in K), and ambient temperature,  $T_o$  (in K) is given by (DiPippo, 2007)

$$\eta_{th} \cong 0.58 \left( \frac{T_{geo,in} - T_o}{T_{geo,in} + T_o} \right) \quad (4)$$

So for example, with a geothermal heat resource temperature of 130°C and ambient temperature of 25°C, the thermal efficiency is estimated to be 8.7%, using Eq. (4). It should be noted that Eq. (4) is valid for resource temperatures between 100 and 140 °C. The estimated net power output produced by the geothermal power system can also be determined using (DiPippo, 2007)

$$\dot{W}_{out} \cong 2.47 \dot{m}_{geo} \left( \frac{T_{geo,in} - T_o}{T_{geo,in} + T_o} \right) (T_{geo,in} - T_{sink}) \quad (5)$$

In Eq. (5),  $\dot{m}_{geo}$  is the geo-fluid mass flow rate; and  $T_{sink}$  is the heat sink temperature. It should be noted that the above correlations given by Eqs. (2) through (5) provide quick estimate of the thermal efficiency and net power output. However, for more accurate system performance predictions, a detailed energy analysis should be performed to predict the net power, the available geothermal heat, and overall thermal efficiency using Eq. (1). Since the geothermal energy is produced at low enthalpy levels, ORC-based low-temperature geothermal power generation plants tend to have low thermal efficiencies: 10-13% reported by (DiPippo, 2007), 2.8-5.5% reported by (Gupta & Roy, 2007), and 5-9% reported by (Hettiarachchi et al., 2007). Maximizing generating power capacity is normally sought from these power plants by maximizing the geo-fluid flow rate (depending on the capability of the production well) with a limited geo-fluid temperature available from the geothermal resource. It was reported (Chandrasekharam & Bundschuh, 2008) that low-temperature geothermal production wells with geo-fluid temperature < 150 °C and geo-fluid flow rate > 900 l/min could generate electric power ranging from 50 to 700 kW<sub>e</sub>. When appropriate, multiple production wells could be installed using the same low-temperature geothermal energy reservoir so that a number of ORC power generation units could be cascaded to obtain larger power production rates from the plant (Gupta & Roy, 2007). Limited by the second-law of thermodynamics, the ideal (absolute maximum) efficiency of a thermoelectric power cycle, such as the low-temperature geothermal ORC power cycle, operating as a reversible heat engine between a heat source at a temperature  $T_H$  and a heat sink at a temperature  $T_L$  is Carnot efficiency, given as (Cengel & Boles, 2008)

$$\eta_{\text{ideal}} = \eta_{\text{Carnot}} = 1 - \frac{T_L}{T_H} \quad (6)$$

For example, for an ORC power system using a geo-fluid extracted from a low-temperature geothermal heat source at 130 °C (403 K) and a heat sink (condenser) at 40 °C (313 K), the maximum ideal Carnot efficiency can be calculated using Eq. (6) to be approximately 22.3%. For an actual (irreversible) ORC-based geothermalsystem operating between the same temperature limits would have lower efficiency. Another measure of the performance of the low-temperature geothermal ORC power plant can be obtained using the Second-Law of thermodynamics in the form of exergetic efficiency,  $\eta_{ex}$ , given as

$$\eta_{ex} = \frac{\dot{W}_{out}}{\dot{Ex}_{geo}} \quad (7)$$

The exergetic efficiency in Eq. (7) is defined as the ratio of the actual net power output from the power generation system to the maximum theoretical power that could be extracted from the geo-fluid at the geothermal resource state relative to the thermodynamic dead-state. This involves determining the rate of exergy carried by the geo-fluid to the ORC power system. Typically, the design and operation of geothermal binary power generation systems should be optimized in order to increase their thermal and exergetic efficiencies guided by the Carnot efficiency (Ismail, 2011b).

### 2.3. ORC-based low-temperature geothermal power generation: Environmental & economic aspects

Geothermal power generation is relatively pollution-free and considered to be a clean technology for power generation (Dickson & Fanelli, 2005) and it tends to have the largest technological potential compared to other renewable energy sources used for power generation (Hammons, 2004). Once up and running, GHG emissions are typically zero when low-temperature geothermal energy reservoirs are utilized using ORC power systems, since all of the produced geo-fluid is injected back into the reservoir (Hammons, 2004). In this case, one of the effective ways of getting rid of hazardous chemical constituents of geothermal water (e.g. trace metals) is re-injection. ORC-based low-temperature geothermal power generation systems are far less environmentally intrusive than alternative power generation systems in several respects, e.g. they are essentially zero-GHG emission systems and have low land usage per installed megawatt (DiPippo, 2008). 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 siting of boreholes and roads will have to be taken into account, soil and vegetation erosion, which may cause changes in ecosystems, has to be watched. It should be noted that many geothermal installations are in remote areas where the natural level of noise is low and any additional noise is very noticeable (Dickson & Fanelli, 2005). There is a relatively larger production of waste-heat energy in geothermal systems, and this needs to be dissipated in an environmentally acceptable way. In ORC-based low-temperature geothermal power sys-

tems, the thermal impact is much reduced by disposing of waste geothermal water using deep re-injection approach so that the thermal impact of the waste heat becomes insignificant (Dickson & Fanelli, 2005). Appropriate measures should be applied to prevent leakage of the binary working fluid from ORC power generation units to the environment (Yamada & Oyama, 2004); normally the installations of these units are made perfectly tight to meet high safety standards.

In theory, geothermal energy potential is present below the entire surface of the Earth. In practice however, special geologic settings are required for geothermal energy to be economically exploited (Grasby et al., 2011). Generating electricity using ORC-based geothermal technology is very cost-effective and reliable (Chandrasekharam& Bundschuh, 2008; Dickson & Fanelli, 2005). Table 1 compares electrical energy costs produced by various renewable energy technologies. The cost of geothermal energy for generating electricity is favourable compared to other energy sources. The reported costs of low-temperature based small geothermal power plants vary from 0.05 to 0.07 US\$/kWh for units generating < 5 MW<sub>e</sub> (Chandrasekharam& Bundschuh, 2008).

Renewable Energy Source	Current Energy Cost (US cents/kWh)	Turnkey Investment Cost (US\$/kW <sub>e</sub> )	Potential Future Energy Cost (US cents/kWh)
Geothermal	2-10	800 – 3,000	1-8
Wind	5-13	1,100 – 1,700	3-10
Solar photovoltaic	25-125	5,000 – 10,000	5-25
Solar thermal	12-18	3,000 – 4,000	4-10
Biomass	5-15	900 – 3,000	4-10
Tidal	8-15	1,700 – 2,500	8-15
Hydro	2-10	1,000 – 3,000	NA

**Table 1.** Energy and investment costs for electric power production from different renewable energy sources (Hammons, 2004; Dickson & Fanelli, 2005).

The unit cost of electricity generated from low-temperature geothermal based small power plants is compared in Table 2. Moreover, the unit cost of electricity from small-scale geothermal plants (<5 MW<sub>e</sub>) is much lower than the average cost of 0.25 US\$/kWh supplied through diesel generators (Chandrasekharam& Bundschuh, 2008). The total investment for a geothermal power plant mainly includes the following types of costs: (1) cost of exploitation, (2) cost of drilling, (3) cost of power plant (capital cost of design and construction), and (4) operating & maintenance costs (Chandrasekharam& Bundschuh, 2008). The first two types are referred to as subsurface costs whereas the other two are referred to surface costs. The high initial investments incurred through the exploration, drilling and development of wells and the production field is an important constraint on future geothermal power development. Despite low maintenance and operational costs, high initial investments are often a strong

restrictive(Grasby et al., 2011). For small-scale geothermal power plants (<5 MW<sub>e</sub>) utilizing low-temperature resources, the subsurface cost typically accounts for approximately 30% of the total investment costs whereas the surface cost accounts for the remaining 70%.

Net Power (kW <sub>e</sub> )	Capital Cost (US\$/net kW <sub>e</sub> )			O&M Cost (US\$/year)
	Geothermal Resource Temperature (°C)			
	100	120	140	
100	2,786	2,429	2,215	21,010
200	2,572	2,242	2,044	27,115
500	2,357	2,055	1,874	33,446
1000	2,143	1,868	1,704	48,400

**Table 2.** Unit cost of electricity generated from low-temperature based small power plants (Chandrasekharam & Bundschuh, 2008; DiPippo, 2008).

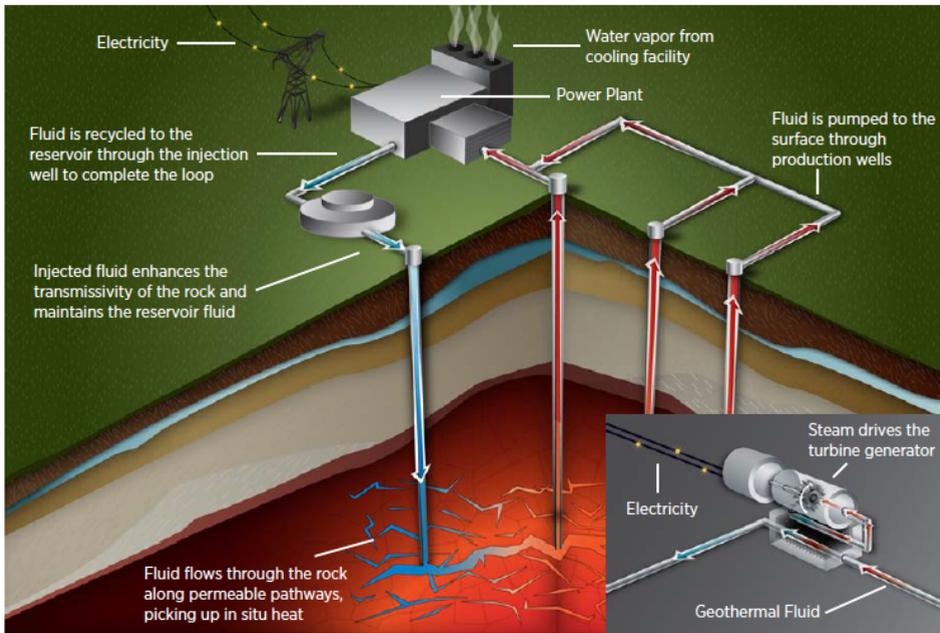
Generating electricity using low-temperature geothermal ORC technology is very reliable due to its advanced technological aspects. However, the maintenance costs and shutdowns could be reduced when the technical complexity of the plant is on a level that is accessible to local technical personnel or to experts who are readily available (Dickson & Fanelli, 2005). As mentioned before, 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. It was reported (Dickson & Fanelli, 2005) that 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. It was also reported (Panea et al., 2010) that 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.

### 3. CO<sub>2</sub> – based EGS for combined power generation& CO<sub>2</sub> sequestration

#### 3.1. Enhanced geothermal systems (EGS) – developments & utilization

EGS, also known as engineered geothermal systems, are reservoirs that have been stimulated(e.g. hydraulic stimulation) and engineered to extract economical amounts of heat from unproductive geothermal resources that lack heat-carrier fluid circulation, permeability and/or porosity. EGS is a new type of geothermal power technology and has the potential to become a significant sustainable and renewable power source for the future (Grasby et al., 2011, Kalra et al., 2012). The EGS concept is currently the subject of several international re-

search investigations and once brought to successful production, will significantly expand the regions where geothermal power generation is feasible. In an EGS, a fluid (typically cold water or brine) is injected and fractures are induced to form subsurface heat exchange systems. The heated fluid is then produced from a parallel well where heat can be used at surface to generate electricity (Huenges, 2010; Majorowicz & Grasby, 2010). Additional production-injection wells are drilled to extract more heat from large volumes of rock mass to meet power generation requirement (Azim et al., 2010). This technology does not require conventional natural convective hydrothermal resources located at depth, nor an initial high permeability of the reservoir, for power generation (once linked with ORC power technology). A schematic diagram showing a typical EGS concept is shown in Figure 3. EGS has the potential for accessing the Earth's vast resources of heat located at depth to help meet future increasing energy demands. The EGS concept has driven increased interest in widely development of this geothermal energy potential by orders of magnitude (Huenges, 2010; Majorowicz & Grasby, 2010; Azim et al., 2010). It was reported (Chandrasekharam & Bundschuh, 2008) that developing countries can access all low-temperature geothermal and EGS sources for green electricity generation immediately.



**Figure 3.** A conceptual model showing how EGS works (Source: <http://energyinformative.org>)

The basis, on which today's EGS projects are developed were laid out in the early 1970s, when an EGS (hot dry rock (HDR)) development concept was implemented at Los Alamos National lab, involving drilling a well into hot crystalline rock, using pressurized water to

create a large vertical fracture, and ultimately to drill a second well to access that fracture at some distance above the first wellbore (Huenges, 2010; Stephens & Jiusto, 2010). It was the first attempt anywhere to make a deep, full-scale HDR reservoir. Significant research and production plants are under construction or operation to take advantage of this abundant renewable energy opportunity (Kalra et al., 2012). For example, power plants driven by EGS are currently being developed and tested in Australia, Germany, Japan, France, USA and Switzerland (DiPippo, 2008; Azim et al., 2010). The largest EGS project in the world is a 25 MW<sub>e</sub> demonstration plant currently being developed in Cooper Basin, Australia. There are several EGS projects that are already or will soon produce power. Some of them are just for research and development (R& D) and some are for commercial purpose. Examples of the EGS projects around the world with their location, capacity, well depth, plant type, and the project type are summarized in Table 3.

EGS Project	Type	Country	Capacity (MW <sub>e</sub> )	Plant Type	Depth (km)
Soultz (EU)	R&D	France	1.5	Binary (ORC)	4.2
Desert Peak	R&D	USA	11-50	Binary (ORC)	(Unknown)
Landau	Commercial	Germany (EU)	3	Binary (ORC)	3.3
Paralana (phase I)	Commercial	Australia	7-30	Binary (ORC)	4.1
Cooper Basin	Commercial	Australia	250-500	Binary (Kalina)	4.3
The Geysers	Demonstration	USA	(Unknown)	Flash	3.5-3.8
Ogachi	R&D	Japan	(Unknown)	Flash	1.0-1.1
United Downs, Redruth	Commercial	United Kingdom	10	Binary (ORC)	4.5
Eden Project	Commercial	United Kingdom	3	Binary (ORC)	3-4

**Table 3.** EGS-based projects around the world (Azim et al., 2010).

An EGS project has several stages (Majorowicz & Grasby, 2010; Huenges, 2010; DiPippo, 2008); namely: (1) Identifying a potential site possessing the necessary characteristics through surface exploration, (2) Drilling an injection well to the depth required to reach the desired temperature, (3) Fracturing the rock in the subsurface by hydraulic stimulation (i.e. injecting a fluid at sufficient pressure to propagate fracture), (4) Creating and testing of the EGS reservoir storage capacity, (5) Drilling a production well for a doublet system or two-production wells for a triplet system (one injection & two production wells), (6) Creating fracture connectivity between the injection and the production wells, (7) Extracting heat en-

ergy from the rock by injecting cool fluid (typically water) through the injection well and producing hot fluid (in some cases steam) from the production wells, and (8) Operating the ORC power plant and maintain the EGS reservoir.

EGS for power generation is still relatively novel technology and remains to be proved on a large scale. Engineers & researchers in several countries throughout the world have been working on advancing EGS technology for few decades, but the technology has received limited attention and minimal financial support from either the public or private sector, with the exception of Australia's significant market investments. The high cost of drilling, which is estimated to account for a third to a half of EGS projected costs, is a major challenge to the technology (Stephens & Justo, 2010). The risks and uncertainties associated with EGS technology are other barriers as well.

### **3.2. Environmental and economic aspects of EGS for power generation**

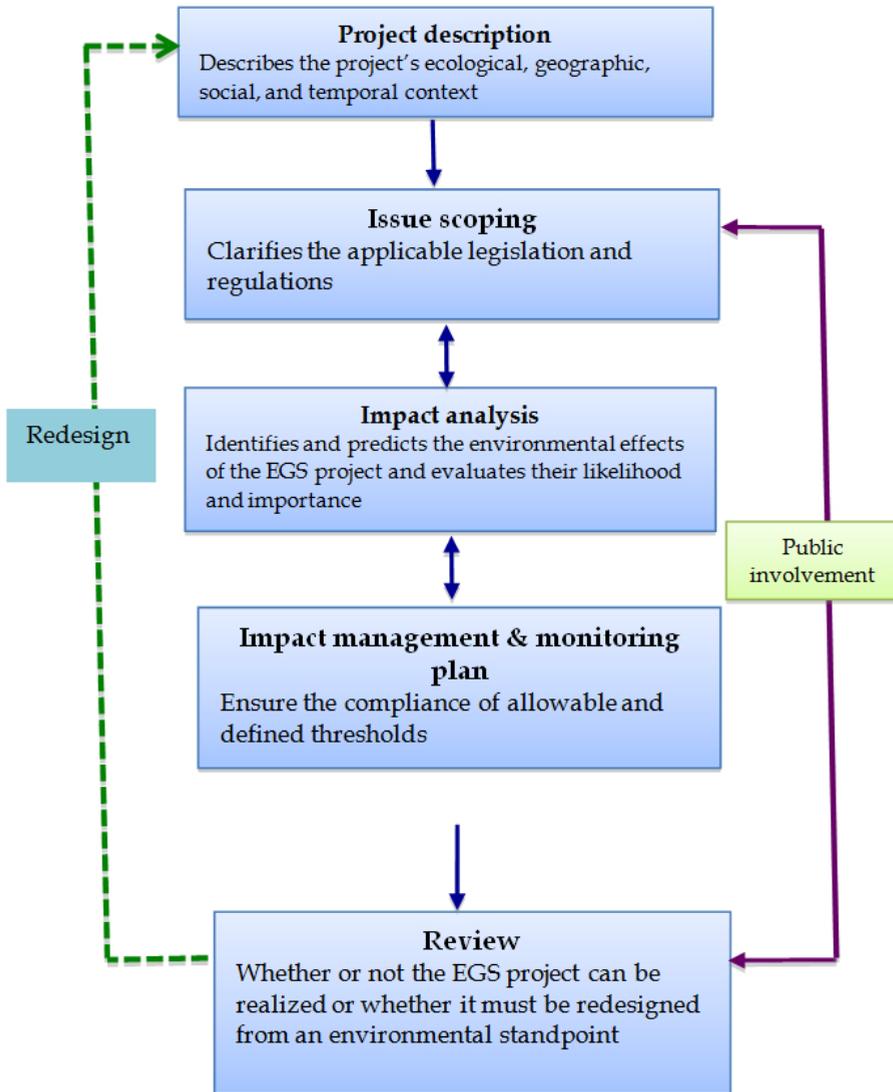
It was reported (Grasby et al., 2011) that impacts of geothermal development are relatively minor compared to many other energy developments, however there are still important challenges to be addressed. More particularly, it was reported (Azim et al., 2010) that the overall impact of EGS power generation plants on environment is remarkably lower than other conventional fossil fuel-fired and nuclear power plants. In addition, EGS plants may have lower impacts in comparison with other renewable energy sources such as solar, wind, hydroelectric, and biomass on an equivalent energy-output basis. This is primarily because a geothermal energy source is contained subsurface and need not to be exposed in the atmosphere and the surface energy conversion system (e.g. ORC unit) is relatively compact, thus making the overall size of the entire system attractively small. EGS power plants also provide environmental benefits by having minimal GHG and other emissions (zero emissions for the case of using ORC technology). Distinct from the conventional fossil fuels, there are minimal discharges of CO<sub>2</sub>, nitrogen or sulphur oxides or particulate matter resulting from its use, and there is no need to dispose radioactive materials. However, still there are impacts that must be considered and managed if enhanced geothermal energy resource is to be developed as part of a more environmentally sound, sustainable energy source for the future. The major environmental challenges for EGS are associated with ground water use and contamination, with related concerns about induced seismicity or subsidence as a result of water injection and production. Induced seismicity is a phenomenon in which a change in fluid pressure within a stressed rock formation leads to movement of the fractured rocks; the energy released is transmitted through the subsurface rock and may reach the surface with enough intensity to be heard or felt by people in the surrounding region (DiPippo, 2008; Majer et al., 2007). To mitigate risks related to induced seismicity, strategies and procedures are needed to set requirements for seismic monitoring and for prolonged EGS field operation. Technologies for imaging fluid pathways induced/injected by hydraulic stimulation in EGS fields would constitute a key improvement of the EGS concept. Issues of noise, safety and land use associated with drilling and production operations are also important but can be fully manageable (Huenges, 2010; Majorowicz & Grasby, 2010; Azim et al., 2010).

EGS technology has impacts on the global and local environment (Huenges, 2010; DiPippo, 2008). Therefore, it is important to identify and evaluate any impact which results from the implementation of an EGS plant at the beginning of a project. The goal must be to avoid or minimize adverse impacts on the environment during all stages of an EGS project (e.g., construction, operation, and deconstruction) and to meet the objectives and requirements of environment protection and preservation of finite resources (Huenges, 2010; Stephens & Jiusto, 2010). Potential impacts need to be addressed during planning environmentally sound EGS plants. The relevance and extent of the addressed impacts can vary from location to location. Even if EGS plants are not related to (continuous) gaseous emissions during operation (due to the carrying of the geothermal fluid in a closed loop system on the surface), environmental impacts such as airborne emissions or the consumptions of the finite energy resources (such as steel used for well completion or fuel for drilling rig operation) occur during other life cycle stages, therefore, all life cycle stages need to be considered in order to analyze the environmental performance of an EGS plant. In this regard, life cycle analysis (LCA) is a widely applied approach to evaluate and compare specific environmental impacts of different products or technologies (Huenges, 2010; Frick et al., 2010). The idea is to carry out a detailed analysis of the life cycle of the product or a duty emerged in response to increased environmental awareness of the public, the governments, and the industries. An LCA involves two main stages: the collection of a data, related to the product or duty and relevant for the environment, and interpretation of the collected information. For transparency and traceability of LCA results, standards, such as ISO 14040, ISO 14044 have been developed (Huenges, 2010; Frick et al., 2010). Based on this approach, aspects, which influence the environmental impact during the life cycle, and parameters, which need to be considered in the planning of the environmentally sound EGS plants, can be identified. According to given standards, the LCA is carried out in four steps: (1) Goal and scope definition to assess selected environmental effects (e.g., global warming potential, cumulated demand of finite energy resources, etc.) in the different life cycle stages and throughout the whole life cycle of EGS plants, (2) Inventory analysis, (3) Impact analysis to quantify the environmental effects (all inventoried material and energy flows are transformed to different impact indicators based on certain conversion factors), and (4) Interpretation of the results from the impact analysis.

EGS plants are related to different impacts on diverse parts of the local environment and different characteristics regarding their duration (continuous or temporary), reversibility, and their degree of probability. Many of the impacts on the local environment are related to assessing the EGS reservoir. Most of these impacts are known and technologically manageable based on the oil and gas exploration experiences. Adverse effects due to reservoir exploitation can be avoided with proper reservoir management and monitoring. Environmental impacts from the construction and operating the surface facilities are comparatively low (Dickson & Fanelli, 2005; DiPippo, 2008). In an EGS project, some environmental impacts and risks, however, need to be considered and evaluated in connection with the following EGS phases and activities (Huenges, 2010; Majer et al., 2007; DiPippo, 2008; Stephens & Jiusto, 2010):

1. **Drilling operations:** Drilling operations have a large impact on the surrounding environment and are associated with various risks. They are normally limited to the period of drilling operations (i.e., last only a couple of weeks or months). Environmental effects related to drilling operations may include: noise emissions, subsurface emissions, site preparations and alterations, airborne emissions, water usage (usually taken from nearby surface or groundwater bodies), waste disposal, and visual impact (due to night-time lighting, etc., from drilling rig).
2. **Reservoir stimulation:** Enhancing a geothermal reservoir for power generation includes injection of stimulation fluids under high pressure which could produce geo-mechanical changes in the subsurface (rocks may slip along pre-existing fractures. Depending on the surrounding rock formations and their magnitude, geo-mechanical alterations can be followed by build-up and dispersion of microseismic activities up to the surface. Induced seismicity, which can result from stimulation, helps to identify the extent of the fracture network in the reservoir. Despite the fact that geo-mechanical changes can lead to damage of buildings and even be hazardous for human beings and animals, the earth tremors caused by EGS reported so far can be categorized a sensible but not as adverse impacts on the environment. In almost all cases, these events in the deep reservoir are of such low magnitude that they are not felt at the surface. However, based on the present state of knowledge, larger impacts cannot be totally excluded since the knowledge about the stress situation and the development of larger microseismic events in the subsurface is still insufficient.
3. **Reservoir exploitation:** The exploitation of an EGS reservoir can lead to different alterations in the reservoir and the surrounding subsurface. Impacts on the local subsurface environment such as hydraulic and thermal alterations as well as circulation losses need to be considered for sustainable reservoir management, but are not considered as adverse environmental impacts.
4. **Installation and operation of surface facilities:** The installation of the subsurface part of an EGS power plant, such as a binary ORC power unit is related to general environmental impacts which come with construction work such as noise emissions and dust creation.
5. **Dismantling of well infrastructure:** In EGS plants, the decommissioning of the deep wells need be managed since abandoned wells are a potential source for material emissions to the subsurface. With proper closing and filling of the wells, this can be eradicated.

For the development of EGS projects, different environmental regulations, standards, and permission procedures are binding depending on the country's legislations. A widely used tool in this context is the environmental impact assessment (EIA); first established in USA in the 1970s and used today in many countries to ensure that all possible environmental impacts of planned EGS projects are identified and assessed before a decision is made for getting permission for an EGS project for power generation (Huenges, 2010). The most important steps of atypical EIA process are briefly outlined in Figure 4.



**Figure 4.** A schematic diagram showing the important steps in an EIA process for an EGS project (Huenges, 2010).

Costs for geothermal plants have been dropping and are becoming more competitive (Pruess, 2006). EGS-based ORC power technology has the potential to replace other more costly and environmentally destructive technologies. It also has the potential to provide greenpower generation at affordable prices, thereby improving the standard of living and socio-economic potential through creation of jobs in many regions (Grasby et al., 2011). The planning of EGS projects and especially the decision to realize a project is based on the

estimation of the costs and revenues, which are related to a project. Since EGS projects are characterized by a long planning period, large initial investments and a long technical life-time, estimating prospective costs and revenues involves uncertainties and risks (Huenges, 2010). This is true because no reliable statements on markets development, detailed geologic site conditions, or technological problems can be made at the start of a project. In order to minimize existing risks, cost influences must be known and risks must be analyzed. The total costs of an ORC-based EGS project are dominated by the investments at the start of the project (Huenges, 2010; Stephens & Jiusto, 2010; DiPippo, 2008). These investments mainly consist of costs for the subsurface components, including: (1) reservoir exploration, (2) well drilling and completion - the most significant cost factor in all geothermal operations is associated with drilling and well completion (Grasby et al., 2011), (3) reservoir engineering measures, (4) installation of the geothermal fluid loop, and (5) construction of the ORC-based power unit. Typical EGS drilling costs as a function of well depth are shown in Table 4. As mentioned before, drilling costs estimated to account for a third to a half of EGS projected costs; a major challenge to the EGS technology (Stephens & Jiusto, 2010). As shown in Table 4, EGS well costs are not a linear function of depth, but additionally reflect, temperature, extent of casing employed, difficulty in drilling, and lithologic characteristics (Grasby et al., 2011). In addition, surface related costs, such as operation & maintenance O& M costs (i.e., annual operating costs for personnel, material consumption, overhaul and maintenance) are considered. The operating and maintenance cost of an EGS power plant has two important components: (a) the O& M for the ORC power plant and (b) the well field maintenance cost. The ORC power plant O& M costs were estimated based on experience in similar power plant configurations and ORC installations. This is usually a percentage of the installed cost of the power plant on a yearly basis (Kalra et al., 2012). It was reported (Grasby et al., 2011) that the techniques and technologies related to EGS projects are evolving rapidly so as its estimated costs and that EGS technology may not be commercially viable at this time. However, it was suggested (Grasby et al., 2011) that renewable resources such as EGS offer attractive power market contributions beyond power generation.

Well Depth (km)	EGS Well Category	Estimated EGS Drilling Cost (\$ millions)
1.5	Shallow well	0.90
2.5		1.81
3.0		2.55
4.0	Mid range well	5.10
5.0		6.45
6.0	Deep well	8.92
7.5		13.83

**Table 4.** Typical EGS drilling costs as a function of well depth (Azim et al., 2010).

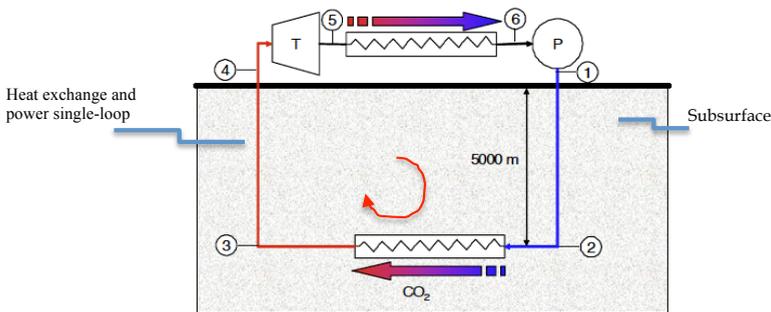
### 3.3. EGS using CO<sub>2</sub> as the working fluid for green power generation and simultaneous carbon sequestration

It was reported (Pruess, 2006) that previous attempts to develop EGS in Japan, USA, Europe and Australia have all employed water as a heat transmission fluid. Although, water has many properties that make it a favorable medium for this purpose, it also has serious shortcomings. An unfavorable property of water is that it is a strong solvent for many rock minerals, especially at elevated temperatures. In this case, injecting water at high pressure into hot rock fractures, as part of an EGS resource operation & utilization, results in strong dissolution and precipitation effects that change fracture permeability and make it very difficult to operate an EGS reservoir in a stable manner. In 2000, Brown, D. (Pruess, 2006) proposed a novel EGS concept that would utilize supercritical CO<sub>2</sub> instead of water as heat exchange (carrier) fluid, and would simultaneously achieve CO<sub>2</sub> geologic sequestration as an additional benefit. There are only very few investigations that characterized the performance of CO<sub>2</sub> as working fluid in EGS applications. For example, Pruess (Pruess, 2006) performed numerical simulations and evaluated thermophysical properties in order to explore the heat transfer and fluid dynamics characteristics in an EGS reservoir that would be operated with CO<sub>2</sub>. It was found that CO<sub>2</sub> is superior to water in its ability to exchange heat from hot fractured rock. Carbon dioxide also offers certain advantages with respect to wellbore hydraulics, in that its larger compressibility and expansivity as compared to water would increase buoyancy forces and would decrease the parasitic power consumption (thus reduce pumping cost) of the EGS fluid circulation system. This is because the larger expansivity of CO<sub>2</sub> would generate large density differences between the cold CO<sub>2</sub> in the injection well and the hot CO<sub>2</sub> in the production well, and therefore provide buoyancy force that would reduce the power consumption of the fluid circulation system. Another interesting feature of CO<sub>2</sub> is that its lower viscosity, tend to yield larger flow velocities for a given pressure gradient. In addition, CO<sub>2</sub> would be much less effective as a solvent for rock minerals, which would reduce or eliminate scaling problems, such as silica dissolution and precipitation in water-based systems (Pruess, 2006). It was also reported (Pruess, 2006) that while the thermal and hydraulic aspects of a CO<sub>2</sub>-based EGS system look promising, major uncertainties remain with regard to geochemical interactions between fluids and rocks. It was concluded in (Pruess, 2006) that an EGS system running on CO<sub>2</sub> has sufficiently attractive features to warrant further investigation. It was suggested that an EGS using CO<sub>2</sub> as heat transport and exchange fluid could have favorable geochemical properties, as CO<sub>2</sub> uptake and sequestration by rock minerals would be quite rapid.

Supercritical CO<sub>2</sub> can also be used as the working fluid of the power cycle before it is sent back to the EGS reservoir. For example, in a study by (Gurgenic et al., 2008), it was reported that there is a significant potential to use supercritical CO<sub>2</sub> as working fluid in the power loop as illustrated (Gurgenic et al., 2008) in Figure 5. Significantly higher energy conversion efficiencies were predicted using a single-loop system with the CO<sub>2</sub> being both the heat exchange and the power cycle working fluid. It was reported (Gurgenic et al., 2008; Atrens et al., 2011) that the loops in either of the two cycles (i.e. subsurface loop and surface power loop) do not have to be closed. For example, if there is ready access to CO<sub>2</sub> (e.g., at a geother-

mal installation situated close to a coal-fired power plant), the captured CO<sub>2</sub> from the plant can be run through the geothermal reservoir first and then sequestered in a geologic sequestration site of choice.

CO<sub>2</sub>-based EGS has been examined in (Atrens et al., 2011) from a reservoir oriented perspective, and as a result thermodynamic performance was investigated. It was reported (Atrens et al., 2011) that economics of the system are still not well understood, however. In their study, the economics of the CO<sub>2</sub>-based EGS technology was explored for an optimized power plant design and best-available cost estimation data. It was demonstrated in (Atrens et al., 2011) that near-optimum turbine exhaust pressure can be estimated from surface temperature. It was found that achievable cooling temperature is an important economic site consideration alongside EGS resource temperature. The role of sequestration as part of CO<sub>2</sub>-based EGS was also examined in (Atrens et al., 2011), and it was concluded that if fluid losses occur, the economic viability of the concept depends strongly on the price associated with CO<sub>2</sub> (Atrens et al., 2011). Potential barriers to implementation of CO<sub>2</sub>-based EGS technology include access to CO<sub>2</sub> at an acceptable cost, proximity of the EGS to the electricity grid, and access to cooling water. Similar issues related to long-term responsibility for the resultant reservoir, including the liability for future CO<sub>2</sub> leakage from the geologic sequestration site. In another study by (Randolph & Saar, 2011), it was suggested that using CO<sub>2</sub> as the working fluid in geothermal power systems may permit utilization of lower temperature geologic formations than those that are currently deemed economically viable, leading to more widespread utilization of geothermal energy. However, additional exploration of economics regarding the opportunities and issues for CO<sub>2</sub>-based EGS technology for combined carbon sequestration and power generation is needed.



**Figure 5.** A conceptual model showing a single-loop system with CO<sub>2</sub> used for combined heat exchange and power cycle (Gurgenic et al., 2008).

## 4. Conclusion

An increasing concern of environmental issues of emissions & pollution, in particular global warming and the constraints on consuming conventional energy sources has recently resulted in extensive research into innovative renewable and green technologies of generating

electrical power. One of these innovative emerging technologies includes renewable low-temperature (low-enthalpy) geothermal energy source for clean electrical power generation. This promising technology offers potential applications in generation of electric power which can be produced using the vast renewable low-temperature geothermal energy resources available worldwide. In this chapter, the concept of ORC binary technology for power generation using low-temperature geothermal heat source was introduced and its potential applications and limitations for small-scale geothermal power generation and its relevant environmental and economic considerations were presented and discussed. Also, recent developments of ORC-based low-temperature geothermal power generation with their significant and relevant applications were presented and discussed. A number of successful ORC binary plants were installed in different locations (e.g. remote and rural sites) worldwide which demonstrated the ability of this promising alternative and green technology to utilize renewable low-temperature geothermal energy sources for generating electricity. Also, several patents were reported on the application of this innovative technology. 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. Currently, ORC power cycles exhibit great flexibility, high safety (installations are perfectly tight), and low maintenance when coupled with low-enthalpy geothermal heat sources. The future use of low-temperature geothermal energy resources for generating electricity would very much depend on further overcoming technical barriers both in utilization and production, and its economic viability compared to other conventional and renewable energy sources used for power production. Another emerging "dual-benefit" technology is EGS using CO<sub>2</sub> as the working fluid for combined clean power generation and geologic CO<sub>2</sub> sequestration. CO<sub>2</sub> is of interest as a geothermal working fluid mainly because it transfers geothermal heat more efficiently than water. While power can be produced more efficiently using this technology, there is an additional benefit CCS for reducing GHG emissions. The second part of the chapter presented the merits and fundamental aspects of CO<sub>2</sub>-based EGS technology. In 2000, Brown, D. (Pruess, 2006) proposed a novel EGS concept that would utilize supercritical CO<sub>2</sub> instead of water as a more efficient heat exchange (carrier) fluid (due to its favorable properties over water), and would simultaneously achieve CO<sub>2</sub> geologic sequestration as an additional benefit. It was found that CO<sub>2</sub> is superior to water in its ability to exchange heat from EGS hot fractured rock and reduce hydraulic power consumption for fluid injection and circulation in the EGS reservoir. It was concluded that an EGS system running on CO<sub>2</sub> has sufficiently attractive features to warrant further investigation. It was also concluded that EGS for power generation is still relatively a novel technology and remains to be proved on a large scale and that further research is needed for additional exploration of technological and economic aspects regarding the opportunities and challenges for CO<sub>2</sub>-based EGS technology for combined carbon sequestration and power generation.

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