1 Introduction

1.1 Motivation and objectives

The economy and the world's population have resulted in an enormous demand for energy. Since the beginning of the 21st century, the total energy consumption has increased to 60 %. By the end of 2019, it has reached 581.1 exajoules (1 EJ = 10^{18} J), an increment of more than three times during the last fifty years. The increase in energy demand between 2010-2019 is shown in Figure 1.1. The highest consumption was recorded for Asia Pacific, North America, Europe, CIS (Commonwealth of Independent States), Middle East, South & Central America, and Africa. However, due to the Covid-19 pandemic in 2020, the world's energy consumption has declined to 4.5 %, the most significant decline ever recorded since World War II. Due to the imposition of lockdowns and limited transportation, the drop in oil consumption has been recorded around three-quarters of the total decline in energy demand. Nevertheless, the energy demand is expected to rebound by 4.6 % in 2021-22 [1].

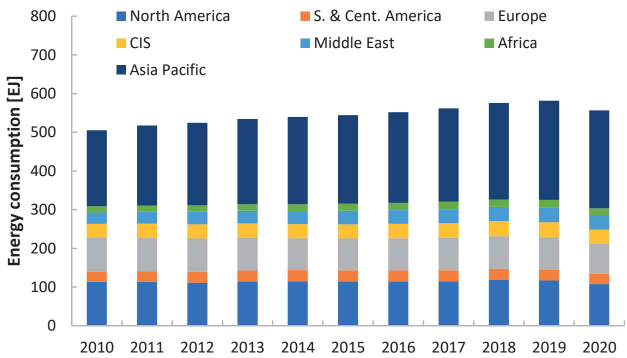

Figure 1.1 World energy consumption by region [2]

Due to the continuous decline in conventional petroleum resources, unconventional energy resources are currently playing an important role in meeting energy demands. In fact, from a broader spectrum, fossil fuels are still contributing a significant share in the total energy supply (Figure 1.2). However, fossil fuels are finite and non-renewable. Once fossil fuels have been produced through natural processes, it takes a long time to replenish them compared to the current consumption rate. In addition, these fuels are creating momentous complications for human health and the global climate.

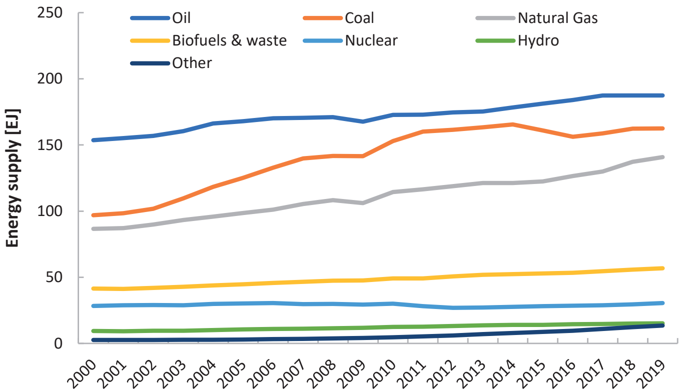

Figure 1.2 World energy supply by source [3]

In the United States, most of the electricity is generated from coal, causing severe industrial pollution. In 2020, coal demand dropped by 220 million tons of coal equivalent (4 %), wherein the advanced economies accounted for more than half of coal's global decline. However, there is still a long way to squeeze out coal from the power sector. According to a survey, burning fossil fuels is responsible for about three-quarters of greenhouse gas emissions globally [4]. China is currently the world's largest energy consumer and accounts for one-third of global CO_2 emissions. However, the Chinese government aims to achieve a CO_2 emissions peak before 2030 and attain carbon neutrality before 2060 [5].

The power, transport, and thermal sectors consume most of the energy each year. It has been recorded that 41% of CO_2 emissions come from the power sector, while the transport and industrial sectors contribute about 42% [6]. These carbon emissions trap solar energy in the atmosphere, raising global temperature. Moreover, extreme weather patterns, adverse effects on food cultivation seasons, severe droughts of water supply, and increasing sea levels are the outcomes of carbon emissions. Therefore, there is an immense need to shift towards zero or low-carbon emission energy sources like renewable technologies.

The energy from natural resources like sun, wind, hydro, and thermal from the earth's crust is categorized as renewable energy. It can replenish itself over a while without exhausting the earth's capital. Renewable energies emit no or low greenhouse gases and air pollutants, which are beneficial for the climate and human health. Promisingly, a tremendous increase in renewable energy generation has been recorded during the last decade (Figure 1.3). In 2020, despite a fall in overall energy demand, energy generation from renewables (excluding hydroelectricity) recorded its largest-ever increase to 358 TWh. More than 65 % of renewable energy from the Asia Pacific region has been contributed from China, with roughly half of the global rise in wind and solar capacity [2]. Moreover, China, the European Union, and the United States expect to generate 900 TWh, 580 TWh, and 550 TWh from solar PV and wind in 2021, respectively [1]. Figure 1.4 shows the share of electricity that has been produced from renewable technologies in 2020 throughout the world, which portrays that renewables tend to have a sufficient stake in the total electricity mix.

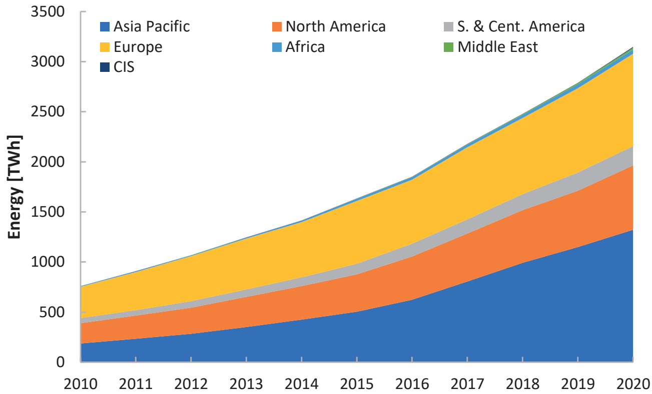

Figure 1.3 Share of renewables in power generation by region [2]

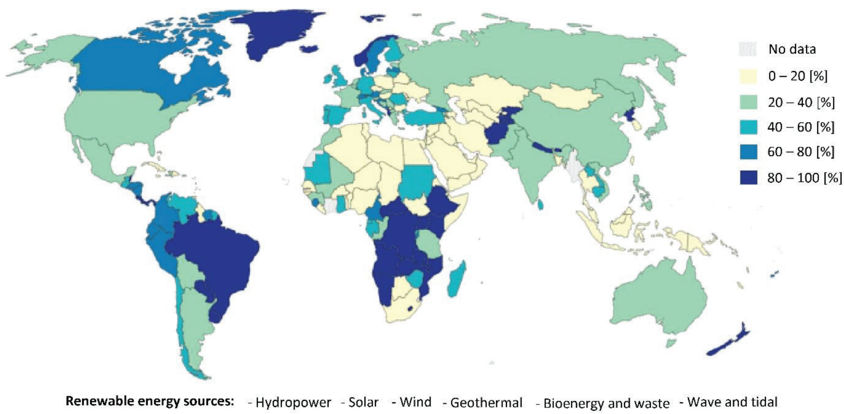

Figure 1.4 Share of electricity production from renewables in 2020 [7]

The primary renewable energy resources such as wind, solar, biomass, and geothermal have acted as suitable alternatives for fossil fuels [8]. Nevertheless, the exploitation of geothermal energy resources has captivated extensive attention due to its unique features like being stable, sustainable, clean, and independent of the weather. In addition, it is available for production for maximum working hours compared to other energy resources. Earth is considered to be a tremendous thermal energy resource. The hot molten core and decay of radioactive minerals are primary heat sources. Besides, the earth crust is a strong absorber of the sun's energy and acts as a solar heat accumulator [9].

The direct utilization of geothermal energy for washing, bathing, cooking, and therapeutic purposes was adopted hundreds of years ago. The first district heating system was installed in France during the fourteenth century, and the first deep well was drilled in Iceland in 1755 [10]. Hot dry rock (HDR) resources with ultra-low porosity and permeability have been exploited through well stimulation techniques and termed enhanced geothermal systems (EGSs) [11] (Figure 1.5). In EGS, cold fluid is injected through the injection well, and heated fluid is produced from the production well [12]. Within the depth of 10 km, more than 13 million exajoules (1 EJ = 10^{18} J) EGS resources have been estimated in the United States, of which 0.2 million EJ can be exploited through current technologies [11].

Similar to the petroleum industry, especially hydrocarbon production through unconventional reservoirs having too small permeability to achieve economic flow rates, reservoir stimulation is also a key technology for HDR development. Different approaches have been developed to enhance the well flow rate through tight formations, including hydraulic fracturing, thermally induced fracturing, and chemical stimulation [13-16]. However, EGSs have been established worldwide by applying hydraulic fracturing with different success rates such as Fenton Hill in New Mexico, Soultz in France, Hijiori in Japan, Paralana in Australia compared with other stimulation methods [17]. In hydraulic fracturing, artificial fractures are created by injecting fluid with high pressure, and fractures are kept open with solid proppants' support. Nevertheless, highly viscous gel and proppants have rarely been used in geothermal field operations [18].

With the rapid developments in petroleum technologies, drilling a horizontal well over 1000 m deep is possible. Multi-stage fracturing through a horizontal well is preferable to acquiring larger stimulated reservoir volume (SRV) for geothermal exploitation. However, individual fracture configuration mainly depends on fracture spacing and orientation of in-situ stresses. Longitudinal and transverse fractures can be obtained by selecting horizontal well trajectories in maximum and minimum in-situ stress direction, respectively (Figure 1.6).

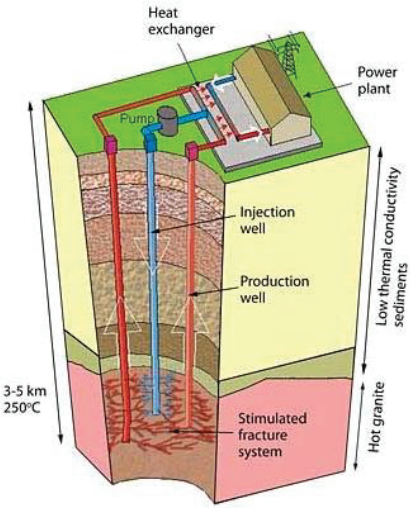

Figure 1.5 Enhanced geothermal system (source:geothermalworldwide.com/egs.html)

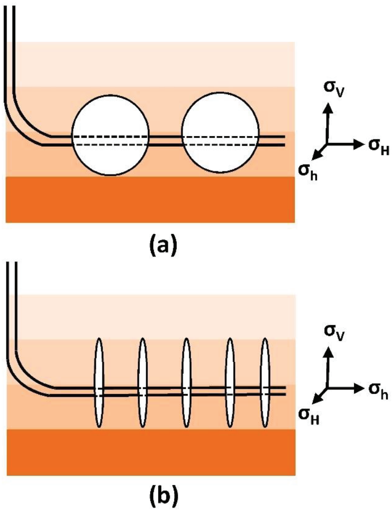

Figure 1.6 Demonstration of multiple fracture system in a horizontal well (a) longitudinal (b) transverse

Currently, many of the conceptual and real EGSs are vertical or sub-vertical, while production performances of horizontal wells are hardly reported. The horizontal well drilling in hard and deep high-temperature formations is a challenging task that involves higher operational costs. In addition, suitable configurations of multiple fractures in connection with preferable flowing paths, maintaining the thermal lifetime of the project with economic fluid production rates and low pumping pressure requirement, are significant issues [11]. However, by combining EGS with horizontal well and multiple hydraulic fractures, many advantages can be obtained: improved well connectivity in tight HDR, adequate SRV, and increased circulation rate with enhanced sweep efficiency.

Therefore, it is imperative to examine and enhance the performance of EGSs using advanced technologies such as multiple hydraulic fracturing through horizontal well, and addressing the related technical issues. In this study, numerical modeling has been conducted to investigate the heat extraction performance of EGSs through multiple hydraulic fractures considering coupled Thermal (T), Hydraulic (H), and Mechanical (M) effects. Moreover, the depleted fractured system has been studied to store surplus renewable energy to extend the EGS project's life.

1.2 Thesis outline

This thesis focuses on the application potential of massive multiple hydraulic fracturing under the influence of stress shadow in EGS to obtain large SRV for heat and electricity generation. In addition, the storage of surplus energy in depleted EGS has also been investigated. The research contents of the thesis are presented in Figure 1.7.

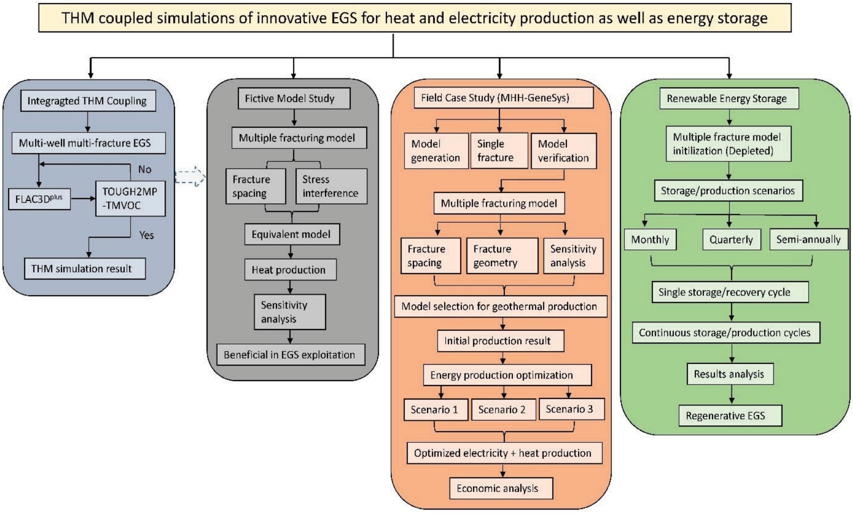

Figure 1.7 Research contents and flow chart of the thesis

In chapter 2, the theoretical background of geothermal reservoirs, their types, use of different geothermal power plants for heat and electricity production, and significant worldwide EGS sites have been briefly discussed. Afterward, governing equations corresponding to geo-processes during stimulation operation are presented. In addition, a comprehensive review of the mathematical models for hydraulic fracturing has been described. Moreover, multistage fracture placement designs and the impacts of stress shadow on fracture configuration are highlighted.

Chapter 3 presents the numerical study performed for geothermal energy production from multiple fractures using a fictive model. Based on the developed powerful simulator FLAC3D^{plus}, fractures are created sequentially through a horizontal well considering stress superposition effects. Subsequently, the fracturing results are imported to the developed simulator TOUGH2MP-TMVOC for energy production. Several recommendations to enhance heat production have been proposed after considering stress shadow effects, fracture spacing, and stimulated fracture areas.

A case study using the field data of the GeneSys-EGS project has been performed after developing the computing scheme during numerical modeling for geothermal energy exploitation, in chapter 4. The generated model has been verified firstly using bottom hole pressure (BHP) history matching. Massive multiple fracturing operations considering different fracture spacing with stress shadow have been conducted, and based on fracturing results, a suitable multiple fracture scheme for geothermal exploitation is selected. The initial energy production results suggested the need for energy production optimization. Therefore, different optimization scenarios have been studied, and enhanced energy production results have been obtained. In addition, a comprehensive economic analysis has been presented by adopting various cost factors, and the levelized cost of electricity has been compared with Germany's current electricity price.

In chapter 5, an innovative concept of regenerative EGS is proposed further to integrate heat and electricity production as well as storage of surplus renewable energy. This concept can make surplus energy usable and keep a geothermal reservoir much renewable by reducing the reservoir temperature reduction rate. In addition, any salt scaling/crystallization in vertical and horizontal sections of wells could be removed using water with high injection pressure and temperature during the energy storage phase. After performing various energy storage/recovery scenarios based on different periods, suitable strategies for surplus energy storage and production during times of shortage have been proposed concerning the investment perspective. The results depict that together with energy storage, an EGS project can be made regenerative in reality.

2 Fundamentals of geothermal reservoirs and hydraulic fracturing

2.1 Geothermal reservoirs

A geothermal reservoir is a volume of hot rock formations through which heat can be produced economically. The basic requirements of a geothermal system include a significant amount of heat, hot fluid, and fluid flow permeability. Geothermal energy is considered one of the most reliable renewable energy sources because of its stability and weather independence. It evolves due to two sources; (a) transfer of energy from the hot molten core to the exterior of the earth (b) decay of the radio-active elements [19]. The major radio-active elements that increase the earth's temperature are uranium-238, uranium-235, thorium-232, and potassium-40. It has been estimated that the earth's internal energy flows at a rate of 44.2 TW and is restored by the radioactive decay of the minerals at a rate of 30 TW [20-21]. The interior of the earth has a temperature above 5000 K [22] and is considered to be a huge source of geothermal energy [23] (Figure 2.1). An enormous amount of heat energy exists within the earth, but the exact calculation of earth energy varies widely due to different calculation procedures [9]. The tentative estimates suggest that the accumulated heat is about 12.6×10^{24} MJ [19]. While, WEC-2013 estimated the amount about 540×10^{7} EJ (1 Exajoule = 1×10^{18} J). Moreover, it has been predicted that the exploitation of only 1% of geothermal energy is enough to accomplish the global energy demand at a constant consumption rate for 2800 years [9].

Generally, a rise in temperature with increase in depth is observed due to heat flow from the much hotter mantle. The temperature gradient ranges between 25 to 30 °C/km near the surface throughout the world. Therefore, a geothermal system can exist in a region with a normal or slightly above average temperature gradient. In addition, the feasibility of higher temperature rises in areas along tectonic plate boundaries and volcanic regions, where seismicity has transported hot material from the earth's interior. In the UK, the average geothermal gradient is 26 °C/km. In contrast, more than 50 °C has been found in southern Australia, signifying one of the most suitable locations for geothermal power plant installations in the world [24]. The practice of geothermal energy in the forms of hot springs and space heating has an old history that links with ancient Paleolithic and Roman times. The geothermal heating system's inception took place in the 14th century from a French town named Chaudes-Aigues, while the first commercial steam-operated turbines commenced in 1958 in New Zealand for electricity generation [9].

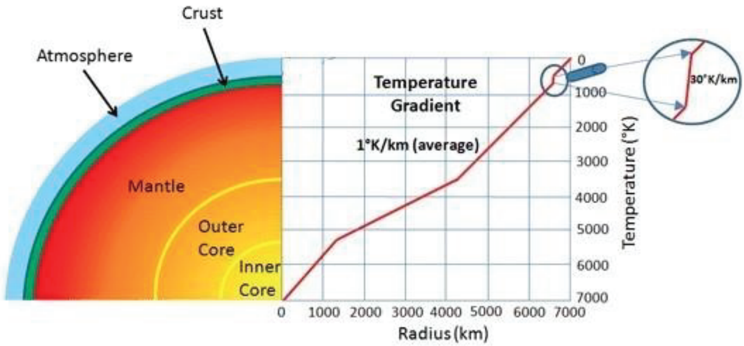

Figure 2.1 Earth's structure and geothermal gradient (modified from source: www.mpoweruk.com/geothermal_energy)

2.1.1 Geothermal reservoir types

Conventional geothermal resources can be either in the form of hydrothermal resources or in the form of petrothermal resources (HDR) [25].

i Hydrothermal systems

The hydrothermal system uses underground fluids (water, steam) present in subsurface formations with adequate permeability to produce geothermal energy. The presence of magmatic intrusions near the earth's crust is helpful for economic geothermal energy developments as these encourage convective circulation of ground water. However, the exact well location to tap the hydrothermal system at industrial levels is vital. The whole system involves one production well and at least one re-injection well to keep the productivity and pressure of the reservoir constant and make a geothermal system sustainable. These systems are further classified based on phase dominance (water or vapor) and formation fluid temperature such as hot (above 100 °C), warm (between 60 to 100 °C), and thermal (> 20 °C) [26]. Water-dominated systems are present throughout the world, such as Olkaria in Kenya, Wairakei in New Zealand, Yangbajing in China, Hatchobaru in Japan. In comparison, vapor-dominated systems are pretty uncommon. Examples include Geysers in the United States, Matsukawa in Japan, and Larderello in Italy [10]. Germany has an abundance of hydrothermal systems, specifically in the regions of the North German Basin, the South German Molasse Basin, and the Upper Rhine Garben [27]. In the North German Basin, many formations contain sandstone strata with a thickness of 20 m, porosity > 20 %, and permeability > 250 mD, making a reservoir suitable for geothermal use. Similarly, the Malm (karstic-dolomotic fractured