TECHNICAL ASSESSMENT FOR GEOTHERMAL POWER

SECTOR: ELECTRICITY GENERATION

AGENCY LEVEL: UTILITIES

KEYWORDS: GEOTHERMAL ENERGY, ELECTRICITY GENERATION, GRID, RENEWABLE ENERGY SOURCE

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ACRONYMS AND SYMBOLS

- GHP - Geothermal heat pumps
- H_2S - Hydrogen sulphide
- H_2 - Hydrogen
- CH_4 - Methane
- NH_3 - Ammonia
- N_2 – Nitrogen
- NCG - non-condensable gases
- ORC - Organic Rankine Cycle
- MIT - Massachusetts Institute of Technology
- AMPERE – Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates
- CO_2 – Carbon Dioxide
- DS – Degree Scenario
- EGS – Enhanced (or Engineered) Geothermal System
- ETP – Energy Technology Perspectives
- EU – European Union
- EWG – Energy Watch Group
- GEA – Geothermal Energy Association
- GEM-E3 – General Equilibrium model for Economy, Energy and Environment
- GHG – Greenhouse Gases
- Gt – Gigatones
- GW - Gigawatts
- HDR – Hot Dry Rock (Hot Drock)
- HSA – Hot Sedimentary Aquifer
- IEA – International Energy Agency
- IEEJ – The Institute of Energy Economics, Japan
- IGA – International Geothermal Association
- IMAGE/TIMER – Integrated Model to Assess the Global Environment/The Targets IMage Energy Regional model
- IPCC – Intergovernmental Panel for Climate Change
- IRENA – International Renewable Energy Agency
- LCA – Life Cycle Assessment
- LCOE – Levelized costs of electricity
- LUT - Lappeenranta University of Technology
- MESSAGE-MACRO – Model for Energy Supply Strategy Alternatives and their General Environmental impact with macroeconomic feedback
- O&M - Operations and maintenance costs
- PPM - Parts per million

- R&D – Research and Development
- RES – Renewable Energy Sources
- US – United States
- USD – United States Dollar
- TAM - Total Addressable Market
- TWh - Terawatt-Hours
- WEO – World Energy Outlook

EXECUTIVE SUMMARY

Project Drawdown defines geothermal as: *geothermal* systems for electricity generation, combining both mature technologies and future expectations for enhanced or engineered geothermal. This solution replaces conventional electricity-generating technologies such as coal, oil, and natural gas power plants. There are three main geothermal technologies: dry steam, flash steam, and binary cycle power plants. Flash plants are the most common type of geothermal, and make up around 70 percent of total global installed geothermal capacity. Binary plants are the most recently developed geothermal technology, and are able to tap into lower temperature reservoirs (at much higher costs) than flash plants. The selection of which technology to use for geothermal power generation depends on a number of factors, including the characterization of the geothermal resource, and the economic feasibility of the project. Geothermal energy has the potential to make a much more significant contribution on the global scale through the development of enhanced or engineered geothermal systems, particularly those exploiting "hot rock." Given the costs and limited full-scale system research to date, enhanced geothermal systems remains in their infancy, with only research and pilot projects existing around the world and no commercial-scale plants available to date.

This analysis models geothermal systems for electricity generation, combining both mature technologies and future expectations for enhanced geothermal systems adoption. The total addressable market for geothermal is based on projected global electricity generation in terawatt-hours from 2020-2050, with current adoption estimated at 0.4 percent of generation in 2018 (i.e. 90 terawatt-hours). Impacts of increased adoption of *geothermal* from 2020-2050 were generated based on three growth scenarios, which were assessed in comparison to a *Reference* Scenario where the solution's market share was fixed at the current levels. *Plausible* Scenario is based on the evaluation of IEA (2017) Energy Technology Perspectives 2DS and B2DS scenarios; IEA (2018) World Energy Outlook SDS; and Grantham Institute and Carbon Tracker (2017) NDC policy levels and original technology costs scenario using a medium growth trajectory, while Drawdown scenario adoption follows a high growth using the same scenarios. On both PD scenarios, geothermal represents around 2.8% and 2.6%, respectively on each scenario total electricity generation in 2050. Optimum scenario is based on three 100% RES scenarios of electricity generation by 2050 from Greenpeace (2015) Advanced Energy [R]evolution Scenario; Ram *et al.* (2019) scenario and Ecofys (2018) 1.5ºC scenario, with geothermal representing 5.7% of global electricity generation adoption by 2050.

Compared to the Reference Scenario, the financial results for the Plausible Scenario show marginal first costs of US$85.0 billion from 2020-2050, with over US$377 billion in savings. Under the *Plausible* Scenario, the adoption of geothermal technologies for electricity generation could avoid 6.4 gigatons of carbon dioxide-equivalent greenhouse gas emissions compared to a Reference Scenario where the solution does not increase its representation on the generation mix. Both the *Drawdown* and *Optimum* Scenarios have higher impacts on greenhouse gas emission reductions over 2020-2050 of 9.9 and 19.0 gigatons of carbon dioxide-equivalent, respectively.

Geothermal could act as a form of baseload power and peaking power, helping to support the increased grid integration of other forms of renewable electricity to further bring down emissions. There exists a vast and untapped technical potential for geothermal energy. Much of the initial development could take place in areas with lots of conventional, high-temperature hydrothermal resources that have yet to be developed. Large upfront costs and the high risk of investing in geothermal power plants are two of the biggest barriers to the expansion of geothermal electricity. Drilling rig rates and associated costs often make up the largest cost component of geothermal plants, and there is a significantly high chance of failure in exploratory stages. Thus, many governments are setting targets for the development of high-temperature hydrothermal resources. These goals could be aided through: renewable portfolio standards requiring a certain amount of renewable energy use; a price on carbon; and guaranteed power purchase agreements or feed-in tariffs for developers to reliably recover development costs.

1 LITERATURE REVIEW

1.1. STATE OF GEOTHERMAL ELECTRICITY

1.1.1 Geothermal Energy Systems

Geothermal energy is derived from Earth's natural heat. Although this heat is available everywhere, geothermal energy is used in regions in the world where the geothermal energy systems occur naturally. In these regions, the occurrence of geothermal energy systems is as a result of a thermal anomaly in the earth's upper crust allowing convective fluid transfers heat from a heat source at depth towards the surface (Fridriksson *et al.*, 2016). Such heat sources are molten hot magma (molten rock) coming quite close to the earth's surface where the crust has been thinned, faulted, or fractured by plate tectonics movement. When this happens, and water is heated by the earth's heat, hot water or steam is trapped in permeable and porous rocks between layers of impermeable rocks to form geothermal reservoirs (Oil&Gas Portal, 2017) (see Figure 1.1 below). The lower impermeable rock is located above the molten magma, acting as the heat source, while the upper impermeable rock has fault line and geyser opening through which rain or surface water seep into the hydrothermal reservoir. Geothermal systems can be classified based on the reservoir temperature; low when teoeratures range from <100–150°C, intermediate (between 100- 150°C and 200°C), and high temperature (>200°C) (Fridriksson *et al.*, 2016). Depending on the dominant state of the fluid (i.e. gas or liquid) in the reservoir, high-temperature geothermal systems can be categorized as liquid dominated or vapor dominated systems (see Figure 1.1 below).
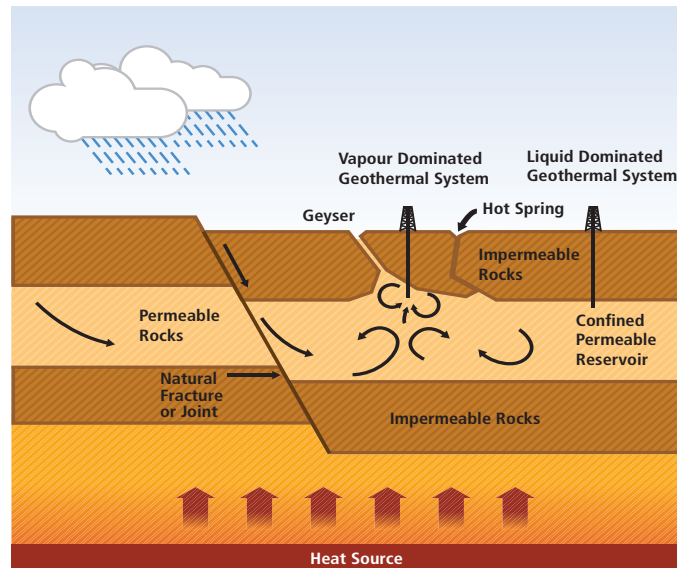

Figure 1.1 - Schema showing convective hydrothermal resources. Source (IPCC, 2011)

Classification of geothermal systems can also be based on their geological nature. Geothermal systems characterized by a volcanic heat source such as hot intrusions or magma are usually the most typical high-temperature geothermal systems. Volcanically active areas along tectonic plate boundaries are therefore some of the locations where volcanic geothermal systems are found on Earth. However, not all volcanic systems develop geothermal systems (Fridriksson *et al.*, 2016) because the sub-surface rock system has to offer suitable conditions (i.e., a layer of highly porous and permeable rock sandwiched between layers of impermeable rocks). The use of geothermal energy has so far been constrained location-wise since conventional hydrothermal reservoirs are location specific. The geographic scope of geothermal energy could be significantly increased through the development of advanced technologies such as enhanced geothermal systems that target lower-permeability reservoirs. Geothermal energy can also be obtained using artificial fluid pathways into lower-permeability reservoirs; extracted using wells or other means that produce hot fluids from hydrothermal reservoirs which naturally have high permeability (IPCC, 2011).

Applications of geothermal energy systems can be categorized into 1) direct utilization and district heating; 2) electricity generation; and 3) geothermal heat pumps. Direct use and district heating applications of geothermal energy include space heating, bathing and swimming (including balneology), horticulture (greenhouses and soil heating), industrial heating (for drying and heating purposes), and aquaculture (mainly in fish farming). When converted to electricity, geothermal electric power can be utilized as a source of baseload power, flexible peaking power, as well as load-following power (Eliasson et al., 2011).

Geothermal power plant is traditionally used as a baseload power plant to continuously provide full-load power output unless in the occasional cases of maintenance shut-down. In the times of maximum power demand (i.e. peak load), and fluctuating power demand (i.e. ramping or transient load), geothermal plants particularly the condensing-type steam/flash plant, and hybrid geothermal plants could be adapted for more flexibility required to load-peak and/or load-follow in times of varying load in the grid (Eliasson et al., 2011). In a well-managed geothermal reservoir, extraction pump and/or throttle valve could be used to regulate steam flow to turbine, and thus regulate the power generated by geothermal plants. Using geothermal plants for load-peaking, and/or load-following purposes will usually come at a more expensive costs than for base-load power. This is because power plants constantly deviating from their maximum operating points to support low or partial load do so to the detriments of their efficiencies. To load-follow is to be able to output low power for a long time, and to ramp up and down in near-zero time. To load-peak is to be able change operating point to support maximum power demand. Geothermal power plant, such as the case of 38 MW Puna plant in Hawaii, has been used to provide ancillary services such as load-following,

frequency regulation, spinning, and non-spinning reserves to Independent System Operators (Edmunds et al, 2014; Edmunds & Sotorrio, 2015; AltEnergy, 2013).

1.1.2   Gases in Geothermal Fluids

Geothermal fluids contain minerals leached from the reservoir rock and variable quantities of gases of which carbon dioxide (CO_2) constitutes the majority, especially in carbonate-rich reservoirs. The heated reservoir water usually dissolves some rock minerals to form brine. In a carbonate-rich reservoir, a high fugacity CO_2 is formed due to Poynting effect (i.e. a sudden over-pressure as water vapor mix with CO_2), and will spontaneously escape through the soil like a jet even without a geothermal plant in the site.

The gas composition and amount depends on the geological conditions of different geothermal fields. Though, geothermal power plants related emissions are much lower than from coal or natural gas power plants. A report from the Geothermal Energy Association (GEA) indicates that geothermal power plants emit about 5% CO_2, 1% of sulphur dioxide, and less than 1% of the nitrous oxide emitted by a similar sized coal powerplant. Certain types of geothermal plants produce near-zero emissions (Holm *et al*., 2012). Other gases that could be found in geothermal fluids are hydrogen sulphide (H_2S), hydrogen (H_2), methane (CH_4), ammonia (NH_3) and nitrogen (N_2). Of the minor gases, H_2S is toxic, but rarely of sufficient concentration to be harmful after venting to the atmosphere and dispersal. Methane, which has global warming potential, is present in small concentrations, from a fraction of a percent to more than one-fourth of the total GHG emissions in the high end cases (Fridriksson at al., 2016). Depending on the technology, most of the mineral content of the fluid and some of the gases are re-injected back into the reservoir (IPCC, 2011). Since these gases do not condense in the power generation process, they are usually referred to as non-condensable gases (NCG). Traces of arsenic, mercury, boron and radon may also be present. In Turkey, CO_2-rich NCGs has been used as a commercial source of producing carbon dioxide for other applications such as fire extinguishers, food preservation, and green houses. Also, revenue could be generated by recovering minerals such as lithium from the spent brine prior to re-injection (Edmunds et al., 2014).

1.1.3   Geothermal Technologies for power

Geothermal resources can be classified into conventional and un-conventional. The conventional resources, also known as hydrothermal resources, are the ones where the natural heat of the earth is found in association with trapped brine (or water) within a layer of permeable rock held between layers of hard rocks. Un-conventional resources include the Hot Dry Rock (HDR) found deep down the earth within a layer of impervious rock, with no associated water or brine; Hot Sedimentary Aquifer (HSA) found deep down the earth within a layer of highly porous sedimentary rocks, and usually contains natural fluid. Hot Sedimentary Aquifer resource is basically like the hydrothermal resource because it contains natural fluid. The main

differences are that HSA is at lower temperature and higher depth than conventional or hydrothermal resources (Geoscience Australia and CSIRO, 2012). Because of its lower temperature, it is potentially more suitable for direct application. Unlike conventional or hydrothermal resources where heat flow is convectively driven by brine or steam, heat flow in unconventional resources is driven by conduction – heat is transmitted through static fluid in the case of HSA, and/or rock matrix in the case of Hot Drock.
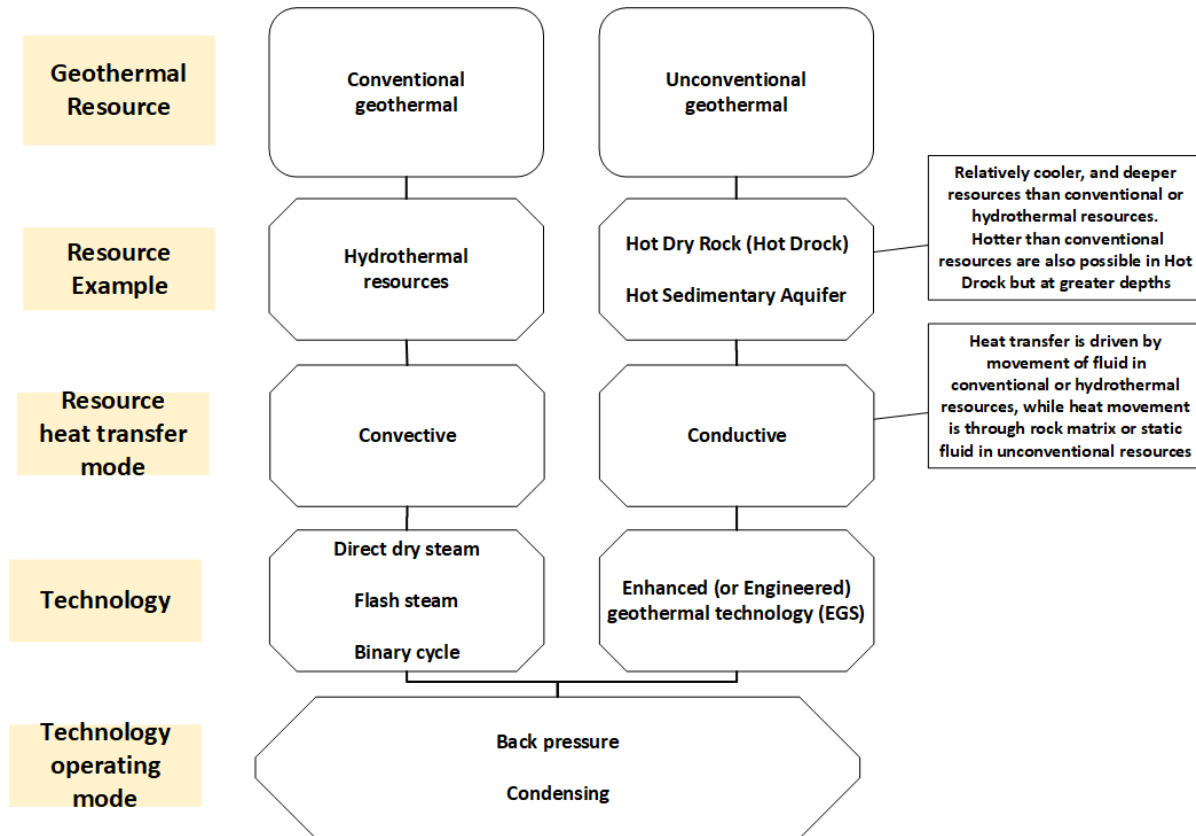
Figure 2.2 - Schema showing conventional and unconventional geothermal resources. (Source: Project Drawdown)

The three-main geothermal electricity technologies for converting the conventional geothermal (or hydrothermal) resource into electricity are direct dry steam, flash steam, and binary cycle power plants as shown in Figure 1.2. Technologies for converting non-conventional resources mostly under development include enhanced (or engineered) geothermal technology particularly for the hot dry rock (Hot Drock).

The anatomy of the main conventional types of geothermal technologies presented in Figure 1.3 shows that geothermal technologies generally comprise of throttling valve, turbine, generator, condenser, cooling tower, as well as extraction, injection, and water pumps. A binary system has heat exchanger network in addition to the afore-mentioned components. The selection of which technology to use for geothermal power generation depends on a number of factors including the characterization of the geothermal resource,

the desired application of the plant (to load peak, load base, load-follow demands, or combinations of these), and the economic feasibility of the project. Typically, low-temperature reservoirs (< 150°C) are used by binary power plants, and dry steam or flash steam plants are employed for moderate to high-temperature reservoirs. The average capacity factor of geothermal power plants worldwide is currently 71–72%, although new plants often achieve more than 90%, leading the IPCC to estimate that geothermal electricity would reach an average capacity factor of 80% by 2020 (IPPC, 2011). Higher capacity factor of up to 90% is achievable in hybrid plants combining features of two or more main types of geothermal plants, and/or multiple flash steam plants. In comparison, the capacitor factor, and capacity credit are close to their conventional counterparts.

The economic feasibility of geothermal project is driven by factors including resource type, resource temperature, reservoir flow rate (pressure), capital costs, financing costs, plant type, and size. Since the same level of labor is required in drilling a geothermal reservoir, a larger megawatt plant size makes better economic sense than smaller one. A typical discounted payback period for a below 1 MW geothermal power plant ranges from 12 – 15 years, and construction time of 3 – 5 years (Budisulistyo & Krumdieck, 2015). The payback for larger or megawatt-scale plants could be as low as 50% less.

Dry Steam Systems

In a dry steam system, the geothermal fluid (high temperature steam) goes directly through the turbine to drive a generator (with prime mover) to produce electricity. The process requires no separation of resource content as the hydrothermal fluid from the geothermal system being used is steam. At the well head, there are valve and steam purifier to regulate steam flow and to strip the steam of impurities to minimize damages to the turbine, and the balance of plant. The steam is condensed after being cycled through the turbine either by dry (air) cooling or by using water-cooling towers. Though cooling the steam is usually expensive, the condensed steam from turbine is often returned into the reservoir to replenish the stock, and/or make-up for the cooling water. Another possible innovation is to use the chilled fluid destined for geothermal reservoir to power underground hydro-turbines prior to re-injection.

Flash Steam Systems

Flash plants are the most common geothermal power technologies, making up nearly two-thirds of total global installed geothermal capacity as of 2015. They are used where water dominated reservoirs have temperatures above 180°C. In flash plants, superheated water rising to the surface under high pressure is sprayed into a tank held at a much lower pressure than the fluid, causing some of the fluid to vaporize rapidly, or "flash". (CEC, 2019). The vapor is piped to drive a turbine which in turn drives a generator to produce electricity. The brine remaining can be used for direct heating. However, the brine together with

the condensed fluid is eventually re-injected to replenish the reservoir. In a dual-flash steam power cycle, any fluid remaining in the flash tank is flashed in a second tank to extract even more energy. The steam from the second-stage flash is used to drive a second turbine. If a single turbine is used, the steam from the second stage flash is introduced to the turbine at an intermediate stage.

Flash steam system comes in different configurations, including single, double, and triple flash, with the triple flash giving better efficiency, in trade-off with costs. Also, hybrid configurations combining in series, the features of some of the three main geothermal technologies are possible. Where multiple flash and/or hybrid configurations are used, heat from other technologies such as concentrated solar power (CSP) could be used as supplement to drive the multiple effects.

Depending on the handling and the destination of the spent steam, direct dry steam and/or flash steam geothermal plants could be categorized as back-pressure or atmospheric exhaust (spent steam not condensed but discharged into the atmosphere) or condensing-type exhaust where spent steam is condensed in condensers, partly used as make-up water, and/or re-injected into the reservoir. While the back-pressure type presents low cost and easy maintenance to the detriment of thermal efficiency, the condensing-type is more expensive and complex but with higher efficiency, and more flexibility making it a good candidate as load-following power plant. In other words, direct dry steam, and flash steam geothermal plants operating as condensing-type offer improved load-following qualities (Eliasson *et al.*, 2011).

Binary Cycle Systems

Binary cycle systems are deployed where only medium-temperature hydrothermal resources are available. Unlike dry and flash steam systems, the hydrothermal fluid from the reservoir never comes in contact with the turbine/generator units in binary cycle systems. The hydrothermal fluid of low to moderate heat is passed through a heat exchanger, where it causes a secondary fluid (multicomponent working fluid with a much higher latent heat of vaporization than water) to flash to vapor, which drives the turbines and subsequently, the generators. As the system loops in a binary plant are closed, the geothermal brine is returned to the reservoir, and the secondary liquid is condensed and repeatedly cycled.

Electricity generation using binary technology that extracts low-temperature hydrothermal resources utilizes processes like the Organic Rankine Cycle (ORC) – a low-temperature counterpart of Rankine Cycle, and the Kalina cycle. The secondary fluid typically used in geothermal power binary cycle plants based on the Organic Rankine Cycle is often isobutane or pentafluoropropane, and that for the Kalina cycle is usually an ammonia-water mix. The working fluids are preferably low-boiling, and high latent heat of vaporization.

Enhanced Geothermal Systems (EGS)

Geothermal energy has the potential to make a much more significant contribution on the global scale through the development of advanced technologies, particularly those exploiting "hot dry rock" (HDR) resources. Hot dry rock resources refer to energy stored deep in the Earth, within rock formations where there are little or no fluids, and/or low permeability. These hot rock resources could be hydraulically stimulated or fractured using enhanced geothermal system (EGS) technologies and techniques. These EGS technologies are designed to target reservoirs at greater depths below the surface than conventional sources, pumping high-pressure water through hot rock. The water heats up and returns to the surface as steam, powering turbines to generate electricity. The recycled water, with some make-up water, is then returned to the reservoir through injection wells, creating a closed-loop system (Fogarty and Lamb, 2012).

EGS has the benefit of cutting down on the risks and high costs associated with hydrothermal exploration. A 2006 study by Massachusetts Institute of Technology (MIT) found that EGS technology could provide 100 GW of global electricity by 2050 (Tester et al., 2006). Although demonstration projects have been piloted, EGS has yet to be used at a commercial scale. The current commercial-scale geothermal power plants are based on hydrothermal resources, and efforts are ongoing to exploit energy from EGS, and supercritical resource. Advanced technologies for EGS, as well as offshore, geo-pressured, and super-critical or magma resources, could unlock a huge additional resource base. The stumbling blocks preventing the development of these new resources are due to lack of advanced technologies, and the concerns about handling high-temperature, high-pressure magma resources to avoid a disastrous blow-out. In Iceland, the world's first 'magma-enhanced' geothermal system was attempted in 2009 after a drilling over a depth of 4 km directly encountered zone of molten magma with high temperature range of over 900°C, prompting the project to be aborted and only completed to a depth of about 2.1 km (Elders et al, 2014; Ommedal, 2018). This project is currently feeding a 60 MW Krafla geothermal power plant with superheated steam.
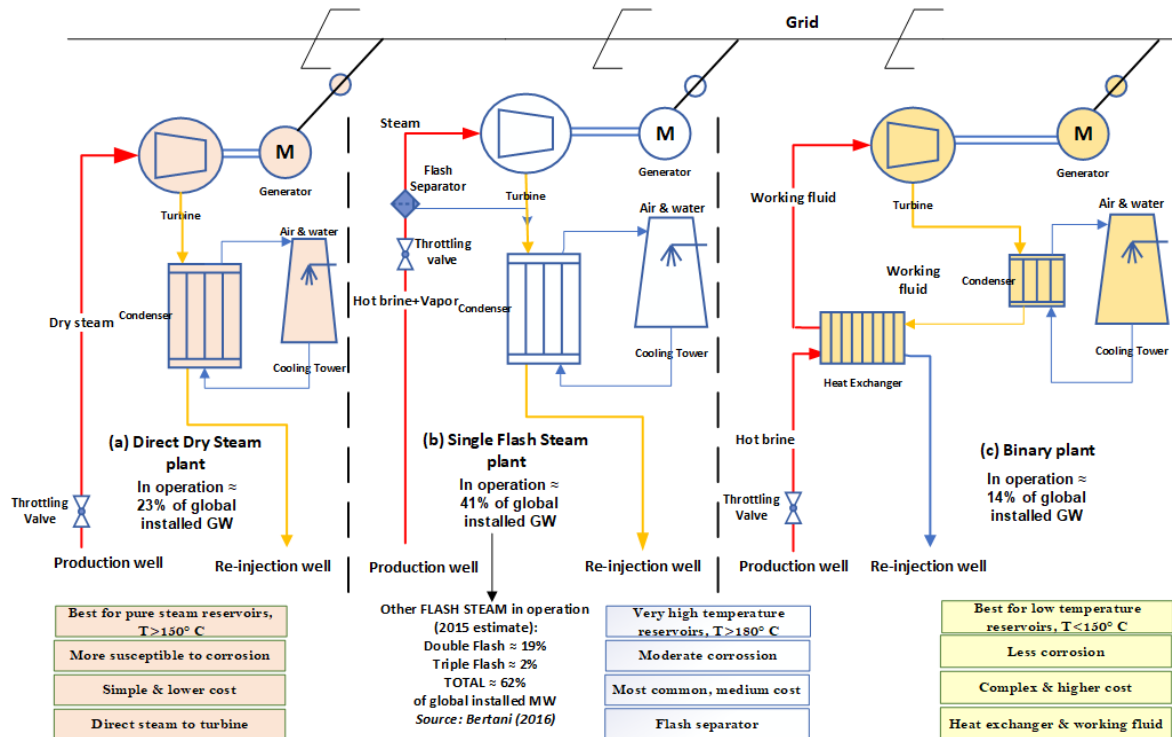
Grid

Turbine — Generator (M)

Dry steam — Condenser — Air & water — Cooling Tower

(a) Direct Dry Steam plant
In operation ≈ 23% of global installed GW

Throttling Valve

Production well — Re-injection well

Steam — Flash Separator — Turbine — Generator (M) — Air & water

Throttling valve

Hot brine+Vapor — Condenser — Cooling Tower

(b) Single Flash Steam plant
In operation ≈ 41% of global installed GW

Production well — Re-injection well

Working fluid — Turbine — Generator (M) — Air & water

Working fluid — Condenser — Cooling Tower

Heat Exchanger

Hot brine — Throttling Valve

(c) Binary plant
In operation ≈ 14% of global installed GW

Production well — Re-injection well

| Best for pure steam reservoirs, T>150° C |
| More susceptible to corrosion |
| Simple & lower cost |
| Direct steam to turbine |

Other FLASH STEAM in operation (2015 estimate):
Double Flash ≈ 19%
Triple Flash ≈ 2%
TOTAL ≈ 62%
of global installed MW
Source: Bertani (2016)

| Very high temperature reservoirs, T>180° C |
| Moderate corrossion |
| Most common, medium cost |
| Flash separator |

| Best for low temperature reservoirs, T<150° C |
| Less corrosion |
| Complex & higher cost |
| Heat exchanger & working fluid |

Figure 3.3 - Schema showing the three main conventional geothermal technologies (Source: Project Drawdown)

1.2. ADOPTION PATH

1.2.1. Current Adoption

Large-scale geothermal power development has been restricted to active heat-flow tectonic areas like near plate boundaries, rift zones, and mantle plumes and hot spots which present thinner crust. Regions and countries near the "Ring of Fire" that have developed geothermal power include the western coast of the United States, Indonesia, Philippines, Japan, New Zealand, and Central America. Rift zone areas that have developed geothermal power include Iceland and East Africa (Ethiopia and Kenya) (IEA ETSAP, 2010). The "Ring of Fire" is a horse shoe-shaped ring around the Pacific that plays host to over 90% of the world's most active volcanoes.

Global installed geothermal electric power capacity at the end of 2018 was at a total of about 14.6 gigawatts (GW) with new additions from 8 countries led by Turkey and Indonesia (ThinkGeoEnergy, 2018). Based on average full load hours of 6.3 GWh/MW$_e$ or 72% capacity factor, the 14.6 GW installed capacity corresponds to an estimated 92 TWh of electricity in 2018. In 2017, IEA estimated a global geothermal electricity generation of 84.8 terawatt-hours (IEA, 2018). The average annualized growth of installed geothermal power capacity over the last five years before 2014 was 3.6% (REN21, 2015). According to REN21 (2015), 612 geothermal power plants were operating at the global level at the end of 2014. Of these,

the most installed global capacity - 7.8 GW and 63% of geothermal generation was represented by 237 flash plants. With 286 plants, binary-cycle were the most deployed technology, however, representing the less capacity of about 1.8 GW and 12% of generation. Dry steam plants were 63 and represented 2.9 GW (22% of generation).

According to ThinkGeoEnergy (2018), the top five countries or gigawatt country club for installed geothermal capacity as of 2018 were United States of America (3,639 MW); Indonesia (1,948 MW); Philippines (1,868 MW);; Turkey (1,347 MW); and New Zealand (1,005 MW). Mexico with its new renewables support policy for geothermal is expected to join the gigawatt country club in the coming years. According to IRENA (2018), the top geothermal electricity generation countries in 2016 include USA (18,584 GWh); Philippines (11,070 GWh); Indonesia (10,656 GWh); Mexico (6,148 GWh); Turkey (4,819 GWh); and Kenya (4,758 GWh).

1.2.2. Trends to Accelerate Adoption

The environmental and social impacts from geothermal energy use are site and technology dependent and largely manageable (IPCC, 2011). Geothermal technology development has historically focused on natural hydrothermal reservoirs, such as high-temperature hydrothermal resources along tectonic plate boundaries, although low- and medium-temperature hydrothermal resources have also been increasingly accessed through binary (combined heat and power) plants, and more recently using engineered geothermal system to hydraulically fracture or stimulate impervious hot rocks.

Although geothermal power often has large upfront costs, its plants have significantly lower operational, maintenance, and fuel costs than coal and natural gas plants, evening out the levelized cost of electricity (LCOE) between the different energy sources over time (BNEF, 2014). According to IRENA (2014), the LCOE of conventional global geothermal power varied from US$0.05 to US$0.10/kWh for projects between the year 2010 and 2014. However, the LCOE can be as low as US$0.04/kWh for the most competitive projects, such as those utilizing well-documented resources or brownfield developments. These LCOE costs are within the range of fossil fuels, which had an estimated LCOE of $0.04 to $0.13/kWh, without accounting for their external costs (IRENA 2014). Moreover, since geothermal plants do not require additional fuel, the price of geothermal power is stable, making it a natural hedge against the volatility of fossil fuel prices. When commercially integrated, engineered geothermal system is expected to come at a much higher LCOE up to $0.2/kWh or higher (AREA, 2014), considering the resource-intensive nature, especially in drilling, more materials requirement in well completion/casing to a higher depth, and the use of thermally and chemically stable fluid to serve the dual purposes of creating a porous reservoir and extracting the heat.

1.2.3. Barriers to Adoption

Geothermal has been used for electricity generation since the early 1900s in Larderello, Italy (WEC, 2016) and is therefore considered a more mature energy source. Although the cost of geothermal power has changed less over time compared to many newer energy technologies, capital expenditures, in particular, can vary widely by plant type and region. The key barriers to adoption could be viewed from the lenses of technical, financial, policy, and regulatory hurdles.

Geothermal projects typically require high upfront investment costs related to the need to drill wells and construct power plants, and relatively low operational costs. These costs may vary due to plant capacity, make-up fluid and/or injection well requirements, and the chemical composition of the geothermal fluids. Due to the inexistence of fuel costs, the operating costs for geothermal plants are predictable in comparison to fossil fuel power plants that are subject to market fluctuations in fuel prices (Goldstein et al., 2011).

Due to the limited geographic availability of natural geothermal systems and the infancy of EGS technologies, many forecasts of future geothermal power deployment tend to be modest. Cost is a determinant factor since there is a significant variation in geothermal forecasts creating uncertainty for investment in new technologies. The high pre-development and project development risks associated with the prospecting, drilling, and completion of well for hydrothermal resources, and the construction of surface plants for the conversion also adversely affect adoption growth (Chatenay & Jóhannesson, 2014). Owing to these high risks, securing financing could be challenging in the absence of government policy support in the form of risk guarantee, and/or reliable 'take or pay' power purchase agreement (PPA).

Grid integration of geothermal power does not present variability, and reserve capacity requirement issues because of its base load capability, and the inertia to provide voltage stability support to the grid. Compared to conventional alternatives, geothermal power plant offers high capacity credit (i.e. the fraction of the installed capacity that is firm or conventional-like). Depending on resource location site relative to grid infrastructure and/or sub-station, grid extension may be needed for interconnection, and/or grid reinforcement to wheel the electricity to the market without grid congestion. This factor also determines deep and/or shallow connection charges to be paid by the project developer, which in-turn affect the overall planning of geothermal power plant.

It is also important to note that many geothermal resources are not only remotely located, but also on lands that are usually government-owned, and therefore challenging to obtain planning permissions especially by small companies that dominate the geothermal energy market.

1.2.4. Adoption Potential

There exist vast global geothermal energy technical potential. Theoretical estimates suggest that about 45 EJ per year of geothermal power (and 1040 EJ per year of heat) could be obtained by tapping 10 kilometers into the earth's crust. In additional to this theoretical potential, geothermal energy potential exists in off-shore hydrothermal systems, supercritical fluids, magmatic and geo-pressured resources. This extra potential could be harnessed via enhanced geothermal technologies (Bromley & Beerepoot, 2011).

The MESSAGE model appears to have pessimistic assumptions and high costs for geothermal that resulted in little future growth, even under a 450 parts per million (ppm) scenario. GCAM, conversely, had very optimistic assumptions, calculating costs for all geothermal resources (hydrothermal and advanced) at $2,600/kW, making a much larger amount of geothermal resources available at low cost (Hannan et al. 2009). Under these assumptions, there was substantial future growth for geothermal in both GCAM's 450 and base (business-as-usual) scenario – the base scenario, in fact, had more future growth in geothermal than the International Energy Agency (IEA)'s 2°C scenario. This scenario could be highly plausible under conditions in which advanced geothermal technologies like EGS become more commercialized and come down in cost, potentially foreshadowing the significant role that geothermal may play in the global energy mix. However, for now, EGS remains at the pilot stage.

The expansion of geothermal power in IEA Energy Technology Perspectives (ETP) results are dominated by the accelerated deployment of conventional high-temperature hydrothermal resources and is therefore limited to areas where such resources are available (i.e. Asia, Central and South America, and East Africa). There are abundant high-temperature hydrothermal resources particularly in Indonesia and the Philippines that are yet to be exploited. Deployment of low- and medium-temperature hydrothermal resources in deep aquifers is also growing quickly, particularly in OECD nations. The IEA expects advanced hot dry rock geothermal technologies to become commercially viable shortly after 2030, and its deployment to help geothermal electric capacity to continue to grow after conventional hydrothermal resources are developed, and reach more geographic areas.

Figures 1.4 and 1.5 present the installed capacity and electricity generation adoptions for the three scenarios presented in the 2017 Energy Technology Perspectives by the International Energy Agency (IEA). It shows that adoption of geothermal electricity in 2050 is expected to increase 7 times more than the current adoption (84.8 TWh) even in the absence of any ambitious decarbonization policy.
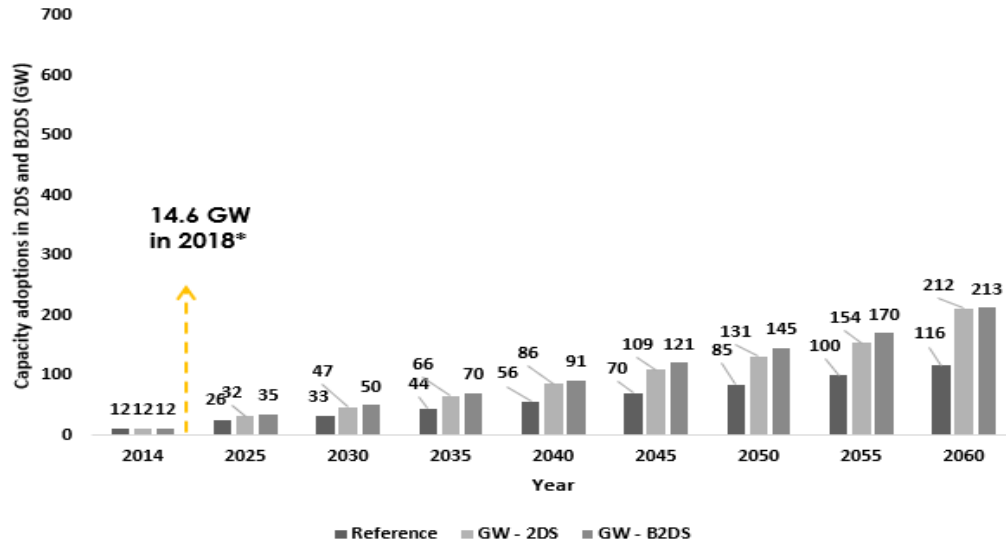
Figure 4.4 - Geothermal capacity adoption in various scenarios (Adapted from IEA ETP, 2017, & ThinkGeoEnergy, 2018*)
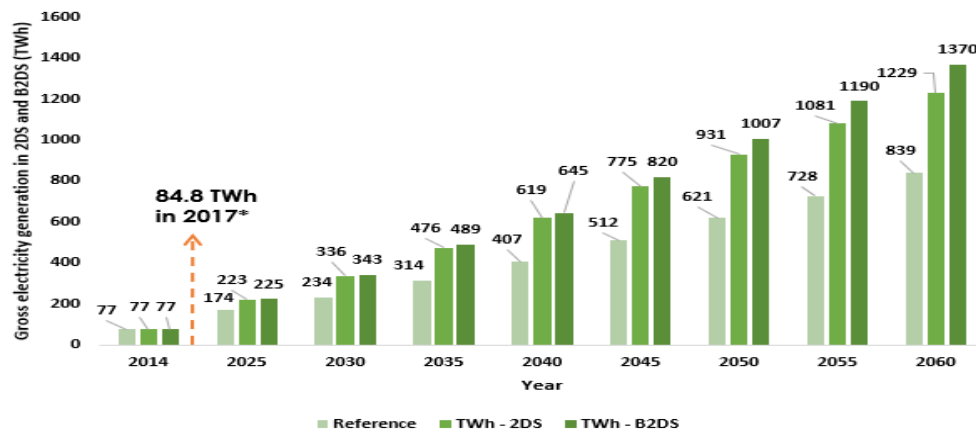
Figure 5.5 - – Geothermal electricity generation in Ref., 2DS and B2DS scenarios (Adapted from IEA ETP, 2017; IEA, 2018*)

1.3 ADVANTAGES AND DISADVANTAGES OF GEOTHERMAL POWER SYSTEMS

1.3.1   Similar Solutions

There are several solutions in the electricity generation sector that replace conventional electricity-generating technologies such as coal, oil, and natural gas power plants, and that could be considered similar solutions.

Geothermal power plant is essentially a steam plant with its own in-situ heat source. In other words, it can be likened to a gas power plant, where the required fuel (i.e. hydrothermal for raising steam) throughout its lifetime must be procured upfront so that no exposure to future fuel price fluctuation risks. Other clean

technologies that could be considered similar to this solution at the same or different level of agencies include:

- Cogeneration or combined heat and power plant: In some geothermal system variant, they are combined to form geothermal cogeneration system which can provide electricity as well as district heating services.
- Modular geothermal plant or MiniGeo: Usually, binary cycle plant constructed in small units in kilowatt-scale could be used to power mini-grids or connected in series to reach megawatt utility-scale.

1.3.2 Arguments for Adoption

Geothermal energy is classified as a renewable resource because the tapped heat from an active reservoir is continuously restored by natural heat production as a result of the constant heat flow from the enormous amount of heat stored within the earth, while the hydrothermal formation is driven by replenishable hydrological cycle such as rain or ocean water seepage through the line of fault on the earth's crust. Geothermal power is also sustainable in that, the heat removed from the resource is replaced within the same time scale. For a given geothermal power generation system, and mode of production, there exist a certain level of maximum power generation, below which it is possible to obtain a constant level of energy production from the geothermal system over and beyond the economic lifespan of the system (over 100 years) (Axelsson *et al.*, 2010).

Geothermal technologies are considered relatively mature within the renewable energy; while having different cost drivers from wind and solar technologies. Contrasting to other renewable energy sources, the large amount geothermal plant's cost occurs prior to confirmation of resource availability during the process of drilling test wells (WEC, 2013).

Also compared to other renewable power sources such as solar and wind, geothermal power is immune from weather effects and seasonal variations. It can, therefore, be used as both a form of baseload power and peaking power. Thus unlike many other renewable sources of energy, the increased deployment of geothermal power does not impose load-balancing requirements on the electricity system. On the other hand, geothermal power could be used to balance out the effects of increased deployment of intermittent renewables using submersible pumps that reduce the amount of fluid extracted from geothermal reservoirs to generate electricity when demand falls. From the schema in Figure 1.3, it is likely that the geothermal plants may be useful as peaking power plant because the hydrothermal fluid flow could be regulated with throttling valves and pumps, thereby enabling the plants to ramp up and down to follow varying load conditions. In addition to providing base load and possibly peak load, geothermal plant is also compatible

with distributed power generation systems, and can produce both electricity and heat in combined heat and power (CHP) plants.

The increased use of geothermal power has many environmental and climate benefits. Geothermal power has the smallest surface land footprint per kilowatt compared to other power generation technologies (IPCC, 2011, Tester et al., 2006). Its increased deployment can reduce effects of water and air pollution from the burning of fossil fuels, and eliminate the mining, processing, and transport of fossil fuels as inputs for electricity generation. Geothermal plants do emit some amounts of CO_2 but from natural fluxes, rather than combustion. Direct carbon dioxide emissions have been report to be high ranging from close to 0 to 740 g CO_2/kWhe dependent on technology design and composition of the geothermal fluid in the underground reservoir. Direct CO_2 emissions for direct use applications are insignificant and EGS power plants are expected to be planned with zero direct emissions (Goldstein *et al.,* 2011). A 2011 comprehensive literature review by the Intergovernmental Panel on Climate Change (IPCC) on geothermal plants concluded that lifecycle GHG emissions are less than 50 grams of CO_2-equivalent per kilowatt hour for flash steam plants, and less than 80 gCO_2-eq/kWh for projected EGS plants (IPCC, 2011). In closed-loop power plants such as binary system, when geothermal fluid is completely re-injected into the ground without loss of vapor or gas to the atmosphere, emissions are negated.

In carbonate-rich reservoirs such as the Mount Amiata in Italy, higher CO_2 emissions are observed due to carbonate rocks dissolving in the hydrothermal fluid to liberate CO_2 spontaneously. This occurs when a high fugacity vapor- CO_2 mixture is formed due to Poynting effect (i.e. a sudden over-pressure as water vapor mixes with CO_2), and will spontaneously escape through the soil, even without the geothermal plant (Pratiwi, 2018). While high GHG emissions of about twice the coal-fired plants are possible in the high temperature carbonate-rich reservoirs (ESMAP, 2016), emissions that are attributable to the geothermal plant itself is lower. The CO_2 accompanying the hydrothermal fluid, especially in flash or dry steam system, also poses threats to the geothermal plant as it is non-condensable. In binary plant, however, emissions are much lower during hydrothermal flow because all the fluid (non- CO_2 laden) is stripped of heat in a heat exchanger and re-injected back into the reservoir without coming in contact with the turbine system.

1.3.3 Additional Benefits and Burdens

One of the main barriers to geothermal plant expansion is the large upfront costs: drilling rig rates and associated costs often make up the main cost component of geothermal plants, upwards of 55%, and costs can increase substantially with drilling failures and vary with the complexity of the well (BNEF 2013). Also, project developers have reported difficulties in securing power purchase agreements to recoup the development costs. The large upfront costs and uncertainty in locating sufficient geothermal resources can make it difficult to attract investors. Concessionary financing and innovations in private investment,

coupled with take or pay PPAs could significantly reduce these risks. Risk guarantees through federal exchequer could also mitigate the project development risks related to market uncertainties, and forex hedging in the event of substantial fluctuation in exchange rate. This is particularly key in regions where the project financing is done in currency other than cost recovery or tariff currency. Table 1.1. presents a comparison of selected pros and cons of the solution with others in the same sector and with the same energy source.

Table 1.1 Comparison of geothermal to conventional electricity generation technologies

Parameter	Conventional electricity generation technologies	Conventional geothermal power plant	Enhanced geothermal system (EGS)	Cogeneration or CHP plant	Modular geothermal power plant
Land Area Requirement	Very High	Much Low	High	Low	Lowest
Water Requirement	Very High	High	Very High	Low	Lowest
Visual Disamenity	Very High	Low	Low	Low	Lowest
GHG Emissions	Very High	Lower	Low	Low	Lowest
Electricity Generation Flexibility	Very High	High	High	High	High
Labor Requirement	Very High	High	Very High	Low	Lowest
Grid Balancing Requirement	Nil	Nil	Nil	Nil	Nil
Operation and Maintenance	Very High	Low	High	Lower	Lowest
System integration cost	Medium	High	Very High	Low	Lowest
Deployment Costs	Medium	High	Very High	High	Lowest

2   METHODOLOGY

2.1 INTRODUCTION

Project Drawdown's models are developed in Microsoft Excel using standard templates that allow easier integration since integration is critical to the bottom-up approach used. The template used for this solution was the Reduction and Replacement Solutions (RRS) which accounts for replacement of conventional electricity generation technologies (i.e. coal, oil, natural gas) and related emissions for an alternative solution (see the Drawdown RRS Model Framework and Guide for more details). These technologies are assumed to compete in markets to supply the final functional demand which is exogenous to the model, but may be shared across several solution models. The adoption and markets are therefore defined in terms of functional units (TWh), and for investment costing, adoptions are also converted to implementation units (TW). The adoptions of both conventional and solution were projected for each of several scenarios from 2015 to 2050 and the comparison of these scenarios (for the 2020-2050 segment) is what constitutes the results.

For this solution, the approach was to analyze the climate and financial impacts of increased adoption of geothermal systems for electricity generation across level of agencies. The model used for this analysis constructs both alternative ambitious adoption pathways (PD scenarios) and a Reference scenario (REF) for geothermal electricity systems. Following project Drawdown methodological assumption (further description available on the Drawdown RRS Model Framework and Guide), in order to grasp the total impact of an increased adoption of the solution during the assessed time frame; the REF scenario assumes future adoption of geothermal remains fixed at the current base-year (i.e. 2014) percentage of Total Addressable Market (TAM), estimated at 0.33 percent of generation (i.e. 74,195 terawatt-hours) (IRENA, 2016).The TAM for this solution is based on the common project Drawdown projected global electricity generation in terawatt-hours till 2050 (Section 2.3.).

The developed alternative PDS scenarios, draw on existing adoption scenarios for geothermal to model several alternative adoptions. The RRS model contains both financial and climate analyses in order to model the global and regional impacts of adoption in the PDS scenarios compared to the REF scenario. What the model thus prognosticates is the total financial costs and benefits of adoption cases for geothermal power, as well as the contribution this adoption can make to annual and cumulative emissions reduction.

2.2 DATA SOURCES

This section presents key data sources utilized in the mode to evaluate the adoption of Geothermal power technologies. Data inputs for the model come from a variety of sources, primarily from peer-reviewed publications and from institutional reports. For all variable inputs, it was done a variable meta-analysis of existing literature to create low, high, and mean estimates. For each solution variable, it is conducted a sensitivity analysis of, on average, ten data points reported in the literature and in some cases as many as 21. This allows to calculate robust and reliable inputs for the financial, technological and climate analyses that represent both optimistic and conservative estimates for the future costs and benefits of adopting this solution.

For the geothermal electricity global adoption, it were selected six sources with eleven (11) possible scenarios including IEA (2018) World Energy Outlook (Current Policy, New Policy, and Sustainable Development scenarios); IEA (2017) Energy Technology Perspectives (Reference Technology, 2 Degrees, and Beyond 2 Degrees scenarios); Grantham/Carbon Tracker (2017) Report (moderate fossil fuel intensive or NDC_PV_EV_Medium); IEEJ (2018) Outlook (Reference and Advanced Technology scenarios); and Ecofys (200) 100% Renewable Energy scenario. While these sources present the afore-mentioned scenarios explicitly, some sources in literature present the 'geothermal+other renewables' such that it is difficult to isolate.

These scenarios are projections of the role of geothermal energy technologies on the future global electricity generation mix related to different climate mitigation pathways or RES adoption from 2018 to 2060 inclusive. The scenarios are grouped in the RRS Drawdown model to be included under Baseline, Conservative and Ambitious climate cases and 100% RES adoption for electricity generation in the power sector.

Since costs can vary widely depending upon plant type and region, recent capital cost estimates from several data sources determine the average capital cost of geothermal installations (e.g. WEC, 2013; JRC, 2013; JRC, 2014). It is acknowledged that capital costs for geothermal power systems can vary significantly by region and plant type, but exhaustive regional data was not available to calculate an average cost weighted by installation size/region.

Learning rates for geothermal power are expected to continue to reduce costs, making the technologies more competitive and cheaper. Yet, the opportunities for cost reductions for more mature plant types might be low, there is a good opportunity for EGS since they are on an early stage of development and its commercial deployment is in its infancy. According to Rubin *et al.* (2015), the cost of geothermal energy is sensitive to site-specific resource temperature, the fluid chemistry, the geothermal fluid flow rate, and

the ambient temperature. Also, plant selection, and condenser type also affect costs – all of which make it quite difficult to establish a global learning rate for geothermal systems. However, using U.S Energy Information Administration (EIA) on the cumulative net electricity generation from geothermal plants between 1980 to 2005, Rubin *et al.* (2015) derived an inferred learning rate of approximately 30% based on a one-factor model. Other sources give estimates of 7 – 8% (Lukawski *et al.*, 2014; Karali *et al.*, 2015; Hayward and Graham, 2013).

Cost estimates for fixed and variable operation and maintenance (O&M) of geothermal power are reliably low for geothermal plants because they require little maintenance and no additional fuel, data was collected from e.g. JRC, 2013; JRC, 2014; Lazard, 2016. These estimates were used to calculate total operating costs of geothermal power adoption, which, combined with capital costs for installation, represent the total financial costs of adopting this solution in the PD scenarios. Fixed operation and maintenance costs for both renewable and conventional generation technologies can include expenses such as day-to-day preventative and corrective maintenance, labor costs, asset and site management, and maintaining health and safety, among others (Lo, 2014). Average fuel price was calculated considering average prices for both coal, oil and natural gas from 2005-2014 using IEA data (IEA, 2016a).

The average lifetime of a geothermal plant is around 35 years (GEA 2014). However, the capacity factor of the plant decreases over time, from a high of over 90% for young plants to around 70% for more mature plants, leading the IPCC to estimate a global average of 80% by 2020 (IPCC 2011).

In order to compare capital and OM costs of geothermal power systems adoption in the PD scenarios to that of conventional generation technologies, it was obtained cost data for fossil fuel-based electricity generating sources from the IPCC 5th Assessment Report (IPCC, 2014) which conducted its own sensitivity analysis of a number of sources from the literature[1], and other sources such as OECD (2015), Lazard (2016). In all variables for conventional electricity generation sources, data for coal, oil and natural gas (primarily pulverized coal and combined cycle gas turbine technologies) were included and a weighted average. The weights are based on the percentage, for each fuel on the total global electricity generation for 2014 (World Bank, 2015).

To calculate the total impacts and benefits of increased solution adoption (on PDS scenarios), technical data was also integrated, including average annual use, plants lifetime, and average efficiencies. All three of these are key to determining the variable OM costs and the total fuel costs for conventional generation

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[1] The IPCC's 5th Assessment Report analyzes the following sources: <u>Coal:</u> Black and Veatch (2012), DEA (2012), IEA/NEA (2010), IEA (2013a), IEA-RETD (2013), Schmidt et al. (2012), US EIA (2013). <u>Gas Combined Cycle:</u> Black and Veatch (2012), DEA (2012), IEA/NEA (2010), IEA (2011), IEA (2013a), IEA-RETD (2013), Schmidt *et al.* (2012), US EIA (2013).

sources, as these costs are determined by the average number of hours the power plant is generating electricity, as well as the average price of fuel inputs and the average efficiency rate. Average plants efficiency is calculated from several global sources (IPCC, 2014; IEA, 2010), as well as from the U.S. EIA (2015).

Though the average annual use of conventional generating technologies is lower than that of geothermal power systems, the range of capacity factors for different conventional generating sources can still vary based on type of technology and location. For this reason, data was collected from a range of different sources (JRC, 2013; NTEL, 2013; JRC, 2014, IRENA, 2018) that represent most of the regions contained in this analysis.

The model's analysis of the climate impacts of adoption are primarily derived from the direct emissions factor associated with the replacement of conventional generating technologies with geothermal power plants. This methodology is explained in greater detail in Drawdown RRS model framework and guidelines. To account for indirect emissions from conventional technologies and geothermal systems—primarily those lifecycle emissions associated it is also considered: a) the construction of the power plant and surface installations, b) drilling and completion of wells, the production of the materials needed for these installations, and c) eventual decommissioning of the facilities, normalized over the lifetime of the powerplant cycle emissions. The fuel cycle emissions refer, in the case of geothermal projects, to the release of geothermal GHGs during the energy conversion process. Fugitive emissions are expected to go down: the majority of new geothermal plants, including EGS plants, are designed as closed-loop systems and are supposed to have near zero direct emissions during operation (Fridriksson et *al.,* 2016).

2.3 TOTAL ADDRESSABLE MARKET

Solutions assessed in the Electricity Generation Sector share a common market for future adoption defined by the total terawatt-hours (TWh) of generation demanded from 2015-2060. This shared total addressable market (TAM) is used to bound this sector technologies rollout over time. The TAM is determined based on the assessment of estimations of current and future electricity generation from a combination of models and scenarios from different sources, including Greenpeace (2015); International Energy Agency (IEA) - Energy Technology Perspectives (IEA, 2017); IEA World Energy Outlook (WEO) (IEA, 2018); Equinor (2018); Ecofys (2018); The Institute of Energy Economics Japan (IEEJ) Outlook 2019 (2018) and Ram et al. (2019). See Project Drawdown report - Assessing the Total Addressable Market and Major Assumptions for more details on the methodology used to develop the electricity TAM. The updated 2019 study follows the same methodological approach with the inclusion of newer sources.

Four prognostications of the TAM for this assessment were derived by using comparable scenarios from each of the above-mentioned sources which were categorized by expected climate mitigation scenarios (i.e. Ambitious, Conservative, and Baseline) and the scale of deployment of renewable energy sources (RES) (i.e. 100% RES scenarios). The sources used mostly provide results at a decadal level, which were interpolated to provide annual values for Project Drawdown calculations.

The Ambitious Project Drawdown TAM Scenario is constructed from the average of yearly values of four scenarios: the IEA (2017) 2D Scenario, the IEA (2017) B2D scenario, Renewal Scenario from Equinor (2018), and IEA (2018) WEO SD scenario. The Conservative Project Drawdown TAM Scenario follows the average yearly values of the IEA (2018) WEO New Policy scenario (NPS); Reform Scenario from Equinor. (2018), IEEJ Outlook (2018) Advanced Tech scenario, and IRENA (2019b) Roadmap 2050 REmap case. The Baseline Project Drawdown TAM Scenario is built by the average of the Equinor (2018) Rivalry Scenario, IEEJ Outlook (2018) Reference Scenario, IEA (2017) Reference Case and IEA (2018) WEO Current polices Scenario (CPS). These three Project Drawdown TAM scenarios show an estimated range of electricity generation from 45,286TWh to 49,706TWh by 2050. Baseline TAM is used for PD Plausible scenario assessment.

An ambitious TAM scenario for a 100% RES by 2050, which is aligned to project Drawdown Optimum and Drawdown scenarios, utilizes the Greenpeace (2015) Advanced [R]evolution Scenario, Ram et al (2019) analysis and Ecofys (2018) 1.5ºC degree scenario were considered. The estimated electricity generation for this TAM reaches 70,942 TWh by 2050.

2.4 ADOPTION SCENARIOS

Two different types of adoption scenarios were developed: a Reference (REF) Case which was considered the baseline, where not much changes in the world, and a set of Project Drawdown Scenarios (PDS) with varying levels of ambitious adoption of the solution. Published results show the comparison of one PDS to the REF, and therefore focus on the change to the world relative to a baseline.

2.4.1 Reference Case / Current Adoption

For the Reference (REF), adoption is fixed at the current adoption[2] (in percent) of the market. That is, the current percentage of total electricity generation (TWh) provided by Geothermal power systems constant throughout the study period to 2050. As the market grows, the total number of geothermal plants for electricity generation adopted grows equally to maintain the percent adoption at its starting value in 2018.

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[2] Current adoption is defined as the amount of functional demand supplied by the solution in 2018. This study uses 2014 as the base year due to the availability of global adoption data for all Project Drawdown solutions evaluated

It is acknowledged that this, in reality, may not be a "business as usual" considering changes taking place worldwide, but it allows measurement of the impact of recent and even more aggressive policies on greenhouse gas emissions.

2.4.2 Project Drawdown Scenarios

Three Project Drawdown scenarios (PDS) were developed for each solution, to compare the impact of an increased adoption of the solution to a reference case scenario, being:

Plausible Scenario

This scenario represents an incremental and plausible growth of renewable energy solutions using medium to high growth trajectories to 2050 depending on the current maturity levels of the technology, and bounded by existing ambitious projections from other global energy systems models. For geothermal systems, this scenario is based on the evaluation of yearly averages of four optimistic scenarios: IEA (2017) Energy Technology Perspectives 2DS and B2DS scenarios; IEA (2018) World Energy Outlook SDS; and Grantham Institute and Carbon Tracker (2017) NDC policy levels and original technology costs scenario using a medium growth trajectory.

Drawdown Scenario

This scenario is optimized to reach drawdown by 2050 using more ambitious projections from existing sources. The scenario projects a 100% adoption of non-fossil fuel-based technologies in 2050; mainly RES but also includes several technologies that are considered transitional solutions (as nuclear energy) (See section 6). For geothermal systems, this scenario is based on the same sources of the Plausible scenario, with the evaluation of yearly averages of four optimistic scenarios: IEA (2017) Energy Technology Perspectives 2DS and B2DS scenarios; IEA (2018) World Energy Outlook SDS; and Grantham Institute and Carbon Tracker (2017) NDC policy levels and original technology costs scenario, though using a high growth trajectory.

Optimum Scenario

This scenario represents the most optimistic case, in which clean, renewable energy solutions such as wind, solar, and other renewable energy sources capture 100% of electricity generation by 2050, with both fossil fuels and transitional solutions fully phasing out by 2050. This scenario for geothermal systems is based on the yearly average values of three 100% RES scenarios of electricity generation by 2050, being Greenpeace (2015) Advanced Energy [R]evolution Scenario; Ram et al. (2019) scenario and Ecofys (2018) 1.5ºC scenario.

2.5 INPUTS

2.5.1   Climate Inputs

In order to calculate the climate impacts of the project Drawdown scenarios, in terms of maximum annual emissions reduction, total emissions reduction, and PPM equivalent, it was estimated geothermal electricity generation globally and regionally from 2020-2050 and then calculated the emissions reductions due to the replacement of conventional electricity generation sources with the solution. The detailed methodology of these calculations is available at the Project Drawdown Integration Methodology report.

Project Drawdown modeling considers the analysis of direct and indirect emissions related to the different factors that contribute to a LCA for geothermal systems. In modeling the lifecycle emissions of geothermal adoption in the scenarios, it is used a fixed value (t CO_2-eq per TWh) considering information from several technologies rather than a decreasing one due to the difficulty of projecting future grid-tied emissions on a regional basis. The climate results will thus be more conservative than would be the case if it was assumed a decreasing average lifecycle emissions value for geothermal systems.

The values collected in the RRS model show lifecycle GHG emissions for a range of different geothermal technologies across different regions and system sizes. The analysis draws from recent published GHG emission estimates for geothermal that have ranged from 4 to 1,800 g CO_2eq/kWh over their lifetime (*e.g.* Masanet et *al.*, 2013; NTEL, 2013; IPCC, 2014; Aksoy et al., 2015; Mac Kinnon et al., 2018). The wide span in results for geothermal systems reflects different assumptions around capacity factor, conversion efficiency, operating lifetime and quality of geothermal resource. Table 2.1 presents the boundaries of the data boundaries on the model and the selected model input.

Table 2.1 Climate Inputs

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Indirect CO_2 Emissions (Solution)	*t CO_2-eq/TWh*	0^3 – 298,25	102,998	46	13

Note: Project Drawdown data set range is defined by the low and high boundaries which are respectively 1 standard deviation below and above the mean of the collected data points[3].

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[3] In some cases, the low boundary is negative for a variable that can only be positive, and in these cases the lowest collected data point is used as the "low" boundary.

2.5.2   Financial Inputs

RRS model constructs PDS adoption scenarios for geothermal electricity generation globally and regionally for each year until 2050. It is modelled both the capital costs and the fixed and variable OM costs associated with the alternative scenarios compared to those of the REF scenario. A detailed description of the methodology used is available in the Drawdown RRS Model Framework and Guide.

The financial calculations examine the first cost in US$ per kW and the operating cost in US$ per kW (fixed costs) and US$ per kWh (variable costs). For this, many inputs estimating annual output and lifetime output per geothermal electricity generation, along with first costs (per functional unit), were calculated. A lifetime capacity of 229,893 hours (around 31 years) was considered depending on the average powerplant annual use.

For the solution (i.e. geothermal power plant), the conventional current mix of fossil fuel electricity generation technologies (coal, gas, and oil) replaced were identified. Costs and operation for both generation technologies (solution and conventional) were considered to obtain the differential result.

Fuel prices for conventional technologies are derived from IEA (2019) data, averaging 2007-2018 historical registries for oil, coal and natural gas used for electricity generation and calculated through a weighted average by fuel from the current electricity generation mix.

A mean value of the data set range collected is assumed for installation costs of geothermal systems which results in a total first cost of US$4,491 per kilowatt[4]. Estimates in the literature presented for the learning rate of geothermal systems vary (1% to 20% have been presented (e.g. Hayward and Graham, 2013; Lukawski et al., 2014; Karali et al., 2015). A first cost learning rate of 10.0 percent was considered; and this has the effect of reducing the installation cost to US$3,056 per kilowatt in 2030 and to US$2,475 in 2050, compared to US$1,786 (in 2014) per kilowatt for the conventional technologies (i.e. coal, natural gas, and oil power plants). Additionally, a net present value discount rate is fixed at 9.68 percent appropriate for utility-scale projects and use across all Drawdown electricity generation solutions with this level of agency. The discount rate used herein was benchmarked to the Power generation technologies of the PRIMES model used in the impact assessment of the EU 2030 targets, that considers 9% (EC, 2014). Tables 2.2. and 2.3 depict the dataset ranges and the model inputs for the conventional and solution technologies.

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[4] All monetary values are presented in US$2014

Table 2.2 Financial Inputs for Conventional Technologies

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs (Conventional)	*US$2014/kW*	470.5 – 3,101	1,786	24	8
Fixed Operation and Maintenance Costs (Conventional)	*US$2014/kW*	3.44 – 65.86	32.95	18	4
Variable Operation and Maintenance Costs (Conventional)	*US$2014/kWh*	0.0014 – 0.0079	0.0048	22	7
Fuel Price (Conventional)	*US$2014/kWh*		0.0492		1
Learning Rate Factor (Conventional)	%		2.00%		

Table 2.3 Financial Inputs for Solution

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs (Solution)	*US$2014/kW*	2,914 – 6,068	4,491	40	12
Fixed Operation and Maintenance Costs (Solution)	*US$2014/kW*	16.03 – 292.62	154.33	21	8
Variable Operation and Maintenance Costs (Solution)	*US$2014/kWh*	0.002 – 0.032	0.017	22	9
Learning Rate Factor (Solution)	%	3.8 – 16.2%	10%	7	3

2.5.3　Technical Inputs

Table 2.4 Technical Inputs Conventional Technologies

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Lifetime Capacity (Conventional)	hours	121,807 – 222,351	172,079	12	6
Average Annual Use (Conventional)	hours	3,337– 6,587	4,962	23	4

Table 2.5 Technical Inputs Solution

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Lifetime Capacity (Solution)	hours	179,479 – 280,315	229,893	20	14
Average Annual Use (Solution)	hours	6,857 – 8,218	7,537	20	10

2.6 ASSUMPTIONS

Six overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions. These are that infrastructure required for solution is available and in-place, policies required are already in-place, no carbon price is modeled, all costs accrue at the level of agency modeled, improvements in technology are not modeled, and that first costs may change according to learning. Full details of core assumptions and methodology will be available at www.drawdown.org. Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

Assumption 1: The adoption data from the different sources are usually given on interval of 5 to 10 years. To achieve data completeness for the years within the gap, data interpolation was performed using the best fit model amongst 1st, 2nd, and 3rd polynomials. In cases where there are spikes, stepwise interpolation with one or more of the outlier datapoint(s) removed are performed to smooth out the trend, and complete the data for the missing years.

Assumption 2: Most of the scenario sources adopted for this work made assumptions around demographic drivers such as population growth, economic drivers such as GDP, policy drivers such as past policy trends, and the recent Paris Agreement. Other assumptions include international energy prices, exchange rates, international trade and investment, declining costs of renewables, and energy efficiency improvement.

Assumption 3: Different existing technologies of geothermal power as flash, organic rankine cycle (binary) are considered in this solution. Enhance Geothermal Systems data points are not considered in the conducted variable meta-analysis in the RRS model, due to their early levels of maturity and low deployment. Future analysis may also include this technology.

2.7 INTEGRATION

The complete Project Drawdown integration documentation with details on how all solution models in each sector are integrated, and how sectors are integrated to form a complete system will be available at www.drawdown.org. Those general notes are excluded from this document but should be referenced for a complete understanding of the integration process. Only key elements of the integration process that are needed to understand how this solution fits into the entire system are described here.

Therefore, the data derived from individual solutions models was then inputted into sector-level integration models to generate final results for all solutions within a global system. The links between this sector and all the others is important, but major interactions occur with energy demand-side sectors like Transport and Buildings and Cities.

Through the process of integrating geothermal power with other solutions, the total addressable market for electricity generation technologies was adjusted to account for reduced demand resulting from the growth of more energy-efficient technologies (for example LED lighting and heat pumps) as well as increased electrification from other solutions like electric vehicles and high-speed rail. Grid emissions factors were calculated based on the annual mix of different electricity generating technologies over time. Emissions factors for each technology were determined through a meta-analysis of multiple sources, accounting for direct and indirect emissions.

2.8 LIMITATIONS / FURTHER DEVELOPMENTS

More research and modeling will be necessary to help policy-makers and project developers understand in detail the benefits of adoption on a more resolute scale, as geothermal will not always make economic sense nor fit perfectly into any country's future electricity generation portfolio. In particular, the RRS model holds a number of factors constant in order to keep global-scale modeling from becoming too complex, but it is acknowledged that many of these factors, including prices of fuel and operating costs for conventional electricity, could change considerably over the period of analysis.

Global analysis is complicated in many ways by the fact that the technical performance and costs of geothermal power can vary widely across regions depending on the viability of the geothermal resource

and related factors of production. To account for these differences results where weighted appropriate, but this cannot be done in every case, and due to this limitation, it was often selected a more conservative estimate for the climate and financial inputs in order not to overstate the potential benefits of adoption.

In this modeling approach, resource proximity to transmission assets, and the potential implications of deep and/or shallow connection costs were not accounted separately as these are context-specific. More so, the effects of policy, regulatory, and political environments were assumed to be in the context of the adoption scenarios, and not modelled separately.

3 RESULTS

In the following section are depicted selected results derived from the RRS model evaluating the impact of increased adoption of Geothermal Power technologies for electricity generation when compared to conventional technologies.

3.1 ADOPTION

Comparing the results from the three modeled scenarios to the Reference Scenario allow to estimate the climate and financial impacts of increased adoption of geothermal systems. The Plausible Scenario (PDS1) projects 2.55 percent of total electricity generation worldwide coming from geothermal systems by 2050. In the Drawdown (PDS2) and Optimum Scenarios (PDS3), the market share capture 2.6 percent and 5.7 percent, respectively. Below in Table 3.1 are shown the adoptions of the solution in 2050 in functional units and percent. Figure 3.1 depicts the long term pathway trajectories for the different scenarios of adoption of geothermal plants.

Table 3.1 World Adoption of the Solution

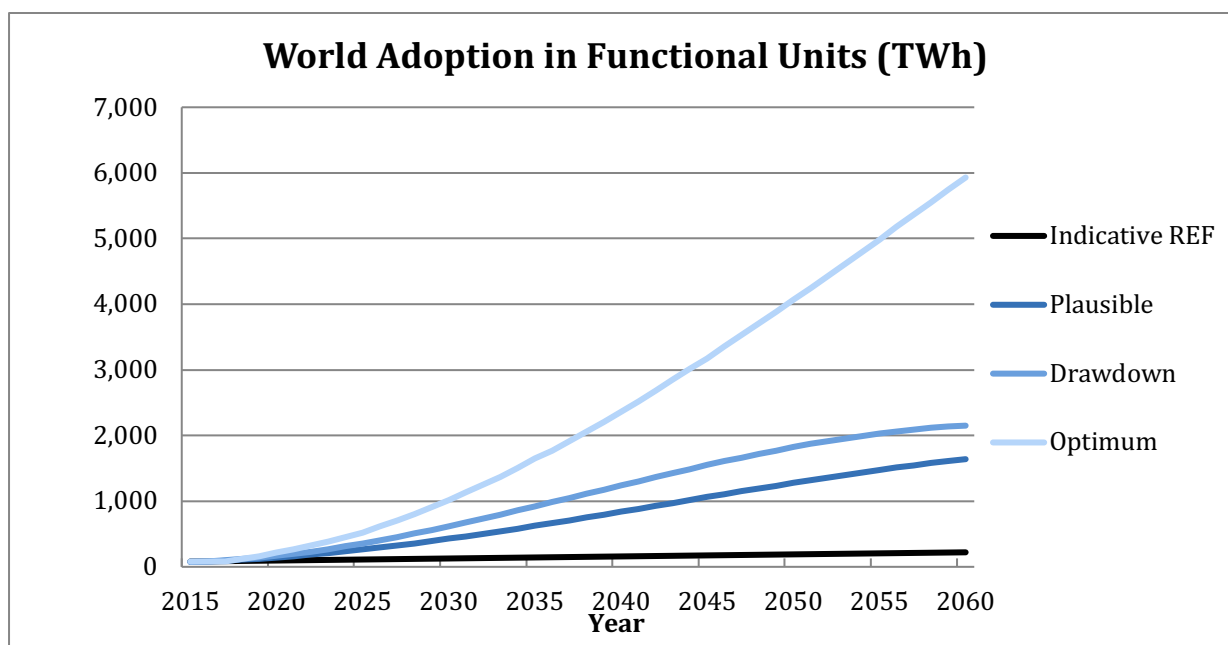| Solution	Units	Base Year (2014)	World Adoption by 2050		
			Plausible	Drawdown	Optimum
Geothermal Power	*Electricity Generation (TWh)*	74.20	1,277	1,823	4,065
	(% market)	0.33%	2.8%	2.6%	5.7%

World Adoption in Functional Units (TWh)

Figure 3.1 World Annual Adoption 2015-2060

3.2 CLIMATE IMPACTS

Below are the emissions results of the analysis for each scenario which include total emissions reduction and atmospheric concentration changes. For a detailed explanation of each result, please see the glossary (Section 6). The Plausible Scenario results in the avoidance of 6.8 gigatons of carbon dioxide-equivalent greenhouse gas emissions between 2020-2050. Both the Drawdown and Optimum Scenarios are more ambitious in the growth of geothermal technologies, with impacts on greenhouse gas emissions reductions over 2020-2050. 10.7 gigatons of carbon dioxide-equivalent emissions are reduced on PDS2 and even higher on PDS3 with 22.2 emissions avoided by the use of geothermal replacing conventional technologies. Tables 3.2 and 3.3. provide additional information on the climate impacts of the solution adoption.

Table 3.2 Climate Impacts

Scenario	Maximum Annual Emissions Reduction	Total Emissions Reduction	Emissions Reduction in 2050
	(Gt CO$_2$-eq/yr.)	*Gt CO$_2$-eq/yr. (2020-2050)*	*(Gt CO$_2$-eq/year)*
Plausible	0.44	6.82	0.44
Drawdown	0.66	10.72	0.66
Optimum	1.56	22.18	1.56

The solution was integrated with all other Project Drawdown solutions and may have different emissions results from the models. This is due to adjustments caused by interactions among solutions that limit full adoption (such as by feedstock or demand limits) or that limit the full benefit of some solutions (such as reduced individual solution impact when technologies are combined). After integration, the impact on emission reduction for this solution 6.4 gigatons of carbon dioxide-equivalent in the *Plausible* scenario, 9.9 gigatons of carbon dioxide-equivalent for the *Drawdown* Scenario and 19.0 gigatons of carbon dioxide-equivalent for the *Optimum* Scenario. Figure 3.2. show the world annual emissions reduction trajectories for the different scenarios for the long term.

Table 3.3 Impacts on Atmospheric Concentrations of CO₂-eq

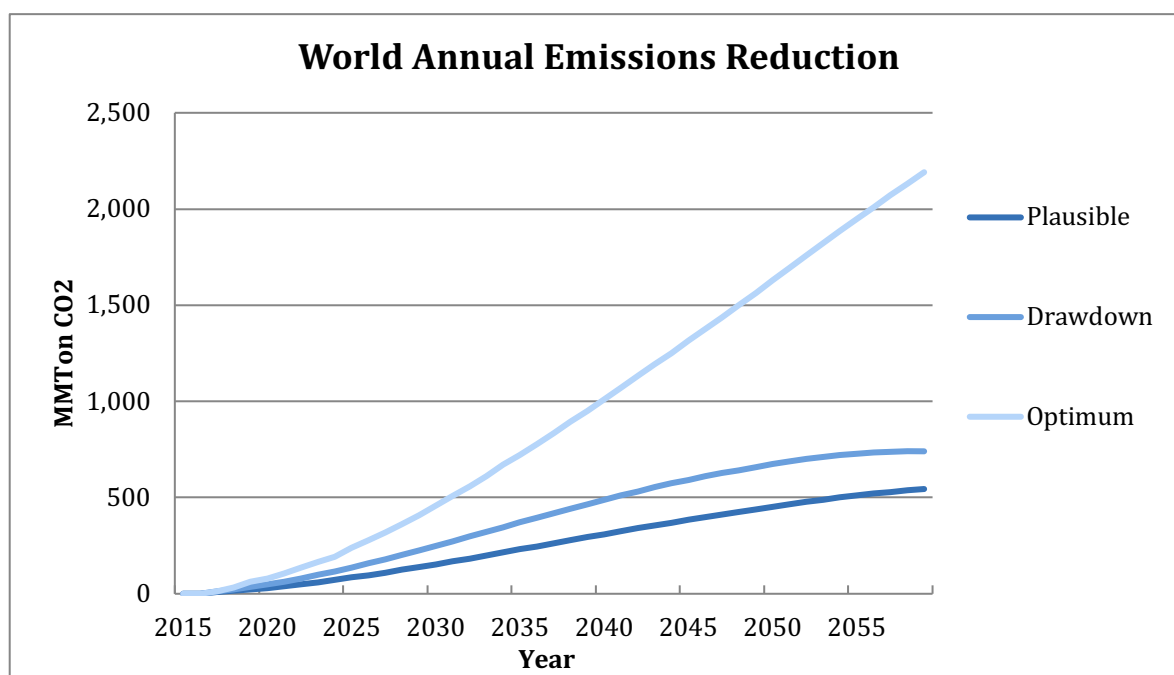| Scenario	GHG Concentration Change in 2050	GHG Concentration Rate of Change in 2050
	PPM CO₂-eq (2050)	*PPM CO₂-eq change from 2049-2050*
Plausible	0.58	0.03
Drawdown	0.91	0.05
Optimum	1.90	0.13

Figure 3.2 World Annual Greenhouse Gas Emissions Reduction (2015-2060)

Note: Drawdown and Optimum Scenarios have the same global adoption for this solution and therefore the operation costs reduction over time for both scenarios are overlaid in the figure.

3.3 FINANCIAL IMPACTS

The financial impacts incurred by replacing conventional grid electricity sources with geothermal systems in the Plausible scenario presents US$80.6 billion in marginal first costs and over US$376.9 billions of net operating cost savings are projected over the same period (2020-2050). PDS2 results show US$86.5 billions of marginal first costs and over $US592 billions of net operating savings. PDS3 have higher positive results numbers with near US$80.3 billions of marginal first costs and over $US1,232 billions of net operating savings. This is due to the long lifetime of the plants before retirement, the lack of disposal costs, and the significantly lower maintenance and fuel costs over a reference scenario with high share of fossil fuels.

The capital costs for PDS adoption of geothermal systems will require significant investments, as the cumulative capital costs are over $US542 billion under the Plausible Scenario, $US746 billion for the PDS2 and $US1,523 on PDS3 which relate with more ambitious PD adoption scenarios. Below in Table 3.4 are the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the glossary (Section 6).

Table 3.4 Financial Impacts

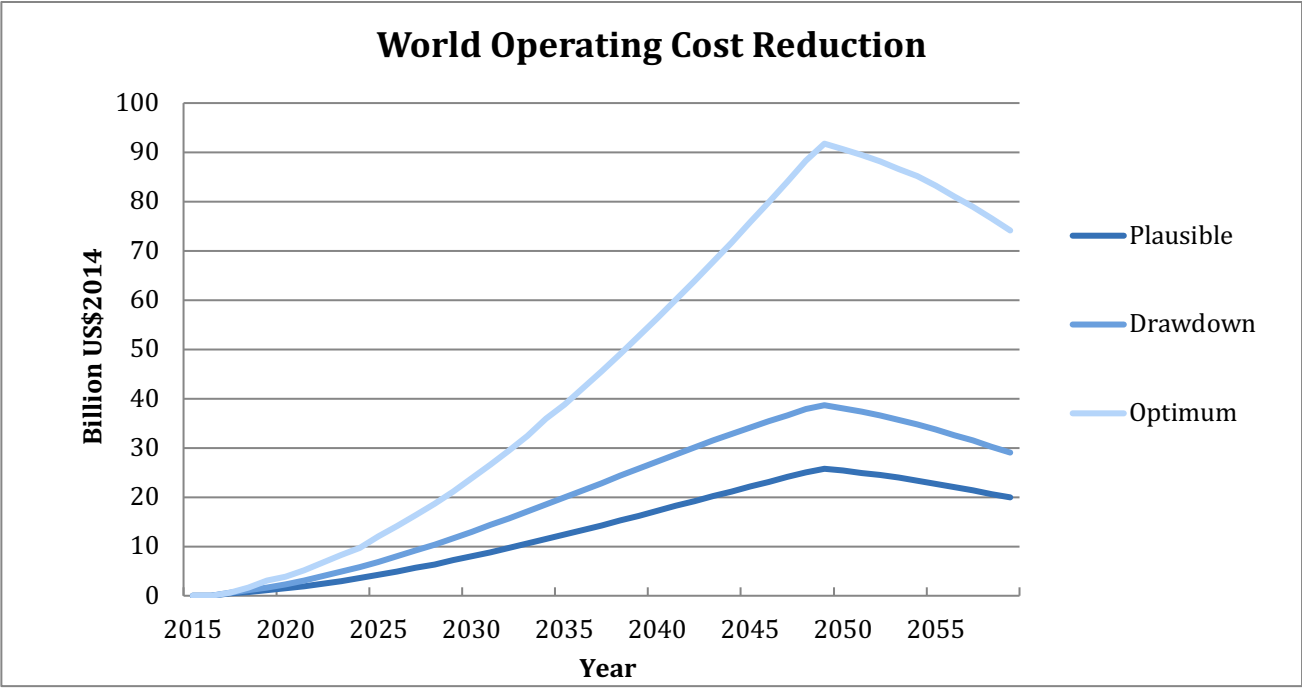| Scenario	Cumulative First Cost	Marginal First Cost	Net Operating Savings	Lifetime Cashflow Savings NPV (of All Implementation Units)
	2015-2050 Billion USD	*2015-2050 Billion USD*	*2020-2050 Billion USD*	*Billion USD*
Plausible	548	88.0	377	29.6
Drawdown	754	93.3	592	52.4
Optimum	1,537	93.0	1,232	117.5

Figure 3.3 World Operating Cost Reduction (2015-2060)

4 DISCUSSION

Herein it was examined the financial and climate effects of a significant increase of geothermal electricity compared to a reference scenario for geothermal. Results suggest that the increased use of geothermal could substantially both bring down emissions and save money. As indicated by several other modelling initiatives results, much of the initial development could take place in areas with lots of conventional, high-temperature hydrothermal resources that have yet to be developed, such as Indonesia, the Philippines, Central and South America, and East Africa. Many governments are setting targets for the development of high-temperature hydrothermal resources. These goals could be aided through renewable portfolio standards requiring a certain amount of renewable energy use, and guaranteed power purchase agreements or feed-in-tariffs for developers to reliably recover development costs.

Government bodies should also introduce policies to cover the financial risk involved in geothermal exploration, and support the development of financial instruments to cover this phase of geothermal development. International bodies like the World Bank are also helping fund and support projects in less wealthy countries, as well as facilitate private-public partnerships and the international transfer of technology and other resources. A publicly accessible and continuously updated database of geothermal resources could also aid in exploration and cut down production costs.

In the private sphere specialized financial institutions have started to develop alternative financing instruments, such as Islandsbanki's resource verification loan, which was used to cover the costs of drilling and testing two initial production wells for a geothermal power plant in California (IEA 2011). Other approaches use by developers are the raise of funds and receive project contributions from large corporations (BNEF 2013).

Governments could also begin setting long-term targets for advanced geothermal technologies, based on exploration of the potential of all types of geothermal resources. Increased private-public R&D into geothermal technologies could also help develop and bring down the costs of these growing technologies, and make geothermal energy more widely available. Indeed, given its many environmental and climate benefits, its reliability, and its low operational and fuel costs, geothermal energy could be a key player in the global goal to create an affordable and sustainable future.

In terms of power purchase agreement, geothermal electricity is different from other renewables electricity which are characterized by high variability. Geothermal electricity system is far more reliable, and therefore geothermal power purchase agreement could be consummated for the capacity contribution, energy generated, and sometimes the ancillary services (AS) it provides. Unlike other renewables such as solar PV, and wind, PPA for geothermal power plant has additional peculiar requirements with regards to Renewable

Energy Credits or Certificates (RECs) associated with both the energy generated, and the station service, geothermal resource depletion with time, station service (required for the extraction, processing, conversion, and re-injection of geothermal resource), operational force majeure (Stoel Rives, 2008), and royalty payment. Study by Edmunds et al (2016) indicates the additional revenue potential for a shift from energy-only PPA to a flexible PPA arrangement that allows provision of regulation ancillary services and load-following supports by the geothermal plant operator. Owing to the load-following and base-load capability, and the dispatchability of geothermal power plant, it is suitable for both firm and non-firm or flexible power purchase agreement (PPA) where the off-taker has the flexibility of taking only electricity it demands at any point in time. Generally, power purchase agreement has the advantage of helping the seller or IPP to secure adequate and predictable cash flow, while enabling the off-taker to hedge against future fluctuations in energy prices. In practice, PPA can be structured in two ways - direct (retail-sleeved or physical) and financial (virtual or synthetic or Contract for Difference) PPAs. While direct PPA is a contract for net energy generated and for which a legal title is taken, financial PPA on the other hand, is a contract for financial or price difference between a strike price and market price. Since geothermal resource are usually located in remote locations, it is most likely to be best suited to financial or virtual power purchase agreement which does not require the seller and the buyer to be in the same grid region (EPA, 2016).

4.1 LIMITATIONS

Like all new electricity generation technologies, for EGS to enter and compete in evolving global electricity markets, positive policies at the state, country and regional levels will be required. This study does not examine existing policies and strategies for promoting geothermal power development, except for power purchase agreement discussed in section 4. This report therefore suggests further research on how policies similar to those in existence for oil and gas and other mineral extraction operations as well as new innovative policy strategies - including provisions for accelerated permitting and licensing, loan guarantees, depletion allowances, intangible drilling write-offs, and accelerated depreciations can be used to spur the deployment of geothermal power (CENR, 2007). Also, further research on the potential of geothermal power serving as source of distributed power generation and how policies associated with cleaner and renewable distributed energies such as feed in tariffs, renewable credits and portfolio standards etc. could be used to accelerate the market penetration of EGS.

This research does not look at the aspects of environmental and social safeguards of geothermal power plant which is one of the major sustainability standard requirements for most lenders like the development finance institutions (DFIs). Consideration of ESS may affect variables such as the level of investment, and in-turn the adoption of geothermal energy.

4.2 BENCHMARKS

Table 4.1 depicts a benchmark of Project Drawdown results for 2050 on the three developed scenarios to other 11 publicly available scenarios from IEA ETP (2017), Greenpeace (2015). The benchmarked results account for geothermal power electricity generation.

Table 4.1 Benchmarks

Source and Scenario	Electricity Generation in 2050 (TWh)	Market Share in 2050 (%)
Project Drawdown – Plausible Scenario (PDS1)	**1,277**	**2.8%**
Project Drawdown – Drawdown Scenario (PDS2)	**1,823**	**2.6%**
Project Drawdown – Optimum Scenario (PDS3)	**4,065**	**5.7%**
Greenpeace Energy [R]evolution (2015) – Reference Scenario	425	0.85%
Greenpeace Energy [R]evolution (2015) – Energy Revolution Scenario	3,286	6.59%
Greenpeace Energy [R]evolution (2015) – Advanced Energy Revolution Scenario	4,547	6.73%
IEA WEO (2018) – Current Policy Scenario	417	0.82%
IEA WEO (2018) – New Policy Scenario	566	1.18%
IEA WEO (2018) – Sustainable Development Scenario	949	2.02%
IEA Energy Technologies Perspectives (2017) – Reference Technology Scenario	621	1.32%
IEA Energy Technologies Perspectives (2017) – 2DS	931	2.19%
IEA Energy Technologies Perspectives (2017) – B2DS	810	1.8%
IEEJ Outlook (2019) – Reference Scenario	307	0.65%
IEEJ Outlook (2019) – Advanced Technology Scenario	473	1.09%

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6 GLOSSARY

Adoption Scenario – the predicted annual adoption over the period 2015 to 2060, which is usually measured in **Functional Units**. A range of scenarios is programmed in the model, but the user may enter her own. Note that the assumption behind most scenarios is one of growth. If for instance, a solution is one of reduced heating energy usage due to better insulation, then the solution adoption is translated into an increase in the use of insulation. There are two types of adoption scenarios in use: **Reference (REF)** where global adoption remains mostly constant, and **Project Drawdown Scenarios (PDS)** which illustrate the high growth of the solution.

Approximate PPM Equivalent – the reduction in the atmospheric concentration of CO_2 (in **PPM**) that is expected to result if the **PDS Scenario** occurs. This assumes a discrete avoided pulse model based on the Bern Carbon Cycle model.

Average Abatement Cost – the ratio of the present value of the solution (**Net Operating Savings** minus **Marginal First Costs**) and the **Total Emissions Reduction**. This is a single value for each solution for each **PDS Scenario** and is used to build the characteristic "*Marginal Abatement Cost*" curves when Average Abatement Cost values for each solution are ordered and graphed.

Average Annual Use – the average number of functional units that a single implementation unit typically provides in one year. This is usually a weighted average for all users according to the data available. For instance, the total number of passenger-km driven by a hybrid vehicle in a year depends on the country and the typical number of occupants. We take global weighted averages for this input. This is used to estimate the **Replacement Time**.

Cumulative First Cost – the total **First Cost** of solution **Implementation Units** purchased in the **PDS Scenario** in the analysis period. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

Direct Emissions – emissions caused by the operation of the solution, which are typically caused by the lifetime use of the solution. They should be entered into the model normalized per functional unit.

Discount Rate- the interest rate used in discounted cash flow (DCF) analysis to determine the present value of future cash flows. The discount rate in DCF analysis takes into account, not just the time value of money, but also the risk or uncertainty of future cash flows; the greater the uncertainty of future cash flows, the

higher the discount rate. Most importantly, the greater the discount rate, the more the future savings are devalued (which impacts the financial but not the climate impacts of the solution).

Emissions Factor– the average normalized emissions resulting from consumption of a unit of electricity across the global grid. Typical units are kg CO_2e/kWh.

First Cost- the investment cost per **Implementation Unit** which is essentially the full cost of establishing or implementing the solution. This value, measured in 2014$US, is only accurate to the extent that the cost-based analysis is accurate. The financial model assumes that the first cost is made entirely in the first year of establishment and none thereafter (that is, no amortization is included). Thus, both the first cost and operating cost are factored in the financial model for the first year of implementation, all years thereafter simply reflect the operating cost until replacement of the solution at its end of life.

Functional Unit – a measurement unit that represents the value, provided to the world, of the function that the solution performs. This depends on the solution. Therefore, LED Lighting provides petalumen-hours of light, Biomass provides tera-watt-hours of electricity and high-speed rail provides billions of passenger-km of mobility.

Grid Emissions – emissions caused by the use of the electricity grid in supplying power to any operation associated with a solution. They should be in the units described below each variable entry cell. Drawdown models assume that the global electric grid, even in a Reference Scenario, is slowly getting cleaner and that emissions factors fall over time resulting in lower grid emissions for the same electricity demand.

Implementation Unit – a measurement unit that represents how the solution practice or technology will be installed/setup and priced. The implementation unit depends on the solution. For instance, implementing electric vehicles (EV) is measured according to the number of actual EV's in use, and adoption of Onshore Wind power is measured according to the total terawatts (TW) of capacity installed worldwide.

Indirect Emissions – emissions caused by the production or delivery or setup or establishment of the solution in a specified area. These are NOT caused by day to day operations or growth over time, but they should be entered into the model normalized on a per functional unit or per implementation unit basis.

Learning Rate/Learning Curve - Learning curves (sometimes called experience curves) are used to analyze a well-known and easily observed phenomenon: humans become increasingly efficient with experience. The first time a product is manufactured, or a service is provided, costs are high, work is inefficient, quality is marginal, and time is wasted. As experienced is acquired, costs decline, efficiency and quality improve, and waste is reduced. The model has a tool for calculating how costs change due to learning. A 2% learning rate means that the cost of producing a good drops by 2% every time total production doubles.

Lifetime Capacity – this is the total average functional units that one implementation unit of the solution or conventional technology or practice can provide before replacement is needed. All technologies have an average lifetime usage potential, even considering regular maintenance. This is used to estimate the **Replacement Time**. and has a direct impact on the cost to install/acquire technologies/practices over time. E.g. solar panels generate, on average, a limited amount of electricity (in TWh) per installed capacity (in TW) before a new solar panel must be purchased. Electric vehicles can travel a limited number of passenger kilometers over its lifetime before needing to be replaced.

Lifetime Operating Savings–the operating cost in the PDS versus the REF scenarios over the lifetime of the implementation units purchased during the model period regardless of when their useful life ends.

Lifetime Cashflow NPV-the present value (PV) of the net cash flows (PDS versus REF) in each year of the model period (2015-2060). The net cash flows include net operating costs and first costs. There are two results in the model: Lifetime Cashflow NPV for a Single **Implementation Unit**, which refers to the installation of one **Implementation Unit**, and Lifetime Cashflow NPV of All Units, which refers to all **Implementation Units** installed in a particular scenario. These calculations are also available using profit inputs instead of operating costs.

Marginal First Cost – the difference between the **First Cost** of all units (solution and conventional) installed in the **PDS Scenario** and the **First Cost** of all units installed in the **REF Scenario** during the analysis period. No discounting is performed. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

Net Annual Functional Units (NAFU) – the adoption in the PDS minus the adoption in the REF in each year of analysis. In the model, this represents the additional annual functional demand captured either by the solution in the **PDS Scenario** or the conventional in the **REF Scenario**.

Net Annual Implementation Units (NAIU) – the number of **Implementation Units** of the solution that are needed in the PDS to supply the **Net Annual Functional Units (NAFU).** This equals the adoption in the PDS minus the adoption in the REF in each year of analysis divided by the average annual use.

Net Operating Savings – The undiscounted difference between the operating cost of all units (solution and conventional) in the **PDS Scenario** minus that of all units in the **REF Scenario**.

Operating Costs – the average cost to ensure the operation of an activity (conventional or solution) which is measured in 2014$US/**Functional Unit**. This is needed to estimate how much it would cost to achieve

the adoption projected when compared to the **REF Case**. Note that this excludes **First Costs** for implementing the solution.

Payback Period – the number of years required to pay all the **First Costs** of the solution using **Net Operating Savings**. There are four specific metrics each with one of **Marginal First Costs** or **First Costs** of the solution only combined with either discounted or non-discounted values. All four are in the model. Additionally, the four outputs are calculated using the increased profit estimation instead of **Net Operating Savings**.

PDS/ Project Drawdown Scenario – this is the high growth scenario for the adoption of the solution.

PPB/ Parts per Billion – a measure of concentration for atmospheric gases. 10 million PPB = 1%.

PPM/ Parts per Million – a measure of concentration for atmospheric gases. 10 thousand PPM = 1%.

REF/ Reference Scenario – this is the low growth scenario for the adoption of the solution against which all **PDS scenarios** are compared.

Replacement Time- the length of time in years, from installation/acquisition/setup of the solution through usage until a new installation/acquisition/setup is required to replace the earlier one. This is calculated as the ratio of **Lifetime Capacity** and the **Average Annual Use**.

TAM/ Total Addressable Market – represents the total potential market of functional demand provided by the technologies and practices under investigation, adjusting for estimated economic and population growth. For this solutions sector, it represents the world and regional total addressable markets for electricity generation technologies in which the solutions are considered.

Total Emissions Reduction – the sum of the grid, fuel, indirect, and other direct emissions reductions over the analysis period. The emissions reduction of each of these is the difference between the emissions that would have resulted in the **REF Scenario** (from both solution and conventional) and the emissions that would result in the **PDS Scenario**. These may also be considered as "emissions avoided" as they may have occurred in the REF Scenario, but not in the PDS Scenario.

Transition solutions - are considered till better technologies and less impactful are more cost-effective and mature.

TWh/ Terawatt-hour – A unit of energy equal to 1 billion kilowatt-hours.