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# Geothermal Energy Resources: Potential Environmental Impact and Land Reclamation

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## Abstract

With increasing costs, finite sources and adverse environmental impacts of fossil fuels, global attention has focused on developing renewable and clean sources of energy. Although geothermal energy is considered one of the most promising sources of renewable and clean energy, it may not be as benign as widely believed. In this paper, we evaluate the environmental challenges for geothermal resource extraction and describe potential reclamation strategies for disturbed ecosystems. Generally the environmental impacts of geothermal power generation and direct use are minor and in most cases controllable. Geothermal plants have low emissions of carbon dioxide, hydrogen sulfide and ammonia, and low land and water usage; these impacts can be minimized through appropriate mitigation measures. Other potential emissions such as mercury, boron and arsenic may result in local and regional environmental consequences, although their impacts are poorly understood on a global scale. Geothermal plants can alter vegetation and wildlife habitat by reducing species diversity and community composition. There are small risks of subsidence, induced seismicity and landslides, with potential serious consequences. Integration of timely reclamation during and after plant operation can significantly contribute to reducing long term reclamation costs while enhancing ecosystem recovery. This paper is expected to contribute to understanding environmental impacts associated with geothermal energy production and to determining appropriate mitigation and land reclamation strategies.

**Keywords:** Climate change; ecosystem resilience; environmental impact; geothermal energy; green energy; reclamation.

## 1. Introduction

Projected exponential growth in energy demand (International Energy Agencies 2018), concerns over climate impacts of carbon based fuel emissions (Intergovernmental Panel on Climate Change 2007) and debate over long term steady supplies of conventional energy (e.g. oil, gas, coal) lead to growing interest in increasing renewable and green energy supplies such as solar, wind, geothermal and hydro (Hunt 2001; Grasby et al. 2012; Agemar et al. 2018; Manzella et al. 2018; Dhar et al. 2020a). Among these renewable energy resources, geothermal has several advantages that make it attractive for future energy systems (Varun et al. 2009; Glassley 2015; Shortall et al. 2015). The most important advantage of geothermal energy is its high capacity factor (actual output versus generation potential) relative to other renewable energy sources (Kagel et al. 2007; Fridleifsson et al. 2008; Grasby et al. 2012). This allows for a reliable baseload energy supply for energy production. Globally, geothermal has been a cost competitive source of energy, as it does not rely on the international market (Kristmannsdóttir and Ármannsson 2003; Fridleifsson et al. 2008; Bayer et al. 2013; Leitch et al. 2017). With its low carbon footprint and small environmental impact, geothermal energy may have great potential as a significant contributor to future global energy markets (Fridleifsson 2001; Fridleifsson et al. 2008; Lund et al. 2011; Leitch et al. 2017).

Geothermal energy is heat beneath the earth's surface that originates from the outward flow of heat from the earth's core and decay of radioactive elements in the earth's crust (Glassley 2015). The total heat content of the earth is immense and estimated at approximately $10^{13}$ EJ (exajoules ($10^{18}$ joules)); it would take over $10^9$ years to exhaust it through today's global terrestrial heat flow of 40 million MWt (Rybach 2007). The thermal power of 40 million MWt is equivalent to that of approximately 13,000 nuclear power plants of one gigawatt (GW) class (Rybach 2003). Thus, the geothermal resource base is huge and ubiquitous.

Currently more than 80 countries are involved in geothermal energy production (Lund and Boyd 2016); among them the United States of America, Philippines, Indonesia, Mexico, Italy, Iceland, New Zealand and Japan produce more than 90% of the world's geothermal energy (Bayer et al. 2013;

Agemar et al. 2014) estimated at 67,846 GWh electricity and 121,696 GWh thermal energy (Lund et al. 2011). In 2017, global geothermal power generation increased to 84,800 GWh, while the cumulative capacity reached 14 GW and is expected to grow 28% and reach over 17 GW by 2023, where countries such as Indonesia, Kenya, Philippines and Turkey would be the biggest contributors (International Energy Agencies 2018). The United States is the leading geothermal power producing country with an estimated 3.6 GW in 2018 followed by the Philippines (1.9 GW), and Indonesia (1.4 GW) (International Energy Agencies 2018). Although, Canada is endowed with substantial geothermal resources for generating geothermal energy, attention has been sparse to date and mostly concentrated on heating and cooling (Grasby et al. 2012; Hal 2013; Thompson et al. 2015). Based on 2007 data, geothermal energy has already displaced the consumption of 60 million barrels of oil per year, with ~29 million tonnes carbon dioxide ($CO_2$) emissions per year, from the United States (Kagel et al. 2007).

While geothermal energy is considered environmentally friendly or green, researchers have shown that it is not free of adverse environmental impacts (Hunt 2001; Kagel et al. 2007; Bayer et al. 2013; Shortall et al. 2015; Mutia 2016; Manzella et al. 2018). Based on existing studies, the major environmental impacts of geothermal energy development and use are land subsidence due to mass fluid and steam withdrawal, negative visual and spatial effects on the landscape, ground water depletion, air and water contamination and degradation of ecosystems by altering vegetation and wildlife habitat (Hunt 2001; Kristmannsdóttir and Ármannsson 2003; Albertsson et al. 2010; Bayer et al. 2013; Glassley 2015; Shortall et al. 2015; Mutia 2016; Manzella et al. 2018). Generally, geothermal plant establishment requires a smaller land area than conventional energy production (Bayer et al. 2013); however, that area needs to be reclaimed to a resilient ecosystem. In a natural ecosystem, the common goal of land reclamation will be to a self-sustaining ecosystem that will be subject to ecological succession and change over time (Macdonald et al. 2015a; Dhar et al. 2018a; Lupardus et al. 2019; Dhar et al. 2020a).

Knowledge regarding the reclamation process of geothermal energy production sites is scarce. Geothermal energy reclamation has been considered comparable to that of other geo-mining operations as many challenges in reclaiming ecosystems are common to different regions and types of disturbance. Reclamation for geothermal energy has similarities to reclamation for oil and gas well sites (Lupardus et al. 2019), therefore, much of the existing knowledge regarding well sites reclamation can be transferable when developing a geothermal energy sites reclamation plan.

This paper is focused on the potential environmental challenges of geothermal energy resources derived from reviewing the current global state of knowledge. We conclude by suggesting how those environmental challenges can be mitigated and geothermal production sites can be reclaimed. We identify knowledge gaps where further research could significantly improve our understanding of environmental challenges and land reclamation success for geothermal energy resources.

## 2. Geothermal Energy Systems

Archeological studies have documented that North American Indigenous people utilized geothermal springs several thousands of years ago (Stober and Bucher 2013), and that Romans, Chinese, Japanese, Turks, Icelander and Maori in New Zealand used hot springs for cooking, bathing and house heating. Four main types of geothermal resources are hydrothermal, geopressure, hot dry rock and magma, of which hydrothermal are most commonly used (Stober and Bucher 2013). Hydrothermal resources occur where magma comes close enough to the surface to heat ground water trapped in fractured or porous rocks, or where water circulates at great depth along faults (DiPippo 2003; Stober and Bucher 2013; Xydis et al. 2013). They can be used for different energy purposes depending on reservoir temperature (low and high, low enthalpy and high enthalpy), ability to generate energy (high and low) (Lee 1996) and depth. Low temperature geothermal resources, generally <100 °C, can be used directly in spas, heat buildings, grow crops, warm fishponds or for other uses, and generally are not suitable for conversion to electricity (Allen and Milenic 2003; Xydis et al. 2013). This can be done by an open or closed loop system, and the choice depends on characteristics of the mine system (Preene and Younger 2014). In closed loop systems ground water does not move, but exchanges heat with a vertical or horizontal loop of water antifreeze solution; in open loop systems ground water acts as a refrigerant to transfer thermodynamic energy (Lund et al. 2004).

High temperature geothermal resources, where temperature is >100 °C, can be used to generate electricity (DiPippo 2003; Stober and Bucher 2013). Two types of hydrothermal resources to generate electricity are dry steam (vapour dominated) and hot water (liquid dominated) reservoirs (DiPippo 2003; Stober and Bucher 2013). Dry steam power plants draw from underground steam. The steam is piped directly from underground wells to the plant to power a turbine or generator unit (DiPippo 2003). Flash steam power plants are most common and use geothermal reservoirs of water with temperatures > 182 °C. This hot water flows up through wells in the ground under its own pressure. As it flows upward, pressure decreases and hot water boils into steam that is used for power. Any leftover water and condensed steam are injected back into the reservoir. Binary cycle power plants are used when water in a hot reservoir is not hot enough to flash into steam, and they operate on water with temperatures between 107° and 182 °C (Stober and Bucher 2013). These plants use organic compounds with a low boiling point to boil the working fluid to power the turbine; water is reinjected into the ground to be reheated (DiPippo 2003; Stober and Bucher 2013).

## 3. Environmental Impacts of Geothermal Plants

When aiming to use geothermal energy, potential environmental effects and their potential mitigation measures need to be clearly identified, and counter measures devised and adopted to avoid or minimize their impacts (Table 1). Environmental effects from geothermal plants are commonly categorized based on safeguard subjects and types, and pathways of stresses and emissions. Most of these categories emphasize environmental burdens, although apart from provision of renewable energy, geothermal activities are sometimes associated with secondary benefits. Environmental impacts of low temperature geothermal energy was not considered in this paper as they have relatively less environmental impact and only require water (sometimes water and antifreeze) and electricity to operate the heat pump (Johnston et al. 2011).

### 3.1. Soil

Geothermal power plants influence physical and chemical properties of soils and impacts are generally greater in the construction phase than in operation and distribution phases. During construction, site exploration and construction of roads, well pads and structures related to the power plant (e.g. cooling station, auxiliary buildings, substation, pipelines, transmission lines) significantly influence soil physical properties (Kristmannsdóttir and Ármannsson 2003; Bayer et al. 2013). For example, soil can be compacted as a result of construction activities, which can reduce soil aeration, permeability and water holding capacity, causing an increase in surface runoff, potentially increasing sheet, rill and gully erosion; soil compaction and soil admixing can influence the viability of future vegetation (Bayer et al. 2013). The overall impact on soil is much greater in high temperature geothermal systems than low temperature systems due to disturbance intensity.

Soils are secondary receptors of emitted elements, either directly from the air or through contaminated litter fall; impacted soils lead to vegetation damage such as necrosis, defoliation, reduced growth, early senescence and chlorosis (Bussotti et al. 2003; Mutia 2016). Several studies based on high temperature geothermal systems reported that geothermal plants were associated with increasing concentrations of boron, ammonia, sulphur, arsenic and mercury in the surrounding soils, that decrease with increasing distance (Albertsson et al. 2010; Bayer et al. 2013; Mutia et al. 2016; Yilmaz and Kaptan 2017). Baladi (1988) reported highest concentrations of mercury (Hg = 0.3 $\mu g\ g^{-1}$) in soil close to the plant and concentrations tend to decrease with distance (0.02 $\mu g\ g^{-1}$ at a distance of 600 m). In China, Huang and Tian (2006) reported an average is 0.265 $\mu g\ g^{-1}$ of soil Hg in a Yangbajain geothermal field. Yilmaz and Kaptan (2017) reported that concentration of boron was 0.43-2.34 mg $kg^{-1}$ in soils, which could hamper cotton production in Turkey. Mutia et al. (2016) found distance had a significant effect on sulphur concentrations in soil near Olkaria geothermal plant in

Kenya. Relative to the reference site, highest concentrations of sulphur, arsenic and boron were found near the plant. At the Ohaaki field in New Zealand, intensive soil degassing was measured even 20 years after geothermal power production (Rissmann et al. 2012). Further study regarding sulphur, arsenic, boron, mercury and other trace element in the soil around power plants is needed for better soil management.

### 3.2. Air

Air quality impacts from geothermal plants depend on chemical composition of the geothermal steam, baseline meteorological conditions, resource temperature, geothermal plant type (steam, two phase, hot water), terrain and number of geothermal emission sources and their spatial and temporal distribution (Hunt 2001; Kagel et al. 2007; Bayer et al. 2013; Shortall et al. 2015; Tomasini-Montenegro et al. 2017; Agemar et al. 2018; Manzella et al. 2018). Depending on site conditions and plant type, geothermal energy plants can emit $CO_2$, hydrogen sulfide ($H_2S$), ammonia ($NH_3$), volatile metals, minerals, silicates, carbonates, metal sulfides and sulfates (Kristmannsdóttir and Ármannsson 2003; Kagel et al. 2007; Bayer et al. 2013; Glassley 2015; Shortall et al. 2015). Old geothermal plants, which required permanent steam release during operation can influence cloud formation and local weather conditions by atmospheric emission, (Kristmannsdóttir and Ármannsson 2003). A geothermal plant typically requires 9-11 kg $hr^{-1}$ of steam for each KWh output of which 75 % is released as vapour to the atmosphere after power extraction (US-BLM 1976). Many modern geothermal plants (closed loop binary plants) which do not have permanent steam emissions have less environmental emission (DiPippo 2015). Magnitude of the effects depend on local topographic and meteorological conditions. Although geothermal energy generally produces less $CO_2$, sulfur dioxide ($SO_2$) oxidized from hydrogen sulfide ($H_2S$) and nitrous oxides ($NO_X$) than conventional fossil fuels, these chemical residues still have environmental effects (Kristmannsdóttir and Ármannsson 2003; Shortall et al. 2015). Chemical residue emissions vary substantially across locations, within geothermal fields or their lifetimes. For example, in Iceland $H_2S$ concentration increased more than $CO_2$ during production (Kristmannsdóttir and Ármannsson 2003), relative to geothermal plants in the USA (DiPippo 2015).

Greenhouse gas emissions, such as $CO_2$, generally result from geothermal plants by degassing magma; more rarely from decomposition of organic sediments and metamorphic decarbonization (Ármannsson et al. 2005; Tomasini-Montenegro et al. 2017). Based on International Geothermal Association (IGA) data, Bertani and Thain (2002) found $CO_2$ emissions from geothermal plants were 4-740 g $kWh^{-1}$, with a weighted average of 122 g $kWh^{-1}$. Other studies reported lower $CO_2$ emissions. DiPippo (2015) reported 50-80 g $kWh^{-1}$; Kagel et al. (2007) and Bloomfield et al. (2003) reported 44 and 91 g $kWh^{-1}$, respectively, as a weighted average for geothermal plants in the USA. In Australia Marchand et al. (2015) reported 47 g $kWh^{-1}$, and in Turkey, Atilgan and Azapagic (2009) reported 63 g $kWh^{-1}$. These values are considerably lower than $CO_2$ emissions of fossil fuels such as natural gas(~550 g $kWh^{-1}$), coal (994-1130 g $kWh^{-1}$) and oil (~758 g $kWh^{-1}$) power plants (Kagel et al. (2007).

The $CO_2$ emissions from a geothermal energy plant decrease or increase over time (Bertani and Thain 2002; Sheppard and Mroczek 2004; Fridriksson et al. 2006; Dereinda and Armannsson 2010). Bertani and Thain (2002) found decreasing natural $CO_2$ emissions in the Larderello geothermal field in Italy. A similar observation was reported by Bertani (2012) in a world geothermal review analysis. A three to six fold increase of $CO_2$ emissions during operation were observed in Iceland (Fridriksson et al. 2006; Dereinda and Armannsson (2010), and in New Zealand $CO_2$ emissions at the Wairakei geothermal plant doubled since power plant operation began (Sheppard and Mroczek 2004). Some studies concluded direct $CO_2$ emissions from geothermal operations are negligible and anticipated life term emissions to be less than 50 g $kWh^{-1}$ (Hunt 2001; Shortall et al. 2015) or mostly come from maintenance activities (Rule et al. 2009; Lohse 2018). Rule et al. (2009) quantified that in a 100 year lifespan, maintenance contributes 80 % of total carbon emissions, of which 50 % comes from maintenance activities (water and steam transporting pipes, well production liners), and 25 % comes from fossil fuels used for new well construction. The remaining 20 % occurred at construction (piping system and well).

In geothermal electricity production, potential corrosive effects of non-condensable and/or dissolved gases ($H_2S$, $NO_X$) (<10 % wt of steam) (Santoyo et al. 1991) present a challenge to local ecosystem (acidification, eutrophication) and human health (Bloomfield et al. 2003; Kagel et al. 2007; Bayer et al. 2013; Shortall et al. 2015; DiPippo 2015; Tomasini-Montenegro et al. 2017). When released to the atmosphere, $H_2S$ may react with oxygen to produce $SO_2$. Kagel et al. (2007) reported a small amount of $SO_2$ (0.159 g/kWh) for flash steam and hydrothermal dry steam ($9.8 \times 10^{-5}$ g $kWh^{-1}$) at Geysers USA. Frick et al. (2010) reported $SO_2$ emissions from binary plants of 0.190 mg to 0.400 g $kWh^{-1}$, and that high concentration $SO_2$ can cause acidification near the geothermal location. The most dominant non-condensable gas in geothermal fluids is $H_2S$, reaching an average of 90 % (Bertani and Thain 2002). It is considered an odour nuisance and is toxic to humans at concentrations >30 ppb (>1000 ppm can cause death (Salas et al. 2012)). The $H_2S$ from geothermal plants can corrode electronic equipment containing some metals (silver, copper) (Salas et al. 2012). Lacirignola and Blanc (2013) found emission of particulates and $NO_X$ may impact human health; while NOx, aluminum and zinc emissions can impact ecosystem quality (Pehnt 2006). Geothermal closed loop binary plants have zero emission $CO_2$, $SO_2$ and $NO_x$ relative to traditional geothermal plants (DiPippo 2015).

Geothermal fluids may contain trace elements such as mercury, ammonia, hydrogen, nitrogen, methane, radon and minor quantities of volatile elements such as boron and arsenic (Axtmann 1975; Shibaki and Beck 2003; Kagel et al. 2007; Glassley 2015; Shortall et al. 2015). Although $CH_4$ is emitted at low concentrations from the geothermal steam, it is a concern due to its high global warming potential. The annual $CH_4$ emissions factor from geothermal power production in New Zealand was 0.85 g $kW^{-1}$, consistent with the average for all geothermal power plants (0.75 g $kW^{-1}$) in the USA (Bloomfield et al. 2003).

Using modern techniques and tools can reduce negative environmental impacts associated with release of chemical effluents from geothermal plants. Some common practices including installation of drift eliminators and filters and blowout preventers have been used in geothermal facilities around the world (Lunis and Breckenridge 1991; Kagel et al. 2007). Binary and flash binary geothermal plants exhibit greater potential to reduce emissions, in some cases emitting no non-condensable gas and negligible amounts of particulate matter (Kagel et al. 2007; Glassley 2015; Shortall et al. 2015).

### 3.3. Water

Water is required throughout the life cycle of a geothermal power plant, mostly for drilling and constructing wells, pipelines and plant infrastructure; stimulating injection wells; and operating power plants (Clark et al. 2010; Bayer et al. 2013; Shortall et al. 2015; Sowiżdżał et al. 2017). Water use depends on plant size, technological variant, working temperature, cooling mechanism and geothermal water availability (Bayer et al. 2013; Bosnjakovic et al. 2019). A large quantity of water is required at the beginning of drilling, approximately 5-30 $m^3$ for 1 m well construction, depending on geology, technology, number of liners and depth; thus a 2 km well installation requires 8,000-55,000 $m^3$ of water (Clark et al. 2011). Cost increases with greater depth to geothermal resources. Some geothermal plants (flash steam facilities) may require fresh water to compensate for water loss through evaporation or blowdown before reinjection and cooling purposes (Bayer et al. 2013; Shortall et al. 2015; Sowiżdżał et al. 2017). Water use depends on the size of the power plant, the technology applied, the working temperatures and cooling variant. Total water use by a geothermal plant during operation is much less (2 lit $MWh^{-1}$) than natural gas power plants (1370 lit $MWh^{-1}$) (Kagel et al. 2007). Binary power plants use a small amount of water (lifetime: 0.6 $m^3$ $MWh^{-1}$) due to air cooling systems; flash system power plant uses even less (lifetime: 0.4 $m^3$ $MWh^{-1}$) (Bosnjakovic et al. 2019). Small amounts of water are required during operation to minimize scaling and manage dissolved solids (Clark et al. 2011). Although most geothermal plants can use fresh water for cooling, using geothermal fluid can reduce total water consumption (Macknick et al. 2012). Dry cooling system could be another way to reduce water consumption. Bosnjakovic et al. (2019) reported that adding dry cooling tower can reduce water consumption > 75% when compared with wet recirculation cooling system.

Other significant hydrologic impacts of geothermal energy plants are on water quality within the surrounding areas of plants (Bayer et al. 2013; Shortall et al. 2015; Sowiżdżał et al. 2017). Geofluids are a potential source of water and soil contamination due to elevated total dissolved solids and toxic minerals; well casing failure, pipeline leakage and surface spills are potential pathways for contamination (Tester et al. 2006). Geothermal technology has potential to affect ground water by connecting previously unconnected aquifers via boreholes, or connecting contaminated zones and aquifers (Kagel et al. 2007). Shortall et al. (2015) reported that during plant operation, cooling water or water discharge from geothermal wells to the ground or an evaporation pond could affect shallow ground water quality (chemical contamination) via percolation. Above ground water quality within the surrounding area may be affected by release of more acidic and/or alkaline effluent from the power plant, or effluent containing chlorides, sulfides or other dissolved chemicals, such as arsenic, boron, aluminum) (Kagel et al. 2007; Glassley 2015).

Some geothermal fluids have excessive salts (Salton Sea reservoir 200,000–300,000 ppm) (Austin et al. 1977), which can directly damage the environment (Kristmannsdóttir and Ármannsson 2003). Most high temperature geothermal water contains high concentrations of at least one potentially toxic chemical, including aluminum, boron, arsenic, cadmium, lead, mercury and fluoride (Wetangula 2004). Other potentially toxic chemicals include iodine, aluminum, lithium, hydrogen sulfide, bicarbonate, fluoride, silicate and ammonia (Kristmannsdóttir and Ármannsson 2003; Bayer et al. 2013; Shortall et al. 2015). DiPippo (2015) found quantity of dissolved solids increases significantly with temperature, making high temperature geofluids riskier than moderate or low temperature ones. Dissolved boron and arsenic in surface or ground water could have a direct harmful impact on vegetation or animals (Shortall et al. 2015; Sowiżdżał et al. 2017).

### 3.4. Flora and fauna

Biological, chemical and geological conditions of geothermal sites have potential to facilitate development of rare ecosystems (Grasby and Lepitzki, 2002). Fukutina (2012) found plants, animals and microorganisms and their dependent ecosystems in some geothermal sites were often unique; many were considered fragile or sensitive habitat for endemic species such as *Kunzea ericoides* (A.Rich.) Joy Thomps in New Zealand (Manen and Reeves 2012) and *Magnolia obovata* Thunb. in Russia (Yurchenko 2005). In Canada, some ecologically sensitive and rare species have been found in geothermal habitats, including the Banff springs snail (*Physella johnsoni* Clench.), the southern maidenhair fern (*Adiantum capillus-veneris* L.), the Nahanni aster (*Symphyotrichum nahanniense* (Cody) Semple) and the vivid dancer damselfly (*Argia vivida* Hagen in Selys) (Grasby et al. 2012). Establishing geothermal plants in ecologically sensitive areas or in delicate ecological resource (vegetation, wildlife, aquatic biota, special status species and their habitats) sites could directly influence those biological entities.

Geothermal plant site exploration and construction (clearing, road construction, well drilling) can disturb habitat and degrade habitat quality for flora and fauna. Drilling and seismic surveys may result in erosion, runoff and noise, which may disturb wildlife or affect breeding, foraging and migrating of some species (Hunt 2001). Soil disturbance influences seed bank depletion and erosion, which could lead to native vegetation species loss or decreases in biodiversity (Dhar et al. 2018a). Thus geothermal systems management should integrate use of resources while simultaneously protecting the diversity of thermal features.

Forested areas can become fragmented due to construction of geothermal plants and transmission lines, directly lowering species number and changing community composition (Víquez 2006). Toxic air and aquatic emissions can detrimentally impact adjacent habitat (Bayer et al. 2013). Loppi et al. (2006) found that mercury and $H_2S$ release from a geothermal power plant in Italy had a small to moderate impact on epiphytic lichen. Kagel et al. (2007) concluded that geothermal development posed only small impacts to wildlife and vegetation in the surrounding area relative to other energy extraction methods such as coal mining.

### 3.5. Hazardous waste

Geothermal plants around the world generally produce solid and liquid waste. Overall waste production can be higher in liquid dominated, high temperature, geothermal fields (Bayer et al. 2013). Sources of solid wastes at geothermal sites are drilling mud residues, drill cuttings, power plant and cooling tower chemical wastes and $H_2S$ abatement wastes (Kagel et al. 2007; Bayer et al. 2013; Glassley 2015). Other solid wastes can include scale from cleaning wells and pipelines, drilling additives and filter materials (Kagel et al. 2007). The total amount of solid waste is considered small and not of environmental concern (Kagel et al. 2007; Bayer et al. 2013). Liquid wastes at geothermal plants include spent geothermal fluids and petroleum products such as fuels, lubricants and drilling mud additives (Brophy 1997; Hunt 2001). Similar to gaseous emissions, geothermal fluids are diverse, with many specific constituents and compositions depending on geological setting, production mode, time and technology. Reinjection of such contaminated geothermal fluids can contaminate freshwater aquifers (Heath 2002; Aksoy et al. 2009). Waste fluids from drilling and testing can cause gullying (Maochang 2001), and depending on the composition, lead to contamination of freshwater bodies. For example, thermal waters from the Yangbajing geothermal field in Tibet carried high concentrations of boron and arsenic into a downstream river and created health problems among inhabitants (Guo et al. 2008).

### 3.6. Geophysical and land hazards

Geothermal energy production involves extensive extraction or circulation of geofluids or steam and large scale and local manipulation of shallow and deep ground water (Barrios et al. 2011). Hazards associated with geothermal resources are diverse and case specific (Barrios et al. 2011; Bayer et al. 2013; Glassley 2015; Shortall et al. 2015). Certain hazards are associated with their location (seismically active areas) (Barrios et al. 2011; Evans et al. 2012; Shortall et al. 2015) or potential for geothermal exploitation (changes in geological conditions) (Shortall et al. 2015).

Land subsidence is a consequence of geothermal plants when reservoir pressure declines after fluid withdrawal, which results in a slow, downward sinking of the land surface (Kagel et al. 2007;

Grasby et al. 2012; Glassley 2015; Shortall et al. 2015). Land subsidence is more common in liquid dominated fields than vapour dominated fields which are often located in young unconsolidated volcanic rock (Hunt 2001; Heath 2002; Keiding et al. 2010; Glassley 2015). Subsidence varies with site. At Wairakei New Zealand geothermal fields subsided up to 45 cm year$^{-1}$ (Allis 2000), at Larderello Italy they subsided up to 25 cm year$^{-1}$ (Bayer et al. 2013), and Svartsengi Iceland subsides by 1 cm year$^{-1}$ (Kristmannsdóttir and Ármannsson 2003). Land subsidence can affect stability of pipelines, drains and well casings, and if close to a populated area it can lead to instability of buildings (Maochang 2001; Shibaki and Beck 2003). It can cause formation of ponds and cracks in the ground and may alter regional hydrological flow regimes (Maochang 2001; Shibaki and Beck 2003; Fukutina 2012).

Although the extent to which geothermal development induces landslides is unclear, the steep, volcanic terrain, where geothermal facilities are commonly built, can be the main factor for frequent landslides (Leynes et al. 2005; Kagel et al. 2007; Glassley 2015). Landslides may be stimulated by change in regional water and heat flows, or when unconsolidated sediments, such as pumice, are destabilized (Kagel et al. 2007; Glassley 2015). A catastrophic landslide occurred in the Zunil I geothermal field of western Guatemala in 1995 with an estimated size of nearly 800 m long and 200-300 m wide (Flynn et al. 1991).

Induced seismicity occurs when a change in fluid pressure within a stressed rock formation leads to movement of fractured rocks (Kagel et al. 2007; Glassley 2015). Released energy is transmitted through the rock and may reach the surface with enough intensity to be heard or felt by people in the area. Likelihood and severity of the event depend on the local state of stress within the formation. Nearly every geothermal field under exploitation has had induced seismicity (Kugaenko et al. 2005), most frequently in high temperature geothermal systems (Grasby et al. 2012; Shortall et al. 2015), or during fracking to access thermal energy in an area with low permeability (Glassley 2015). Fracking is generally used in low to moderate temperature systems to stimulate or promote geothermal fluid movement through the reservoir (Glassley 2015).

Occurrences of seismicity have been reported at the Geysers geothermal fields, the Rocky Mountain Arsenal in Denver during high pressure reinjection (Kagel et al. 2007), and at least 30 other sites across the USA (Nicholson and Wesson 1992). Voight (1992) reported that since 1980 2-3 events of magnitude >4.0 per decade, and approximately 18 events of magnitude >3.0 per year, have occurred in Geysers geothermal fields. In Switzerland, a geothermal project was suspended when more than 10,000 seismic events, up to 3.4 on the Richter scale, occurred over six days after water injection (Deichmann et al. 2007). Reinjection induced seismicity occurred at Húsmúli Iceland in 2011 at 4 on the Richter scale (Reykjavik energy 2011). A fracking activity in Pohang, South Korea was responsible for a magnitude 5.4 earthquake (Voosen 2018). Knowledge regarding seismic activities caused by geothermal energy systems can be enhanced if we can determine what induced seismicity is telling us and where the fluid or stresses are going.

### 3.7. Footprint

Geothermal plants are generally built close to the resource for maximizing utilization of heat energy instead of transmitting high temperature steam over long distances by pipeline. The surface area disturbed by geothermal development can vary from 10-50 % of the total development area (including land occupied by pipelines and wells) and is primarily a function of facility electrical capability (Chorney and Sherwood 1981). As generating capacity increases, number of production wells, roads, transmission lines and pipelines increase for high temperature geothermal plants.

The well spacing for geothermal energy extraction is highly variable and dependent on the system. The minimum spacing of wells to avoid interference with the nearest one typically 200-500 m for high temperature power plant and usual capacity of a single well is 4-10 megawatts (MW) and geothermal power plants tend to be up to 600 MW (Bayer et al. 2013; DiPippo 2015). Excluding wells and transmission lines, a geothermal plant requires an estimated land use of 0.12-0.27 ha MW$^{-1}$, and with wells and power stations (without transmission lines) 0.23-3.0 ha MW$^{-1}$. Geothermal plants with super saline brine require huge vessels to process the brine which require 75 % higher land use

(Tester et al. 2006). Transmission lines account for a substantial land use, relative to the power plant which covers one tenth of the footprint. Estimating land use for power transmission lines is difficult, as geothermal power plants can be at remote locations, near recreational parks or areas that are not industrialized and have low populations. Excluding transmission lines, the land footprint of geothermal plants is lower than other energy systems. For example, coal, nuclear and gas power plants require ~5.0, solar ~17.5, wind ~28.3 and hydro ~127.6 ha $MW^{-1}$ (Stevens 2017).

Land quality (national parks, site productivity, forest conservation areas, tourist areas, cultural value) of geothermal areas must be considered in the planning phase. Hunt (2001) concluded that the impact of land use is not only influenced by type and extent of development, but by original use. Many other studies reported that geothermal plants in some countries such as Japan, Indonesia, USA and New Zealand are constrained by land use issues (Pasqualetti 1980; Hunt 2001; Goldstein et al. 2011; Bayer et al. 2013). In some cases, geothermal plants are located in the vicinity of national parks, tourist areas (Goldstein et al. 2011) forest conservation areas (Pasqualetti 1980; Bayer et al. 2013), areas of high cultural value or on highly agriculturally productive lands (eg Imperial Valley, California) (Bayer et al. 2013). A geothermal plant on forested land can lead to removal of forests and changes hydrological patterns of stream flows, negatively affecting agricultural irrigation (Prosini et al. 2005; Shortall et al. 2015). Deforestation of water catchments near geothermal fields may negatively influence recharge of the geothermal resource.

## 4. Mitigative Measures

Even before development and reclamation, many mitigative measures may be employed to reduce environmental impact of geothermal developments. Requiring environmental reviews to categorize potential effects before geothermal plant construction will be required to fully anticipate negative impacts. Detailed monitoring during all phases of exploration, construction, operation and decommissioning could provide a preventive approach and opportunity to address negative issues before they become overly problematic (Table 1).

Simple measures would include controlling water spills from the geothermal plant to soil, local aquatic systems preventing connection of contaminated zones and aquifers. Power plants could be fenced to prevent wildlife access; areas with high wildlife concentrations, specific vegetation and sensitive sites could be avoided. Compliance with regulatory requirements addressing endangered species, forest management or environmental impact management, that protect areas set for development depending on jurisdiction would be essential. Proper waste management must be in place. Development of a geothermal plant in a forested area requires caution to protect the forest around the plant sites, as healthy forests promote rainwater infiltration to reach geothermal reservoirs (Prosini et al. 2005; Shortall et al. 2015).

A properly placed injection well can reduce potential subsidence by maintaining reservoir pressures (Kagel et al. 2007; Glassley 2015); thus incorporating reinjection into reservoir management from the beginning can minimize risk and prolong reservoir life. In the USA, subsidence developed by the Heber geothermal field was resolved by injection (Kagel et al. 2007). Potential landslide hazards can be managed through detailed hazard mapping, ground water assessment and deformation monitoring. Regulations for site selection and improvements in construction methods can be used to minimize potential landslide and erosion risks. In Geysers Geothermal Field, USA, landslides were controlled by several wells drilled at single sites, and 20 % of surface area above the steam reservoir was graded to provide level areas for development (Reed and Campbell 1975). Since the outcome and prevalence of seismicity remains unpredictable, continuous monitoring of the region should be conducted through all phases of geothermal development. Areas naturally prone to significant seismic activities should be avoided and a good understanding of the regional stress field is required.

Combining geothermal systems with other renewable resources can reduce the land use footprint and allow for energy production which could be utilized for different purposes. Solar and wind energy can be co-located with geothermal plants to enhance geothermal reservoirs by supplying heat (solar) or power for pumping (wind) to the fluid injection system that replenishes the reservoir (Mathur

1979; Glassley 2015; Cardemil et al. 2016; McTigue et al. 2018). Resulting improvements in overall efficiency and reservoir management could greatly benefit use of each of these resources. In Chile for example, Cardemil et al. (2016) concluded that combining solar energy with geothermal increased efficiency of the geothermal plant. Site assessment for co-location energy production is thus highly recommended before planning geothermal plant establishment.

Abandoned oil and gas wells can be used for geothermal energy production based on the temperature at the bottom of the well (Grasby et al. 2012; Cheng et al. 2014; Leitch et al. 2017; Caulk and Tomac 2017; Banks et al. 2020; Kaplanoglu et al. 2020). Worldwide there are 20-30 million abandoned oil wells (Cheng et al. 2014). Wells drilled to 5 km cost US$ 5 million each in 2003 (Augustine et al. 2006). Given high drilling costs of geothermal wells, abandoned oil or natural gas wells can be used to reduce geothermal production costs. Reusing abandoned oil and gas wells improves the economic feasibility of geothermal energy production since drilling costs generally correspond to 42-95 % of total costs of a power plant project (Alimonti and Soldo 2016). According to Hickson et al. (2020) three critical factors need consideration to create a commercially viable geothermal project by using oil and gas wells: high water flow (300 lit $s^{-1}$); temperatures above 110 °C; and drilling depths 4,500 m or less. Bank and Harris (2018) reported lower average flow rates (43.03 lit $s^{-1}$) can produce viable geothermal power with similar temperature range. A significant number of abandoned oil and gas wells have potential for geothermal energy production; in some cases, hydraulic fracturing may be required to meet the critical factors (Caulk and Tomac 2017). Hickson et al. (2020) reported that in Canada’s Western Sedimentary Basin (WCSB), especially in Alberta, many abandoned oil and gas wells meet the three critical factors for geothermal energy production. Banks et al. (2020) reported 190 abandoned wells in the Virginia Hills oil field within the WCSB have potential of ~115 $MW_{th}$ and 16 $MW_e$ geothermal power.

## 5. Socio-Economic Aspects of Geothermal Energy Systems

Socio-economic aspects of geothermal energy are being conducted around the world, although the literature is fragmented and loosely connected. Success of geothermal projects often depends on level of acceptance within the local community; thus production sites must undergo environmental and social impact assessments to identify and quantify potential impacts of development. Social impact assessments should be done prior to development, as they can assist in predicting and mitigating negative impacts, and can increase public participation in decision making by identifying opportunities to enhance benefits for local communities and the broader society (Esteves et al. 2012; Lakhan and Stonehouse 2012; Bayer et al. 2013).

Studies in Canada (Lakhan and Stonehouse 2012), Turkey (Baba 2003), Iceland (Ketilsson et al. 2010), USA (Edelstein and Kleese 1995), Kenya (Manyara and Mading 2012) and El Salvador (Arevalo 2006), showed that the legislative framework and politics of a region are important factors, followed by religious beliefs of local people, for determining geothermal plant construction success. Other social impacts related to geothermal development are displacement and disputes over land rights; rights of indigenous people; loss of livelihood, short-term disruptions such as traffic, road, influx of population, noise and odour; lack of stakeholder engagement or consultation; and disputes over employment and economic benefits. A planned 163 MW geothermal plant was cancelled due to disapproval of religious leaders in Indonesia; another was cancelled due to objections from traditional religious followers in Hawaii, USA (Bayer et al. 2013). Proper outreach and education such as prevention of adverse effects on human health, minimization of environmental impacts, and creation of direct and ongoing benefits for resident communities, can significantly influence public perception towards geothermal plants (Goldstein et al. 2011). To increase public acceptance, some companies and government agencies have started to work on social issues by improving local security or building roads, schools, medical facilities and other community assets (Shortall et al. 2015).

Geothermal developments can contribute to financial stability of the local community by creating direct and indirect employment (Goldstein et al. 2012). Direct jobs are those associated with construction and maintenance of geothermal power plants; indirect employment refers to jobs created in all industries that provide goods and services to the power plant company (Bayer et al. 2013). Local job opportunities may be created during exploration, drilling and construction of the plant (Barns and Luketina 2011). Increased economic activity in a region due to the geothermal plant can be significant. Based on the USA Geothermal Energy Association, the geothermal energy sector contributes to the economy with 5,200 direct jobs and 13,100 indirect or induced jobs as of 2010 (Goldstein et al. 2012). The geothermal development at Olkaria, Kenya, received greater acceptability due to greater environmental and social benefits to the local communities (Jennifer 2010).

## 6. Reclamation of Geothermal Energy Systems

The main goal of land reclamation and ecosystem restoration are to create conditions that support long-term use and resilience of ecosystems, although this varies with jurisdiction and end land use. Reclamation time frames and challenges vary with level of disturbance and end land use. Challenges may be few and time frames short for simple reclamation procedures on agricultural systems. Biodiversity and community structure, and their associated ecological complexity, are key components of restoration when land is returned to natural conditions (Hobbs and Harris 2001; Chen et al. 2017), often necessitating longer time frames and involving significantly greater challenges.

### 6.1. Regulatory requirements

Although there are limited reclamation regulations for geothermal resource extraction sites, environmental policies and regulations for reclaiming other energy resource sites are available in many countries and can be adapted for geothermal plant land reclamation. Geothermal and conventional oil and gas operations involve drilling wells to extract fluids; thus existing oil and gas well reclamation regulations could be applied to geothermal projects. Currently in Alberta two acts address oil and gas operations. The Water Act (Alberta Government 2017) regulates water withdrawals, usage, release and diversions. The Environmental Protection and Enhancement Act (Alberta Government 2019) addresses impacts on air, water quality, land and waste management, by outlining aims of reclamation to obtain equivalent land capability. The Conservation and Reclamation Regulation (Government of Alberta 2018a) and the Conservation and Reclamation Directive for Renewable Energy Operations (Government of Alberta 2018b) can be adapted for geothermal plant site reclamation. According to these regulations, operators of a specified land activity are obliged by law to conserve specified land, reclaim specified land and obtain a reclamation certificate. To obtain a reclamation certificate the disturbed site must function similarly to pre-disturbance, and no longer need intervention. The Habitats Regulations Act in Scotland UK presents similar obligations specifically for wind energy (Taylor, 2016) which can be transferable to geothermal site reclamation.

Policy regarding performance and reclamation bonds could be requirements for approval of geothermal plant development. The main goal of such policy is for each company to assume liability to cover costs associated with decommissioning and reclamation of each project. For example, in the USA, under the Federal Land Policy and Management Act 1976 (US-BLM 2001), each company must furnish a bond or other security to secure all obligations associated with decommissioning and reclamation. For solar and wind energy, the performance bond is equal to the estimated costs provided in the initial plan or US \$25,000 ha$^{-1}$ (US-BLM 2012). The term of this bond is generally for one year, and it can be continuously renewed, extended or replaced so that it remains in effect for the remaining term of the agreement or until the secured decommissioning and reclamation obligations are satisfied.

### 6.2. Reclamation

Reclaiming a geothermal site to pre-disturbance conditions may be complex and time consuming as there are always impacts regardless of the type of reclamation intervention (Legwaila 2012). In some cases, land will be reclaimed to a different state or land use (Dhar et al. 2018a), in other cases ecological restoration will be to pre-disturbance conditions. Since geothermal plants require small land areas for electricity generation, the overall impact on land should be smaller than for traditional or some other renewable energy systems. For successful reclamation at geothermal energy sites the following sections outline the processes that should be considered

### 6.2.1. Planning

Planning reclamation prior to construction is critical to achieving successful reclamation in the future. Reclamation becomes significantly more difficult, more expensive and less effective if proper attention is not given during the planning phase, including sufficient topsoil salvage and storage, collection of seed and vegetative propagules from hard to find plant species, and which interim reclamation measures would be appropriate. Knowing reclamation requirements, regulations and potential challenges means issues need to be identified in the reclamation planning stage. Ongoing monitoring and review of reclamation plans are required until the reclamation target is achieved.

### 6.2.2. Reclamation or restoration of ecosystems

The ultimate goal of reclamation is to create conditions (landforms, soils, vegetation, hydrologic regimes) compatible with adjacent or desired end land use; depending on the desired outcome this could result in restoration to original ecosystems (National Research Council 2007; Welstead et al. 2013; Macdonald et al. 2015b; Golder Associates 2016; Dhar et al. 2018a; Lupardus et al. 2019; Dhar et al. 2020a; Dhar et al.2020b). Reclamation of geothermal plants will generally be similar to oil and gas well site reclamation, as extraction follows similar procedures. Reclamation of geothermal plants can involve geothermal plugging the wells, placing salvaged topsoil or other appropriate soil materials, controlling erosion, revegetating with appropriate plant species and appropriate seeding and transplanting methods, controlling undesirable plant species (weeds) and monitoring results. Heavy grazing, insufficient amounts of appropriate quality soil, long-term soil stockpiling, soil placement depth, erosion, soil compactness and contamination are some of the factors that can hinder reclamation, delay overall ecosystem recovery and increase management costs. Reclamation of geothermal sites can occur in two phases, at the time of plant operation and after plant decommissioning. Time for reclamation will vary considerably with original land uses (forestry, grazing, agriculture) (Fthenakis and Kim 2009; Dhar et al. 2018a; Lupardus et al. 2019; Dhar et al. 2020b), specifically with vegetation. For example, grasslands can be restored more quickly than forest (Spellman 2014), but slower than agricultural crop land.

### 6.2.3. Intermediate reclamation

The goal of intermediate reclamation is to facilitate the fastest recovery of the disturbed ecosystem and to reduce the long-term footprint of the operation (Dhar et al.2020a). In this phase disturbed areas within the geothermal plant sites, excluding wells heads, facility structures and infrastructure, will be reclaimed immediately after construction. This approach has several advantages, enhancing partial ecosystem recovery, reducing overall reclamation cost, conserving plant propagules and microorganisms in soils, providing habitat for flora and fauna, providing greater social licence to the operating companies, and supporting research to assess environmental impacts on vegetation and soil caused by the geothermal plant construction, operations and decommissioning.

Before plant construction, soils (particularly topsoil) should be salvaged and stockpiled for future use as they are recognized as a significant resource for seeds and vegetative propagules if native plant species are desired or required (MacKenzie and Naeth 2010; Schott et al. 2016; Dhar et al. 2018a; Dhar et al.2020a). The seed bank in upper soil horizons is a source of inexpensive, diverse and ecologically adapted vegetation (MacKenzie and Naeth 2007; Naeth et al. 2013) and for some plants, it may be the only reserve of propagules from which a species can establish (Koch and Ward 1994; Ward et al. 1996). The use of salvaged soil can accelerate rebuilding soil structure and function (organic matter content, nutrient concentrations, microorganisms, water holding capacity) (Sydnor and Redente 2002) and thus, salvaged soils are widely used in reclamation (Rokich et al. 2000; Zhang et al. 2013; Errington and Pinno 2016; Ulrich et al. 2016).

Effectiveness of the seed bank and vegetative propagules from salvaged soil is influenced by salvage depth, (Rokich et al. 2000; Mackenzie et al. 2012; Macdonald et al. 2015a) storage time and methods and placement depth (Mackenzie et al. 2012; Dhar et al. 2018a). Salvage depth of 10-20 cm is considered ideal for oil sands or well pad reclamation in upland boreal forest sites (Dhar et al. 2018a). Storage of soils is directly related to plant propagule viability (Mackenzie and Naeth 2019) and subsequent plant community development following placement on reclaimed sites (Mackenzie and Naeth 2010; MacKenzie et al. 2012; Dhar at el. 2019). From various studies, it is evident that soil tends to change chemically, biologically and physically during stockpiling due to handling of soil and from anaerobic conditions that may occur within stockpiles (Abdul-Kareem and McRae, 1984; Mackenzie and Naeth 2010; MacKenzie et al. 2012; Mackenzie and Naeth 2019).

To reduce reclamation costs; maintain healthy, biologically active soil; and minimize habitat and forage loss during the life of geothermal plants, all salvaged soils should be spread over the plant sites that are not needed for production operations, rather than stockpiled. Cover soil placement depth should be 10-20 cm as it affects seed germination and seedling emergence (Qi and Scarratt 1998; Rokich et al. 2000). Soils should be placed loosely or in small piles to minimize compaction and to create micro-topographic heterogeneity. Micro-topographic heterogeneity provides diverse conditions for seed germination and vegetation establishment (Tilman 1994; Naeth et al 2018). In grassland reclamation, Naeth et al (2018) reported that topographic microsites can buffer soil temperatures and reduce seed erosion, increasing grass and forb seedling emergence. Melnik (2017) found variability in micro-topography created favourable growing conditions (greater species richness and abundance) at an operational scale and helped to germinate a wider range of species from the propagule bank. During soil placement, sufficient soil may be stockpiled for final reclamation (after decommissioning) of small, unreclaimed areas around the well heads and power plant.

Long term storage can change soil properties, specifically seed bank efficacy (Mackenzie and Naeth 2019). Therefore, design and construction stages of stockpiles need careful consideration (National Research Council 2007; Welstead et al. 2013; Mackenzie and Naeth 2019) and stockpiled soils should be revegetated to prevent erosion and maintain biological viability (Dhar at el. 2019). Other site preparations may include gouging, scarifying, dozer track walking, mulching, fertilizing, seeding and planting, depending on site conditions (National Research Council 2007; Welstead et al. 2013; Dhar and Comeau 2018b). In some case use of woody debris can reduce erosion and facilitate native plant community development (Brown and Naeth 2014). After soils placement the area should be revegetated with desired plant species, depending on the geothermal plant location. For example, if the site is located in a forested area, perennial tree and shrub species should be planted first to facilitate other understory development. Understanding the desired environmental conditions that facilitate ecosystem recovery and plant community succession is an important factor to consider during geothermal site reclamation is to native plant communities.

### 6.2.4. Final reclamation

The final reclamation should be started when geothermal energy production has ceased. This phase includes decommissioning, contaminant remediation, final reclamation and monitoring. Decommissioning consists of removing geothermal installations and any relevant structures such as surface pipelines, wells, transmission lines and roads that have reached the end of their productive lives (Raimi 2017).

Chemical pollution is a potential risk when the power plant is emptied of its working fluid. The potential main risks include fire hazards and hazardous effects in enclosed spaces, which require specific remediation processes. Remediation involves investigation and cleanup of hazardous materials (Raimi 2017). In many countries, remediation during decommissioning of power plants is regulated by government legislation; such as the Alberta Environmental Protection and Enhancement Act in Alberta, Canada. Any contamination must be remediated before reclaiming the land. An environmental site assessment which includes site description, records review, site visit, drilling waste disposal assessment and discussions with former landowners and site operators, will provide information to assess contamination potential. If potential contamination was identified, further assessment will gather detailed information about the nature, depth and extent of contamination, and assess risk and options for remediation techniques.

After decommissioning and remediation, geothermal wells should be plugged and/or capped with previously stockpiled or other soils. If insufficient soil is present, reclamation may require soil building or bringing in soil from off site. Soil building may include use of waste materials produced in the area, such as animal manure or agricultural straw. Surface disruptions accompany facility decommissioning and require efficient clean-up and landscaping. After infrastructure removal, the site and access roads will be regraded to appropriate contours, ensuring drainage and other aspects of hydrologic regime are not compromised. Revegetation will be conducted by selecting the best plant species to meet end land use needs; appropriate methods will be determined, including type of seeding or transplanting (Patton et al. 2013; Boswell Wind LLC. 2017; Dhar et al. 2018a). The final stage of reclamation is monitoring to ensure all regulatory and site use requirements have been met.

## 7. Knowledge Gaps

The prospect of using geothermal energy has considerable potential in reducing greenhouse gas emissions and improving air quality and energy security. In most cases, environmental issues should be of minor concern. Many of these issues are avoidable if considered in advance during the system design phase, and resources are properly managed from establishment to operation phases. It is evident that in spite of numerous studies on environmental impact assessment, reclamation and restoration of geothermal sites are not well documented. Existing geo-mining research specific to oil and gas wells reclamation results and experience from different regions can provide a strong foundation of reclamation principles. Based on this literature review and expert opinion the following knowledge gaps have been identified to control potential of environmental consequences and develop sound reclamation practices for geothermal energy extraction and production sites.

Inadequate knowledge of environmental impacts of geothermal energy systems

- On soils, vegetation and faunal habitat.
- Metals release and hydrogen sulphite emission control or minimization.

- On flora and fauna impact minimization for plant establishment near ecologically sensitive areas.
- Water spill control on soil and below and above ground aquatic systems.
- Environmental risks other than induced seismicity, such as geo-fluids migration.
- Waste management, subsidence, induced seismicity and landslides for mitigation and prevention of serious and possibly disastrous consequences.
- Soil properties and contamination levels surrounding geothermal resource sites and vegetation and wildlife habitat responses.
- Proper environmental regulations and policies in many countries.

Inadequate knowledge of geothermal energy systems reclamation

- Reclamation options from the beginning to after decommissioning and how these options influence recovery to a resilient ecosystem.
- Best approaches to integrate reclamation for fastest ecosystem recovery if abandoned oil and gas wells are used for geothermal energy.
- Potential long-term impacts of integrating reclamation into planning stages of plant construction.
- Managing cover soil in different land use systems to create a resilient ecosystem.
- Maintaining soil propagule viability during storage of cover soils and management approaches.
- Effectiveness of creating desired environmental conditions for ecosystem recovery in disturbed geothermal sites.
- Available soil nutrients that influence long-term plant community development.
- Undisturbed patch influences near geothermal plants on newly reclaimed sites as seed sources or propagule banks.
- Trends and patterns of plant community composition in reclaimed geothermal well sites (types of communities, similarity to natural forest and rates of succession).

- Identification of indicator species that can be used to determine reclamation success and environmental toxicity in different land use systems.
- Effective reclamation strategies that can contribute to resilience of ecosystems in the era of climate change.

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Table 1. Summary of the possible impact and mitigation of geothermal energy plants at different establishment phases

| Impact Phase | Impacts | Potential Mitigation Measures |
|---|---|---|
| Access roads, site preparation for plant construction | Surface disturbance and disposal of waste. | • Reduce permanent by avoiding ecologically sensitive areas, locations of historical value and natural beauty.<br>• Integrate reclamation planning at the beginning of geothermal plant establishment. |
| Well repair, drilling, testing, plant construction and equipment installation phase | Liquid pollutant, noise and vibration, induced seismicity, solid waste, surface release of geothermal fluid, surface disturbance, fresh water requirement during drilling. | • Follow proper care and environmental regulations to reduce harmful impacts during well repair, drilling and testing.<br>• Follow protocol for environmental and induced seismicity associated with geothermal systems. This could vary by country.<br>• Reduce surface disturbance impacts through landscaping once the work is finished.<br>• Erect noise barriers if residential areas are being affected. |
| During plant commissioning and operation | Soil quality: compaction, influence physical and chemical properties.<br>Air quality: greenhouse and toxic gas emissions ($CO_2$, $H_2S$, $SO_2$).<br>Water quality: contamination of shallow aquifers and other water bodies.<br>Solid and liquid waste: spill of contaminated geothermal fluids.<br>Hazards: subsidence and hydrothermal eruptions.<br>Forest and biodiversity: habitat loss, deforestation and ecosystems loss.<br>Land: conflict with other land uses. | After construction reclaim surrounding disturbed area of the plants by reducing compaction and controlling chemical release into soils.<br>• Design the plant to avoid any steam releases to the atmosphere. Treat non-condensable gases or dilute with air at the cooling tower. Monitor release of $H_2S$ emissions from flash geothermal power plants to allow appropriate measures if emissions are above environmental limits. Apply ventilation to avoid gas build up in confined spaces.<br>• Control water spill from geothermal plants to soil and the nearest below and above ground aquatic systems.<br>• Minimize spill of contaminated solid and liquid waste with thermodynamic scaling control rather than inhibitors.<br>• Incorporate reinjection into reservoir management from the beginning to minimize the risk of subsidence and prolong the life of the reservoir.<br>• Assess vegetation and wildlife prior to plant construction and monitor to detect any hazardous impacts.<br>• Avoid ecologically sensitive areas. |
| After decommissioning | Chemical pollution, disposal of hazardous and other waste and surface disruption. | • Take proper care when disposing chemicals, cleaning up equipment and reclaiming disturbed sites to resilient, productive ecosystems that resemble local ecosystems by following appropriate reclamation processes. |