Renewable and Sustainable Energy Reviews 44 (2015) 391–406

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Geothermal energy for sustainable development: A review of sustainability impacts and assessment frameworks

Ruth Shortall [a,*], Brynhildur Davidsdottir [b], Guðni Axelsson [c]

[a] University of Iceland, Gimli, Sæmundargötu 2, 101 Reykjavík, Iceland
[b] UMAUD Environment and Natural Resources Studies, University of Iceland, Sæmundargötu 2, 101 Reykjavík, Iceland
[c] National Energy Authority Iceland, Grensasvegur 9, 108 Reykjavik, Iceland

ARTICLE INFO

Article history:
Received 13 February 2014
Received in revised form
11 November 2014
Accepted 12 December 2014
Available online 14 January 2015

Keywords:
Geothermal energy
Sustainability
Sustainability indicators

ABSTRACT

Sustainable development calls for the use of sustainable energy systems. However, the way in which a geothermal resource is utilized will ultimately determine whether or not the utilization is sustainable. Energy usage is set to increase worldwide, and geothermal energy usage for both electricity generation and heating will also increase significantly. The world's geothermal resources will need to be used in a sustainable manner. The sustainable utilization of geothermal energy means that it is produced and used in a way that is compatible with the well-being of future generations and the environment. This paper provides a literature review of the linkages between geothermal energy developments for electricity generation and sustainable development, as well as a review of currently available sustainability assessment frameworks. Significant impacts occur as a result of geothermal energy projects for electricity generation and these impacts may be positive or negative. The need for correct management of such impacts through a customized sustainability assessment framework is identified and the foundation for sustainability assessment framework for geothermal energy development is built in this paper.

Contents

* Corresponding author. Tel.: +354 8684107.

http://dx.doi.org/10.1016/j.rser.2014.12.020
1364-0321/

1. Introduction

1.1. Geothermal energy development

Energy is a principal motor of macroeconomic growth, prosperity and economic development, a prerequisite for meeting basic human needs, while at the same time a source of environmental stress. Energy in itself is a vital component of sustainable development [1]. Different energy types have different types of impacts during their development. Along all energy chains, from the extraction of the resource to the provision of energy services, pollutants are produced, emitted or disposed of, often with serious health and environmental impacts. During an energy project's lifecycle, emissions and wastes may be also associated with the manufacture or construction of energy systems. Yet, the impact differs widely. Fossil fuels are largely responsible for urban air pollution, regional acidification and climate change. The use of nuclear power has created a number of concerns, such as the storage or disposal of high-level radioactive waste and the proliferation of nuclear weapons. Biomass use in some developing countries contributes to desertification and loss of biodiversity, as well as energy crop cultivation having significant impacts on food prices worldwide [2]. Other renewable energy sources such as hydro- and wind power have significant implications for land-use as well as significant ecosystem and visual impact.

Geothermal energy has not until recently become a significant source of electricity and heat, with of course exceptions in countries such as the USA, Indonesia, Iceland and Italy [3]. In 2008, geothermal energy represented around 0.1% of the global primary energy supply, but estimates predict that it could fulfill around 3% of global electricity demand, as well as 5% of global heating demand by 2050 [4]. Geothermal energy is usually considered a renewable energy source, but its development and use can however have significant multi-dimensional sustainability implications [5]. Given the certainty that geothermal energy usage is set to increase substantially, it is important to ensure that geothermal resources are developed in a sustainable manner, in particular for electricity generation projects. As well as this, the international community has called for the development of indicators to measure progress towards sustainable development [6]. Until now no framework however exists that enables formal assessment of the sustainability of geothermal energy development and use.

1.2. Objective

The objectives of this study are to

- Review the literature on sustainability impacts of geothermal power development for electricity generation and thereby identify the most important issues of concern whilst assessing the sustainability of geothermal energy projects.
- Review the available sustainability assessment frameworks and thereby determine the best structure for an assessment framework for geothermal energy projects.
- Demonstrate the need for assessing sustainability in the geothermal energy sector and to provide the scientific basis for the creation of a formal sustainability assessment framework.

2. Geothermal energy and sustainable development

2.1. Introduction

Sustainable energy development is an emerging paradigm. Its challenges involve reducing negative health and environmental impacts, whilst simultaneously increasing energy access, affordability, security and the efficiency of energy use [7]. Evidencing the move into this new paradigm, energy policy directives of various industrialized countries include common interests such as improving the efficiency of energy production and ensuring a reliable supply, energy security and diversity, economic efficiency, support of research and development and regional partnerships for the development of more advanced technologies [8].

A sustainable energy system may be regarded as a cost-efficient, reliable, and environmentally friendly system that effectively utilizes local resources and networks [8]. Renewability and sustained yield of energy resources is generally agreed to be a necessary but not a sufficient requirement for sustainable energy development [1]. The sustainability perspective requires a much broader assessment of energy development. This implies that there is a need to monitor all of the environmental, social and economic impacts associated with geothermal energy developments [2]. An in-depth overview of the main impacts relating to the utilization of geothermal energy for electricity generation is presented in this section.

2.2. Review of sustainability impacts of geothermal development

Impacts associated with geothermal energy developments fall under a variety of topical areas or themes. To emphasize the multi-dimensional nature of sustainable development, cross-cutting themes, following the Commission for Sustainable Development (CSD) Framework, are used to classify the sustainability issues or impacts associated with geothermal energy developments [9]. The themes reviewed are

- Poverty: including income poverty, income inequality, drinking water, access to energy, and living conditions.
- Health: including mortality, health care delivery, sanitation, nutritional status, health status and risks.
- Education: including education levels and literacy.
- Natural hazards: including vulnerability to natural hazards and disaster preparedness and response.
- Demographics: including population and culture
- Atmosphere: including climate change and air quality.
- Land: including land use and forests.
- Freshwater: including water quantity and water quality.
- Biodiversity: including ecosystems and species.
- Economic development: including macroeconomic performance, employment and tourism, research and development.
- Consumption and production patterns: including energy use, waste generation and management and transportation.

These themes are discussed below in relation to geothermal energy development.

2.2.1. Poverty

The poverty theme includes income poverty, income inequality, access to energy and living conditions, including improved access to drinking water [9].

2.2.1.1. Impacts on income poverty and inequality. During their lifecycle, geothermal energy projects may have an impact on per capita income levels for the areas in which they are based. The income effects may be direct, such as increased salaries for new company employees, or indirect, such as increased income for suppliers of goods and services in the area or due to access to hot water and electricity.

Expenditure on equipment, materials, fuel, lodging, food, and other services are likely to stimulate the local economy over the duration of construction. The duration and extent of these benefits will, however, vary depending on the resource lifespan. Income may increase in a community when geothermal developers often make significant contributions to the communities in which they are located, as well as to the municipal governments under whose jurisdiction they operate. Some contributions could come as royalties or taxes, which are required by the government, while some could come voluntarily from the geothermal company, perhaps in the form of social development initiatives. In addition, wages paid to geothermal employees often circulate back through the community [10]. For example, in the Philippines, 40% of the Philippine National Oil Company – Energy Development Corporation(PNOC-EDC) profits net of tax are given to the municipalities or regions that host the company's geothermal resources as well as a development fund which is used for missionary electrification, livelihood development and reforestation, watershed management, health and environment enhancement. Other community relations projects provide educational support in the form of scholarships, infrastructure development and skills and training assistance. Rural electrification is also a priority of the PNOC-EDC [11].

For energy to be affordable, it should be within the means of all income groups to provide themselves with the necessary energy to ensure a good standard of living. Inforse-Europe, part of The International Network for Sustainable Energy, has defined energy poverty as when a household must spend more than 10% of its disposable income on energy bills [12]. Furthermore, according to Advisory Group on Energy and Climate Change (AGECC), electricity is considered affordable if the cost to end user is compatible with their income levels and no higher than the cost of traditional fuels and should not be more than reasonable fraction of their income (10–20%) [13]. Geothermal energy, despite having high capital costs, often has lower operational costs than other energy types and, once in operation, energy costs are not subject to fluctuations, unlike fossil fuels [14]. Geothermal electricity generation can be a low-cost option, especially if the hot water or steam resource is at a high temperature and near the earth's surface. Geothermal resources are often located in rural areas where direct-use applications can reduce or eliminate dependency on traditional fuels, such as biomass and therefore may have the potential to reduce energy poverty in the developing world by providing affordable energy to the local communities in which they are located. The potential distributed capacity of geothermal generation can bring generation closer to end-users, thus minimizing transmission losses and costs. Geothermal may also be suited to off-grid uses.

2.2.1.2. Access to energy and improved living conditions. Worldwide nearly 2.4 billion people use traditional biomass fuels for cooking and nearly 1.6 billion people do not have access to electricity [7]. To increase human development in developing countries access to high quality energy is an absolute need as for example access to energy services, such as those provided by geothermal projects, tend to have a positive effect on living conditions [7].

Geothermal resources are often located in rural areas where direct-use applications could reduce or eliminate dependency on traditional fuels, such as biomass. Small binary modular power plants are now enabling smaller-scale geothermal electricity generation in low temperature areas. This kind of generation can be useful for rural and remote small-scale electricity needs displacing need for uneconomical transmission lines [15].

Taking Kenya as an example, electricity provision, as a result of geothermal development, in rural homes is predicted to improve standards of living as community residents strive to upgrade the structure of their homes, gradually purchase mobile phones, radios and television sets. Improvements to food security would be possible due to the provision of electricity for food preservation (by refrigeration or drying), small scale water pumping for dry season irrigation, greenhouses for commercial crop production and famine relief [16].

Drinking water access may be enhanced by geothermal projects, either through access to electricity for dry season water pumping or in the cases where freshwater wells may be drilled for both the community and power plant needs [16]. Agricultural products, fisheries and livestock conditions may be enhanced through the provision of better access to water in times of drought, reducing dependence on food aid. Small enterprises are more likely to flourish, creating a more diverse economy and reducing reliance on livestock for income. An overall improvement in local services could therefore result in improved infrastructure for tourism and other industries, resulting in spin-off effects and the creation of direct and indirect employment [16].

2.2.2. Health

The health theme covers such issues as mortality, health care delivery, nutritional status, sanitation, health status and health risks. Geothermal energy developments may have both positive and negative consequences for health in a region.

2.2.2.1. Health benefits associated with geothermal development. Health benefits are mostly derived from geothermal energy development in developing countries. In general access to electricity and high temperature water improves sterilization, water supply purification and sanitation and allows the refrigeration of essential medicines [7]. In remote areas, far from the utility grid, villages and facilities such as hospitals possibly could replace their diesel generators with small-scale geothermal power plants, increasing access and reducing environmental and health impacts [17].

Geothermal energy developments, by bringing access to water closer to the community, can reduce traveling distances to health services such as maternity hospitals. Remote health centers may become possible, with decentralized energy systems [16]. Health benefits may also arise from reducing the indoor emissions from polluting energy sources such as kerosene lamps or firewood [16]. In different cultures worldwide, the restorative and therapeutic properties of geothermal waters have been recognized for centuries. In Iceland, locals and tourists enjoy the therapeutic benefits of direct use geothermal bathing pools. One famous example is the Blue Lagoon spa, using the waste-water from nearby Svartsengi geothermal plant. Its clientele includes psoriasis patients who come to take advantage of the curative properties of the water's chemical composition [18].

2.2.2.2. Health risks associated with geothermal emissions. Geothermal projects may result in the release of certain gases that may pose health or environmental risks above certain concentrations. H_2S gas can be an odor nuisance at a certain level, yet at a higher level can have significant consequences for health [19]. The WHO LOAEL (*lowest-observed-adverse-effect level*) of H_2S is 15 mg/m^3, when eye irritation is caused. In view of the steep rise in the dose–effect curve implied by reports of serious eye damage at 70 mg/m^3, an uncertainty factor of 100 is recommended, leading to a guideline value of 0.15 mg/m^3 (i.e. 150 μg/m3) with an averaging time of 24 h [19]. Preliminary evidence exists for impact of chronic exposure to low levels of H_2S for nervous system diseases, respiratory and cardiovascular diseases. Yet more evidence is sorely needed [20].

Workers at geothermal power plants are at particular risk as H_2S gas can accumulate in any container, closed or semi-closed space in a geothermal plant where pressure drops or cooling of the geothermal steam occurs, as it is heavier than air and settles in low lying areas. Examples exist of fatalities in the geothermal industry due to the impact of H_2S [20]. Carbon dioxide is present in geothermal steam and may accumulate to dangerous concentrations in low-lying areas around geothermal plants as concentrations around 10% can cause asphyxiation by excluding oxygen [21]. Traces of ammonia, hydrogen, nitrogen, methane, radon and the volatile species of boron, arsenic and mercury, may be present as emissions though generally in very low concentrations [22].

2.2.2.3. Health risks associated with geothermal effluent. Geothermal energy projects may result in the release of hot water into the environment during construction or operation. Water quality in the area may be affected by the release of more acidic/alkaline effluent from the power plant, or effluent containing chlorides and sulfides or other dissolved chemicals, such as metals. Most high temperature geothermal water may contain high concentrations of at least one of the following toxic chemicals: aluminum (Al), boron (B), arsenic (As), cadmium (Cd), lead (Pb), mercury (Hg), and sometimes fluoride (F) [23]. This has significant implications for human health. There are a number of known cases of heavy metal water pollution from geothermal power plants, for example since the Wairakei power plant was built in the late 1950s, the amount of arsenic in the Waikato River has more than doubled [24]. Arsenic levels in the river now exceed drinking water standards. This means a high level of water treatment is needed for drinking water supply [25].

2.2.2.4. Radionuclides. The risk of radiation exposure from geothermal power production is not entirely clear and depends mostly on how the power is produced, taking account of factors such as gas volume and chemistry released to the environment over time, as well as other factors such as dilution by air [26]. High-temperature geothermal fluids may contain dissolved minerals, which tend to form a scale inside pipes and production equipment. If the rocks from which these minerals were dissolved also contain radionuclides, such as radium, the mineral scale, production sludges, and waste-water will contain radioactive material. The primary radionuclides which may be produced with geothermal fluids are radium-226 and radium-228 [27]. As a result, there are potential negative health effects associated with the use and disposal of these fluids. Exposure to ionizing radiation can lead to several types of cancer, and extremely high doses of radiation can cause death [28].

2.2.2.5. Noise pollution. A geothermal power plant may generate noise levels in the 71–83 dB range. Unwanted noise can be a nuisance or a health concern. Exposure for more than 8 h a day to sound in excess of 85 dB is potentially hazardous. The WHO guidelines for community noise state that levels should not exceed 55 dB for outdoor living areas and 70 dB for industrial areas [29]. The different phases of geothermal development have different sources of noise. During exploration and drilling, noise sources include earth-moving equipment (related to road, well pad and sump pit construction), vehicle traffic, seismic surveys, blasting, and drill rig operations. Well drilling and testing activities are estimated to produce noise levels ranging from about 80 to 120 dB at the site boundary [5]. During the operation phase, noise sources include the power plant (turbines, transformers, cooling tower fans, separators etc.).

2.2.3. Education

The education theme covers such issues as education levels and literacy [9]. In developing countries, access to electricity from any source frees up time for children to attend schools, since younger children are often expected to spend time on agricultural activities or collecting water and firewood. It is also easier for a community to attract qualified teachers when it has modern energy services [7]. As geothermal energy can be developed in small modular units, it can provide access to electricity in remote rural areas, previously without electricity. This can boost school attendance both by boosting local economies and by enabling electric lighting, making study at night and in the early morning possible. Geothermal energy can also improve access to and the quality of education by increasing e-learning and information access. Furthermore, electricity can also provide better access to radio and television for certain groups, leading to improved access to information [16].

2.2.4. Demographics

The demographics theme covers issues relating to population, including cultural impacts [9].

2.2.4.1. Cultural impacts and indigenous peoples. Geothermal developments may impact the culture of an area or the lives of indigenous people. During construction, noise, dust, visual impacts and habitat destruction can have an adverse effect on traditional tribal ways of life and religious and cultural sites [30]. Resettlement of communities may be necessary to gain more land for geothermal exploration or to ensure the health and safety of persons in the area. For example, in Kenya, Kengen acquired 1700 acres to resettle over 1000 members of the Maasai community living Olkaria to Kedong [31]. Developments in American Indian settlements have required community involvement and discussion to gain acceptance [32]. Social change may arise in some communities due to an increase in access to electricity, or an influx of workers from outside the community. Whilst geothermal energy developments tend to stabilize electricity supply, promote economic growth through increased employment or tourism, they may also carry negative social impacts such as loss of local culture resulting from resettlement or land acquisition or increased crime levels or the spread of contagious diseases [33].

2.2.5. Natural hazards

The natural hazards theme covers such issues as vulnerability to natural hazards and disaster preparedness and response [9]. Certain hazards are associated with geothermal energy projects due to their location in seismically active areas and due to the potential of geothermal exploitation to cause changes in geological conditions.

2.2.5.1. Induced seismicity. Most high-temperature geothermal systems lie in tectonically active regions where there are high levels of stress in the upper parts of the crust, which is manifested by active faulting and numerous earthquakes. Studies in many high-temperature geothermal fields have shown that reinjection and exploitation can result in an increase (above the normal background) in the number of small magnitude earthquakes (microearthquakes) within the field [34,5]. One example is the Geysers, California, where injection-induced seismicity is observed in the form of "clouds" of earthquakes extending primarily downward from injection wells [35]. Another example of reinjection induced seismicity was experienced at Húsmúli, Iceland in 2011. The largest series of quakes occurred on the morning of the 15th of October, 2011 with two quakes of almost 4 on the Richter scale [36].

2.2.5.2. Subsidence. The removal of geothermal fluid from underground reservoirs, may cause the rock formations above it to compact, leading to subsidence of the land surface. While this is rare in vapor-dominated fields, it can happen in liquid dominated fields if reinjection is not practiced to maintain reservoir pressures [22]. Factors which may lead to greatest subsidence include pressure dropping in the reservoir as a result of fluid withdrawal combined with the presence of a highly compressible geological rock formation above or in the upper part of a shallow reservoir, the presence of high-permeability paths between the reservoir and the formation, and between the reservoir and the ground surface [37]. Ground subsidence can affect the stability of pipelines, drains, and well casings. It can also cause the formation of ponds and cracks in the ground and, if the site is close to a populated area, it can lead to instability of buildings [37].

2.2.5.3. Hydrothermal eruptions. Although rare, hydrothermal eruptions are a potential hazards in high-temperature liquid-dominated geothermal fields. Eruptions occur when steam pressure in near-surface aquifers exceeds the overlying lithostatic pressure and the overburden is then ejected, generally forming a crater 5–500 m in diameter and up to (although rarely) 500 m in depth. Such eruptions have occurred in Ahuachapan geothermal field, El Salvador and Wairakei in New Zealand [5].

2.2.6. Atmosphere

The atmosphere theme covers such issues as climate change and air quality [9]. Emissions from geothermal energy plants may result in impacts in all of these areas as carbon dioxide (CO_2), hydrogen sulfide (H_2S), ammonia (NH_3), volatile metals, minerals, silicates, carbonates, metal sulfides and sulfates may be emitted from geothermal plants, depending on site characteristics. In addition, heat emitted in the form of steam can affect cloud formation and affect local weather conditions [38]. However, geothermal energy on average produces less CO_2, SO_2 (oxidized from H_2S,) and NO_X than conventional fossil fuels [10].

2.2.6.1. Climate change. A study of CO_2 emissions from geothermal plants by the International Geothermal Association (IGA) shows that the emissions from geothermal plants range from 4 to 740 g/kWh, with a weighted average of 122 g/kWh. This figure is significantly lower than the CO_2 emissions of fossil fuel power plants (natural gas, coal and oil), which range from approximately 450 g/kWh to 1300 g/kWh [39]. Direct CO_2 emissions for direct use applications are negligible. Lifecycle assessments anticipate that CO_2-equivalent emissions are less than 50 g/kWhe for geothermal power plants [4].

2.2.6.2. Air pollution and gaseous emissions. A study of air pollutants emitted by geothermal power plants in the United States shows that on average, geothermal plants emit very small amounts of nitrous oxides or none at all.

However, emissions of hydrogen sulfide are important as stated before. H_2S is usually considered to be an odor nuisance but is also toxic to humans at concentrations above a certain level. Although H_2S does not directly cause acid rain, it may be oxidized to sulphur dioxide (SO_2) which reacts with oxygen and water to form sulfuric acid, a component of acid rain. H_2S pollution from geothermal plants can also be responsible for the corrosion of electronic equipment containing certain types of metals [40]. Traces of ammonia, hydrogen, nitrogen, methane, radon and the volatile species of boron, arsenic and mercury, may be present as emissions though generally in very low concentrations. Silica may also be a problem, as at Wairakei in New Zealand, where forest damage has been attributed to silica deposition [22].

2.2.7. Land

The land theme covers such issues as land use, agriculture and forests. Land for geothermal energy development may be valued as natural environment or may have other proposed uses. Soils and geologic resources may be impacted during the construction and operation of geothermal projects. Land use requirements for geothermal projects range from 160 to 290 m^2/GWhe/yr excluding wells, and up to 900 m^2/GWh/yr including wells [4]. Impacts to soils and geologic resources are generally greater during the construction phase than for other phases of development because of the increased footprint. Construction of additional roads, well pads, the geothermal power plant, and structures related to the power plant (e.g., the pipeline system and transmission lines) occur during this phase [38]. Soil can be compacted as a result of construction activities, therefore reducing soil aeration, permeability and water-holding capacity, causing an increase in surface runoff, potentially causing increased sheet, rill, and gully erosion. Soil compaction and blending can also impact the viability of future vegetation [41].

Geothermal projects may need to be located in forested areas, leading to some deforestation or impacts on the surrounding ecosystem. Emissions of certain chemicals from the geothermal plant may impact upon forest ecosystems, as outlined in Section 2.2.6.2. The removal of forests can lead to changes in hydrological patterns of stream flows, which may impact on crop irrigation from local rivers. The deforestation of water catchments near geothermal fields may also impact negatively on recharge of the geothermal resource. The use of geothermal energy can also lead to positive implications for deforestation. Geothermal fluid in the Philippines, for example, is known to come from meteoric water stored for thousands of years in deep geothermal reservoirs. Healthy forests keep the rainwater from running off the land by allowing it to infiltrate the ground to reach these geothermal reservoirs. Developers thus became aware of its responsibility to protect the forests around its project sites, which are the source of geothermal power [11].

2.2.8. Freshwater

The freshwater theme covers such issues as water quantity and water quality [9].

2.2.8.1. Water quantity. In water scarce regions, care must be taken to ensure that freshwater usage for geothermal developments does not conflict with other freshwater needs. Two thirds of the world's geothermal resources are found in developing countries [42]. In Kenya, fluid or steam loss and water consumption are potential long-term issues for geothermal expansion in the country [43]. Fresh water is required for drilling, where it is used as a base for drilling mud, to carry away drill cuttings and cool the drill bit, as well as during construction where it is required for activities such as dust control, concrete making, and consumptive use by the construction crew. Geothermal power generation plants may use water for cooling [44]. Some geothermal plants (e.g. flash steam facilities) may also require freshwater to make up for water lost through evaporation or blowdown water before reinjection takes place. As well as requiring freshwater, exploration drilling may involve activities that can lead to increased erosion and surface runoff, potentially allowing geothermal fluids to contaminate shallow aquifers. Furthermore, geothermal technology has the potential to affect groundwater by connecting previously unconnected aquifers via boreholes, or connecting contaminated zones and aquifers [45]. Additionally, during plant operation, cooling water or water discharged from geothermal wells to the ground or to an evaporation pond can affect the quality of shallow groundwater if allowed to percolate downwards.

2.2.8.2. Water quality. Water quality in the area surrounding geothermal plants may be affected by the release of more acidic/alkaline effluent from the power plant, or effluent containing chlorides and sulfides or other dissolved chemicals, such as metals (e.g., arsenic, boron, aluminum). Some geothermal fluids have excessive salt concentrations, which can cause direct damage to the environment [38]. Most high temperature geothermal water may contain high concentrations of at least one of the following toxic chemicals: aluminum (Al), boron (B), arsenic (As), cadmium (Cd), lead (Pb), mercury (Hg), and sometimes fluoride (F) [23]. Chloride brines of Na and Ca can have very high concentrations of metals such as iron (Fe), manganese (Mn), lead (Pb), zinc (Zn) and boron (B). Other contaminants can include iodine (I), aluminum (Al), lithium (Li), hydrogen sulfide (H_2S), bicarbonate, fluoride, silicate and ammonia (NH_3). As and Hg may accumulate in organisms [22,38]. Health impacts due to water contamination from geothermal fluids are outlined in Section 2.2.2.3.

2.2.8.3. Thermal pollution. Thermal pollution of air and water from geothermal plants can represent a significant environmental impact as well as being energy inefficient, since the hot geothermal water could have other potential uses. The discharge of hot water to rivers can damage aquatic wildlife, an example of this being the Waikato River in Wairakei [22], and lead to undesirable vegetation growth. Elevated water temperature typically decreases the level of dissolved oxygen in water, which can harm aquatic organisms. Thermal pollution may also increase the metabolic rate of aquatic animals and may also result in the migration of organisms to a more suitable environment. Biodiversity decreases as a result [22,38]. In limited cases, there may be some positive effects due to thermal pollution, such as the extension of fishing seasons or rebounding of some wildlife populations [46].

2.2.9. Biodiversity

The biodiversity theme covers such issues as ecosystems and species [9]. Geothermal plants may be located in protected areas or development may impact on delicate geothermal ecosystems or ecological resources. Ecological resources consist of vegetation, wildlife, aquatic biota, special status species and their habitats. Geothermal project activities such as site clearing, road construction, well drilling may cause habitat disturbance. Habitat quality may be reduced or habitats may be fragmented. Drilling and seismic surveys may result in erosion, runoff and noise which may disturb wildlife or affect the breeding, foraging and migrating of certain species [5]. Topsoil erosion and seed bank depletion may occur, as well as a loss of native vegetation species or a loss of diversity. Water and seed dispersal may be altered [47].

2.2.9.1. Geothermal ecosystems. Geothermal systems provide unique climatic conditions, creating a delicate habitat for geothermal ecosystems to survive. Geothermal ecosystems comprise various plant and animal life adapted to such extreme environments. Any change in the conditions of the geothermal system will result in changes to the ecosystems associated with it [48], for example, disturbances of thermophilic bacteria, thermophilic vegetation such as algal mats, or thermophilic plants [38]. In New Zealand, a number of native plant species or varieties of geothermal vegetation are considered to be at risk or threatened due to gradual decline and restriction of range as a result of human activities [48]. Geothermal ecosystems may be classed as thermotolerant (able to tolerate heat), thermophilic (needing heat for survival), and/or extremophilic (needing extremes of pH or chemical concentration). Organisms found in these ecosystems are valuable in scientific research. For instance, geothermal bacteria contain enzymes that function at high temperatures and may be used industrial processes and applications [49].

2.2.9.2. Biodiversity hotspots. As many geothermal resources are located near the world's biodiversity hotspots or unique ecosystems, such as those found in the Carribean and the Philippines, particular care is required when deciding on a site for geothermal energy production. An example is the Mindanao Geothermal power plant in the Philippines, which is located near to Mount Apo,a UNESCO world heritage site and biodiversity hotspot [50]. Locating a power plant within or near such locations may be problematic due to the sensitivity and importance of these ecosystems.

2.2.10. Economic development

The economic development theme covers such issues as macroeconomic performance, employment, research and development and tourism [9]. Geothermal energy projects have impacts on energy and economic security, employment rates and other economic sectors as well as research and development.

2.2.10.1. Energy and economic security. Energy security and its impact on economic security is seen as an integral part of sustainable development. Energy security generally involves aiming for energy independence for a nation i.e., reducing geopolitical security risks as well as diversifying the nation's energy portfolio [51]. With regards to electricity generation, introducing a broad portfolio of renewables into a nation's energy system, including decentralized power generation, can improve security. Whilst a nation's diversified energy portfolio may include fossil fuels, domestic renewable technologies can enhance energy security in electricity generation, heat supply, and transportation as their risks are different than fossil fuel supply risks. For example, as the cost of renewables such as geothermal energy does not fluctuate like the price of gas and oil and is generally locally available, this can further contribute to a nation's economic security [52].

The reliability of energy supply is also important for economic security. In terms of reliability, geothermal energy is not heavily climate-dependent and it is thus possible to produce energy from geothermal sources more constantly than other variable renewable sources such as wind or solar energy. Geothermal plants also have a high capacity factor. They typically run between 90% and 97% of the time, whereas wind plants average between 20% and 40% [53] and coal plants between 65% and 75% of the time [37]. Distributed systems, such as those that would be possible using small scale geothermal, can improve the reliability of energy supply because of the tendency of distributed systems not to 'put all the eggs in one basket', through their ability to operate in networks and utilize local resources [8].

Geothermal energy may also reduce a nation's trade deficit. In the US, Nevada's geothermal plants save the equivalent of 3 million barrels of oil each year, as well as generating tax revenue for government [54]. In the Philippines, dependence on imported oil was reduced by 95% with the introduction of an energy plan comprising mostly of renewable energy source use [55]. The economic multiplier effect leads to different types of economic impacts as a result of investments in geothermal energy technologies. Direct effects such as on-site jobs and income created as the result of the initial project investment. Examples of such work would include site drilling, or assembling generators and turbines at a manufacturing plant.

Indirect effects include the additional jobs and economic activity involved in supplying goods and services related to the primary activity. For example, the workers who manufacture or supply road building materials. Induced effects include employment and other economic activity generated by the re-spending of wages earned by those directly and indirectly employed in the industry. For example, jobs created by road materials suppliers spending their wages at local stores [56]. An example of the macroeconomic implications of developing geothermal energy, is the case of Iceland, which, during the course of the twentieth century, went from being one of Europe's poorest countries, mainly dependent upon peat and imported coal for its energy, to having practically all stationary energy and (in 2008) roughly 82% of primary energy derived from indigenous renewable sources (62% geothermal, 20% hydropower), thus drastically reducing dependence on imported energy and raising living standards. The remaining primary energy sources come from imported fossil fuel used for fishing and transportation [57].

2.2.10.2. Employment. It is important to consider the duration and quality of jobs that result from geothermal developments, both direct and indirect employment. Local job opportunities may be created during the exploration, drilling and construction period, typically for at least four years for greenfield projects. Permanent and full-time workers are also required locally, during the operation phase [4]. Although geothermal energy plants themselves may not result in large numbers of workers being hired, the indirect impacts of having a geothermal generating plant or direct use application in a region can be significant. Through the economic multiplier effect, wages and salaries earned by industry employees generate additional income and jobs in the local and regional economy. In the early phases of geothermal projects, there may be a temporary influx of workers to an area, but long-term skilled jobs for the operation of the power plant itself will be much fewer [49]. Direct jobs are those associated with the construction and maintenance of geothermal power plants. During the construction phase, direct employment refers to the jobs associated with power plant construction. During the operation and maintenance phase, it refers to all jobs associated with power plant operation and maintenance [58]. Indirect employment refers to the jobs that are created in all the industries that provide goods and services to the companies involved in power plant construction or operation and maintenance [58]. The range of indirect jobs is broad and includes government regulators, R&D professionals, lawyers, architects, equipment service personnel, business management personnel, and security guards [59]. Increased economic activity in a region with new direct and indirect jobs means additional new jobs that may not be directly related to the geothermal industry but are supported by it. Induced employment refers to jobs that are created to serve the workers, subcontractors and others that are counted as indirect employment [58]. The Geothermal Energy Association's latest estimate of the industry was 5,200 direct jobs as of 2010, for the United States. Indirect and induced jobs were estimated at 13,100 jobs. Construction and manufacturing jobs are expressed as full-time positions for one year (person-years), spread out over several years [58].

2.2.10.3. Impact on other economic sectors. Developing geothermal resources for electricity generation or direct use, will impact the local economy, possibly changing its structure. The impact on other economic sectors may be positive or negative. Using geothermal resources for electricity generation may come into conflict with other uses of geothermal resources such as tourism or recreation. Other land uses such as agriculture may also be impacted. Lands used for grazing or hunting may also be altered by development. On the other hand, as previously mentioned, the economic multiplier effect can give rise to indirect and induced effects such as indirect and induced job creation.

A geothermal development may have an impact on the esthetic quality of the landscape, as may pipes and plumes of steam. Many geothermal energy resources are also located in regions that are considered to be of great natural beauty, in national parks or in esthetically or historically valuable areas. This may affect tourism in the area [38]. Geothermal features may also hold cultural, historical or spiritual significance or be a major tourist attraction or amenity in certain areas. Natural features such as hot springs, mud pools, sinter terraces, geysers, fumaroles (steam vents) and steaming ground can be easily, and irreparably, damaged by geothermal development [60]. For example, the withdrawal of hot fluids from the underground reservoir have caused long-term changes to famous geothermal features such as the Geyser Valley, Waiora Valley, and the Karapiti blowhole in New Zealand. Hot springs and geysers may begin to decline and die as the supply of steaming water from below is depleted. As well as having cultural impacts, the destruction of geothermal features may also affect unique geothermal ecosystems [60].

Cultural tourism may also be impacted by geothermal developments. In New Zealand, geothermal energy developments may have an impact on the way of life of the Maori (indigenous people). The Maori tribe, Tūhourangi – Ngāti Wāhiao at Whakarewarewa began a tourism experience business at the thermal village of Whakarewarewa. Tours allow visitors to participate in their communal lifestyle incorporating Māori culture and traditions. Whakarewarewa had some 500 pools, most of which were hot springs, and at least 65 geyser vents. Many of the thermal features at Whakarewarewa have been affected by geothermal development in Rotorua where the geothermal fluids are extracted for both domestic and commercial use. Following a bore closure program in 1987–1988 there was subsequently some recovery in the geysers and hot springs at Whakarewarewa [61].

2.2.11. Consumption and production patterns

The consumption and production patterns theme covers such issues as waste generation management and transportation and energy use [9].

2.2.11.1. Waste management. Geothermal energy projects have impacts on energy use patterns through their design and also as a result of the behavior of the end-users of the energy. The correct management of waste heat from geothermal plants can increase their efficiency or the reinjection of spent fluids may enhance the resource's resilience against depletion as well as avoiding pollution of waterways with heat or toxic chemicals [62]. Waste materials are also produced during drilling, including drill cuttings and spent drilling fluids. Drill fluid is usually mainly comprised of bentonite and some additives and may be stored in ponds. Drill cuttings may potentially contain trace elements or minerals such as sulfides that could leach into ground or surface water [63]. Furthermore, sulfur, silica, and carbonate precipitates may be collected from cooling towers, air scrubber systems, turbines, and steam separators. The sludge containing these materials may be classified as hazardous depending on the concentration and potential for leaching of silica compounds, chlorides, arsenic, mercury, vanadium, nickel, and other heavy metals [64].

2.2.11.1.1. Energy use. Energy efficiency and renewability are key characteristics of sustainable energy. Efficiency is essential to reducing energy demand and fossil fuel use [65]. The correct management of a geothermal resource is crucial in ensuring its "renewability" and thus its availability for future generations. Unsustainable production patterns can result in early depletion of geothermal resources.

2.2.11.1.2. Renewability. Renewable energy is defined as energy that is

"derived from natural processes that are replenished constantly. In its various forms, it derives directly from the sun, or from heat generated deep within the earth. Included in the definition is electricity and heat generated from solar, wind, ocean, hydropower, biomass, geothermal resources, and biofuels and hydrogen derived from renewable resources [66]".

Geothermal energy has been classified as renewable due to the fact that earth heat and fluids in geothermal reservoirs are replenished over time. The ultimate source of geothermal heat is decay of radioactive isotopes, mostly of uranium, thorium and potassium (U238, U235, Th232 and K40) and primordial heat, roughly 50% of each. This heat is mostly conducted through to the surface. However, a fraction is transported by rising magma and by convecting aqueous fluid in hydrothermal systems, which can then be harnessed for electricity generation or direct uses. The International Panel on Climate Change (IPCC) has also recently identified the potential for the sustainable use of geothermal energy:

"The natural replenishment of heat from earth processes and modern reservoir management techniques enable the sustainable use of geothermal energy as a low-emission, renewable resource. With appropriate resource management, the tapped heat from an active reservoir is continuously restored by natural heat production, conduction and convection from surrounding hotter regions, and the extracted geothermal fluids are replenished by natural recharge and by injection of the depleted (cooled) fluids [4]."

The degree to which a geothermal resource is renewable will depend on several factors. Geothermal energy resources comprise of a fully renewable energy flow from the underlying heat source and a vast stored energy in the geothermal fluid. The importance of each of these two components will vary depending on the characteristics of the resource itself, such as volume or natural recharge rates, as well as on the rate of utilization of the resource, which may be in turn influenced by the type of technology used for plant operation or the management strategies for production and water supply issues.

2.2.11.1.3. Energy efficiency. Geothermal energy efficiency can be represented in a variety of ways, all of which can be useful and accurate depending upon the situation and the needs of the developer. Efficiency is broadly defined as the ratio of the output to the input of any system. All thermal power plants have a fraction of "waste heat" [67]. Exergy analysis has been widely used in the design, simulation and performance evaluation of energy systems [8].

The efficiency of geothermal plants may be impacted by the climate of an area as well as by mineral deposits such as silica. Hot humid climates would mean reduced efficiency for cooling technologies. Plant efficiency typically increases by 15% during colder months and decreases by 15% during warmer months. This means that an air-cooled plant is least efficient during summer peak energy demand, which typically takes place during the hottest hours of the day due to air conditioning uses [67]. Transport and distribution efficiency losses may result from inadequate investment into infrastructure or from poor management practices. Energy efficiency may also need to be compromised in geothermal plants due to the high cost of more efficient turbines.

Mineral deposits such as silica may negatively impact geothermal power plants by clogging pipes, wells, and heat exchangers, thereby reducing efficiency. Plant developers may purposely control the temperature of the geothermal fluid leaving the plant to prevent mineral precipitation. Often keeping fluids at a higher temperature will achieve this. Whilst direct uses of geothermal energy are the most efficient, efficiency from generation varies. Cogeneration and reinjection can increase the utilization efficiency of geothermal power plants [68]. According to one study of geothermal plants worldwide, exergetic efficiencies for indirect use, i.e. geothermal power plants, range from 16.3% to 53.9%, depending on the dead state temperature and technology used. In comparison, the exergetic efficiencies of a solar collector, a PV and a hybrid solar collector were found to be 4.4%, 11.2% and 13.3%, respectively. The exergetic efficiencies of wind ranged between 0% and 48.7% at different wind speeds based on a dead state temperature of 25 °C and a atmospheric pressure of about 101 kPa, considering pressure differences between state points [69].

2.2.12. Summary

In summary, the impacts resulting from geothermal energy developments can be grouped into the themes of poverty, health, education, natural hazards, demographics, atmosphere, land, freshwater, biodiversity, economic development, global economic partnership and consumption and production patterns. The impacts in each theme are summarized in Table 2.1.

When these themes are examined, it becomes clear that the impacts arising as a result of geothermal energy developments are unique, varied, positive and negative. Thus, the desirable characteristics of a geothermal energy project need to be clearly defined.

3. Review of sustainability assessment tools

As has been illustrated, the impacts of geothermal energy developments have significant implications for sustainable development, and require specialized management and monitoring tools to ensure that best practices are followed within the geothermal energy industry. A number of tools and frameworks currently exist that can aid the development of better sustainability assessment tools for geothermal energy projects.

3.1. Sustainability assessment frameworks

3.1.1. Sustainability assessment

Sustainability assessments are intended to provide an integrated understanding of social, economic and ecological conditions that are critical for strategic and coordinated action for sustainable development. Sustainability assessment is a tool to help decision- and policy-makers to decide which actions should

Table 2.1
Summary of geothermal sustainability issues by theme.

Theme	Positive impacts	Negative impacts
Poverty	– Increased per capita income – Increase in salaries – Social development initiatives – Affordable energy supply – Higher living standards – Improved food security – Access to drinking water	– Rising property prices – Community displacement
Health	– Improved sanitation – Improved medical facilities – Lower indoor air pollution – Therapeutic uses	– Odor nuisance – Toxic gas emissions – Water contamination risk – Noise pollution
Education	– Improved education facilities – Improved school attendance	– Sudden or unprecedented cultural change
Natural hazards		– Induced seismicity – Subsidence – Hydrothermal eruptions
Demographics	– Positive social change – Increased tourism	– Negative cultural impacts – Resettlement – Livelihood displacement
Atmosphere	– Displacement of greenhouse gas emissions from other energy sources	– Greenhouse gas emissions – H_2S pollution – Toxic gas emissions
Land	– Small land requirements relative to other energy sources	– Habitat loss – Soil compaction – Conflict with other land uses
Forests	– Replacement of traditional biomass	– Deforestation – Ecosystem loss
Freshwater	– Low lifecycle water consumption relative to other energy sources	– Conflict with other energy uses – Contamination of shallow aquifers and other water bodies
Biodiversity		– Habitat loss or disturbance – Loss of rare geothermal ecosystems
Economic development	– Increased energy security – Low climate dependence – High capacity factor – Direct, indirect and induced economic activity and employment	– Few direct long-term jobs
Consumption and production patterns	– Waste heat can be cascaded or recaptured	– Waste may cause environmental contamination – Risk of overexploitation – High cost of turbines may compromise efficiency

or should not be taken in an attempt to make society more sustainable [70]. The need for the development of sustainability indicators is clearly set out in Agenda 21 and the task was undertaken the by United Nations Commission for Sustainable Development (CSD) [6]. Indicators are essential tools of sustainability assessment. An indicator demonstrates in which direction something is moving [71]. An indicator provides information that measures and quantifies the characteristics or behavior of a system. Indicators or indices intended to make complex reality more transparent, thus enabling decision-makers to make better decisions [72]. There are a number of frameworks available to aid in the development of sustainability assessment tools. These range from overarching guidelines, such as the Bellagio STAMP principles to specific sustainability indicator development approaches, such as the thematic approach.

3.1.2. Sustainability appraisal (SA)

SA can be defined as a framework that promotes sustainable development by the integration of social, environmental and economic considerations into the preparation of plans and programs. Sustainability appraisals (SAs) are now carried out in many countries, sometimes incorporating the requirements of strategic impact assessment (SEA). In the United Kingdom, SAs are mandatory under the Planning and Compulsory Purchase Act 2004 [73] in addition to SEAs, and the two are often integrated. SAs must incorporate the requirements of SEA such as those found in the Strategic Environmental Assessment Directive (EU Directive 2001/42/EC). For regional and local development project plans, including renewable energy projects in the U.K., it is required that sustainability indicators be developed during the baseline information collection stage of SA. An “SA framework” is created, consisting of sustainability objectives which, where practicable, may be expressed in the form of targets, the achievement of which is measurable using indicators [74].

3.1.3. Thematic approach to indicator development

The Commission for Sustainable Development [9] used a theme-based approach in its most recent set of indicators for sustainable development. Theme-based approaches are more common for national energy indicator sets, and dividing the indicators into themes and sub- themes allows for more emphasis on the systematic cross-linkages between the indicators.

3.1.4. Pressure-State-Response Framework

Two well-known frameworks for the creation of sustainability indicators are the Pressure-State-Response (PSR) or Driving Force-State-Response (DSR) models. The PSR framework was initially developed for environmental statistics in Canada, then further developed and adopted internationally for use in methodological handbooks and country studies [75]. These frameworks have been used in the past for indicator development by the OECD and Commission for Sustainable Development (CSD) [9] and are used in particular when defining environmental indicators.

According to the CSD's guidelines and methodologies for indicator development, when using the DSR framework, indicators are categorized as driving force, state or response indicators. Driving force indicators describe processes or activities that have a positive or a negative impact on sustainable development. State indicators describe the current situation, whereas response indicators reflect societal actions aimed at moving towards sustainable development [9]. The DSR framework is a modified version of the PSR framework, the difference being that while the pressure indicators point directly to the causes of problems, driving-force indicators describe underlying factors influencing a variety of relevant variables, i.e., basic sectoral trends that are not very responsive to policy action. The OECD cautions that while the PSR framework has the advantage of highlighting the links between pressures, states and responses, it tends to suggest linear relationships in human–environment interactions. More complex relationships exist in ecosystems and in environment–economy interactions, and this should be kept in mind [76]. The OECD do say however, that more socio-economic and environmental information could be included in the framework, with a view to fostering sustainable development strategies [76].

Hartmut Bossel, in his report to the Balaton Group, offers a critique of the PSR or DSR models, claiming that even though these models attempt a more systemic approach than others, they neglect the systemic and dynamic nature of processes for environmental problems, and their embedding in a larger system that has many feedback loops. He argues that impacts in one causal chain may be pressures or states in another and multiple pressures or impacts are not considered, and non-linear relationships cannot be accounted for [77]. As stated in the discussion paper of the IISD, this is also the main reason why the DSR framework was abandoned in the UN (2001) indicator report [75].

The OECD also points out the difficulties associated with using the PSR indicator framework. They warn that for societal response indicators, it must be taken into account that such indicators are in the early stage of development conceptually and terms of data availability, and sometimes they may not be suited to quantitative measurement, such as policy areas. They also warn that the distinction between pressure and response indicators can easily become blurred. They therefore recommend that indicators be supplemented by other qualitative and scientific information, to avoid the danger of misinterpretation if indicators are presented without appropriate supplementary information. They recommend that indicators must be reported and interpreted in the appropriate context, taking into account the ecological, geographical, social, economic and structural features of the area. Key information on methodology for indicator derivation should also accompany the use of indicators in performance reviews [76].

Janne Hukkinen offers further advice when using the PSR framework, arguing that while we do not need to throw it out completely, we should be aware of certain issues when using it. He argues that indicator systems tend to assume the existence of just one sustainability scenario, a scenario being a plausible causal description of future trends and events. It may be that indicators are included in a set just because they are easy to measure or easily available, not really related to the scenario of sustainability. There may in fact be several stable states (scenarios) possible for a system, no one sustainability scenario being correct or optimal. The question of temporal and spatial scale must be dealt with carefully, i.e. having alternative scenarios is advisable to show contradictions between the scales. [78]. This is similar to what Bossel advises in the Balaton Report [77].

3.1.5. Energy-specific indicator development frameworks

3.1.5.1. International Atomic Energy Agency energy indicators of sustainable development. In 2005 the International Atomic Energy Agency (IAEA) in collaboration with several other bodies published guidelines and methodologies for a set of energy indicators for sustainable development (EISDs), emphasizing national self-examination [2]. Their interpretation depends on the state of development of each country, the nature of its economy, its geography and the availability of indigenous energy resources [2]. The EISDs were created to provide policy-makers with information about their country's energy sustainability. They are intended to provide an overall picture of the effects of energy use on human health, society and the environment and thus help in making decisions relating to choices of energy sources, fuels and energy policies and plans. Collecting the indicator data over time is intended to provide a picture of the long-term implications of current decisions and behaviors related to the production and use of energy. The EISD indicators consist of a core set of 30 indicators classified into three dimensions (social, economic and environmental). These are further classified into 7 themes and 19 sub-themes. The social indicators cover aspects of energy equity and health. The economic indicators cover energy use and production patterns such as efficiency and end use and security aspects such as dependency on fuel imports. The environmental indicators cover impacts on atmosphere, water and land as well as waste issues. Some indicators are clear measures of progress such as the rate of environmental degradation whilst others simply give information about certain aspects of energy use such as the fuel mix in a country. The EISD framework was initially developed using the DSR framework, and then later the indicators were classified using themes and sub-themes [2]. Since the IAEA indicators are designed to be used at a national level, for all types of energy project and not geothermal projects specifically, it is not feasible to use the EISD framework to assess individual geothermal projects, however this framework provides some valuable insight into what constitutes the sustainable development of energy resources.

3.1.5.2. International Hydropower Association Sustainability Assessment Protocol. The International Hydropower Association published a set of indicators for hydropower projects in 2006 [79]. The IHA-SAP is currently in trial and assesses the strategic basis for a proposed hydropower project including demonstrated need, options assessment and conformity with regional and national policies and plans; the preparation stage of a new hydropower project during which investigations, planning and design are undertaken; the implementation stage of the new hydropower project during which preparations, construction, and other management plans and commitments are undertaken and the operation of a hydropower facility with focus on continuous improvement [80]. Although specifically geared towards hydropower projects, the IHA-SAP still serves as a good example of how a Sustainability Assessment Protocol might be developed and implemented. However, the IHA-SAP framework does not consist of sustainability indicators as such, relying more on qualitative assessment by auditors. For this reason it does not lend itself to being used or modified to suit quantitative geothermal sustainability assessment.

3.1.5.3. Gold Standard Foundation Indicators for carbon projects and credits. The Gold Standard Foundation provides a sustainability assessment framework for new renewable energy or end-use efficiency improvement projects. Projects must go through a number of steps, including a sustainability assessment, to become accredited with the Gold Standard. These steps include a stakeholder consultation process and development of a sustainability monitoring plan, which uses indicators of sustainable development relevant to the project. The aim of the Gold Standard is to promote investments in energy technologies and energy management techniques that mitigate climate change, promote (local) sustainable development and are directed towards a transition to non-fossil energy systems [81]. The Gold Standard accredits greenhouse gas reduction projects that generate credible greenhouse gas emission reductions, show environmental integrity and contribute to local sustainable development. Project eligibility is defined by several aspects, including the scale of the project and project location. Only reductions in carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are eligible under the Gold Standard [82]. The Gold Standard indicators are not specifically tailored to geothermal projects and thus they are not suitable to be used themselves to carry out geothermal assessments, since they do not deal with all of the unique issues associated with geothermal projects.

3.1.5.4. Other frameworks. The Commission for Sustainable Development (CSD) has produced guidelines for the creation of sustainability indicators for energy at the national level [9]. In the EU, these indicators have been used in creating an indicator framework to monitor implementation of the main EU directives and other policy documents targeting sustainable energy development. However as these frameworks exist at the national level, they are not specific enough and thus not suitable for a geothermal assessment protocol to be used for individual development. Other renewable energy associations have attempted to improve sustainability assessment for energy projects. The World Wind Energy Association (WWEA) have developed Sustainability and Due Diligence Guidelines [83], for the assessment of new wind projects, similar to those developed by the International Hydropower Association in Section A of their Sustainability Assessment Protocol. These guidelines do not cover the operation stage of a wind energy project and do not provide a set of comprehensive indicators. The WWF Sustainability Standards for Bioenergy [84] does not provide any indicators but does highlight sustainability issues in bioenergy and offer recommendations for its sustainable use. UN-Energy has also published a report with a similar focus entitled Sustainable Bioenergy: A Framework for Decision-Makers [85]. However no indicators exist for assessing the sustainability of geothermal power.

4. Discussion

Significant environmental and socio-economic impacts are possible as a result of geothermal energy developments. All efforts should be made to ensure that positive impacts occur as a result of geothermal developments. To this end, a systematic framework is required to guide the management of such impacts. Such a framework should aim to maximize the positive impacts and to avoid or ameliorate the negative impacts arising from geothermal projects. The tool best suited to doing this is an assessment framework using sustainability indicators.

Given the numerous potential impacts of geothermal energy projects on sustainable development, embodied by the CSD sustainability themes, desirable characteristics of sustainable geothermal energy developments can be defined, in order to guide best practices in the planning and management of geothermal projects. This lays the foundation for the development of a customized sustainability assessment framework. The need for this customized framework is discussed in Section 4.2, based on the review of currently available sustainability assessment frameworks.

4.1. Characteristics of sustainable geothermal energy developments

Based on the review of the sustainability impacts in Section 2.2, the desirable characteristics of sustainable geothermal energy developments can be identified. Whilst some impacts may be more relevant in developing countries (such as improvements in education or health services) a sustainable geothermal project and its derived services should

1. Result in positive social impacts: in areas such as reducing poverty, enhancing equality, health or education as well as ensure community safety.
2. Be environmentally benign: the project should avoid, remedy or mitigate air or water pollution and biodiversity should be protected.
3. Be economically and financially viable: the project should result in net positive economic benefits and be financially viable.
4. Be renewable, efficiently produced and used.
5. Be equitable and thus readily accessible, available and affordable.

4.1.1. Positive social impacts

Geothermal energy projects should result in positive social outcomes wherever they are located. Such outcomes can include poverty reduction, provision of equitable energy, improvements in healthcare, education services and gender equality, whilst safeguarding the community and avoiding negative cultural impacts due to displacement or changed community lifestyles. Correctly managed geothermal energy developments should help to meet the millennium development goals by providing a local source of energy, helping to reduce reliance on food aid and providing power for schools and homes and businesses [16]. Community safety should also be ensured from activities resulting from the construction and operation of the plant. This includes such hazards as induced seismicity and subsidence.

Frequently, energy projects fail to execute according to environmental and sociological guidelines and recommendations established in the early phases of the project and often the requirement for budgetary provision for implementation of these recommendations are totally ignored [17]. The successful realization of geothermal projects often depends on the level of acceptance within the local community, which indicates the importance of public participation in decision-making regarding each project. The public should be informed and educated of probability and likely severity of any impacts. The most important actions that can help public acceptance of a project include the prevention of adverse effects on people's health; the minimization of environmental impacts; and the creation of direct and ongoing benefits for the resident communities [4]. Some geothermal companies and government agencies have dealt with social issues by improving local security, building roads, schools, medical facilities and other community assets, which may be funded by contributions from profits obtained from operating the power plant. Multiple land use arrangements that promote employment by integrating geothermal energy extraction with labor-intensive activities, such as agriculture, may also be useful [4]. In order to ensure that positive social impacts occur, a social impact assessment should be carried out before project development begins and a social management plan should be implemented for all project stages.

4.1.2. Environmentally benign

Given the large number of potential environmental impacts associated with geothermal projects, avoidance and/or mitigation measures need to be considered. An environmental impact assessment should be carried out before development takes place and an environmental management plan should be put in place for the entire project. Various options are available for avoiding environmental impacts associated with geothermal energy projects.

4.1.2.1. Avoidance of atmospheric pollution. Technologies to separate, isolate and control concentrations of certain emissions to acceptable levels can be used in geothermal plants. The reinjection of spent brines can also limit emissions [22]. The removal of H_2S is mandatory in some countries, such as the US [86], where in most states hydrogen sulfide abatement systems are required by law. Absorption and stripping techniques are available for the removal of H_2S gas and there are no emissions at all if binary plant technology is used [22]. However, care must be taken to manage byproducts of the scrubbing technology. As carbon dioxide and hydrogen sulfide are heavy gases and tend to concentrate in pits and lows, careful monitoring is required to ensure that hazardous conditions do not develop locally [38].

4.1.2.2. Avoidance of water pollution. Water pollution can be mitigated through effluent treatment, the careful storage of waste water and its reinjection into deep wells and through careful monitoring of the condition of holding ponds and well casing [22]. By cooling waste water in ponds, thermal pollution of ecosystems can be avoided but care must be taken that this does not also cause chemical pollution. Reinjection of fluids or making use of the spent fluid for multiple purposes can also prevent thermal pollution [38]. Extracting geothermal fluids can also cause drawdowns in connected shallower aquifers, potentially affecting connected springs or streams. The potential for these types of adverse effects is moderate to high; but may be reduced through extensive aquifer testing and selection [45].

4.1.2.3. Protection of biodiversity, impact on land and forestry. The World Bank recommends avoiding significant conversion or degradation of critical natural habitats during energy developments. In cases where projects adversely affect non-critical natural habitats, development should only proceed if viable alternatives are not available and if appropriate conservation and mitigation measures, including those required to maintain ecological services they provide, are in place. Mitigation measures that minimize habitat loss and establish and maintain an ecologically similar protected area should also be included [87]. The amount of land used in a geothermal project can be reduced by the use of directional drilling techniques, as advocated by the Sierra Club [22]. A drill site usually covers 200–2500 m^2 and can be kept at a minimum by directional drilling of several wells from one site [38]. As they do not require large power plants and transmission lines, distributed energy systems tend to have less environmental impact [8]. Geothermal projects, in some cases may incorporate beneficial environmental strategies. In the Philippines, geothermal projects have involved integrated total community development and forest protection. The government owned Philippine National Oil Company – Energy Development Corporation (PNOC-EDC) has instituted schemes that, along with optimized and sustained operation, adopts the integrated social forestry (ISF) approach [11]. Forestry projects in the area of the geothermal field can enhance ground water recharge, leading to better sustainability of the geothermal system, as well as providing additional benefits such as increased availability of ground and surface water for use in the community, creation of carbon sinks, reduced soil erosion and water sedimentation [44].

4.1.3. Economically and financially viable

Sustainable energy development requires that an energy project must provide positive net economic benefits, be economically viable and carry minimal financial risk [8].

4.1.3.1. Net positive economic benefits. Geothermal developments should be economically viable compared to other types of energy developments. To be economically viable, the project must produce a net positive result, after all social and environmental costs have been taken into account (e.g. through a cost-benefit analysis). Economic benefits should be considered at the macro and micro levels. At the project level, aspects such as energy efficiency and environment and health-related costs should be taken into account, whereas at the macro level, benefits in the form of employment creation, economic developments due to the multiplier effect, as mentioned in Section 2.2.10.1 or the effects on other economic activities such as tourism and farming should be considered [88]. In developing countries, previously underdeveloped sectors can benefit from geothermal utilization. This has been observed in Kenya where geothermal development has created much enterprise and employment for locals in areas such as horticulture [43]. Ways of increasing profits through secondary means or synergies, e.g., through the sale of mineral byproducts or tourism relating to the geothermal plant itself should be explored. Direct use of geothermal energy can be more energy-efficient than conversion to electricity, and tends to provide more local employment opportunities [49]. While planning a geothermal energy development, the relative benefits of electricity generation should be weighed with the opportunities provided by direct use applications of the resource, or indeed a do-nothing or “zero” option, where no development would take place.

4.1.3.2. Financial viability. The financial viability of a geothermal project will ultimately determine whether it is successful economically. The cost of financing could make an economically justified project financially unviable. The financial risk associated with geothermal developments is high in the initial stages due to the high costs and uncertainty associated with exploration and drilling to determine the viability and renewability of the resources. Drilling can account for 30–50% of a geothermal project's total cost, and a geothermal field may consist of 10–100 wells [37]. As investments needed to address the high, upfront risks for geothermal development are large, this has important consequences for a geothermal project's financial feasibility, as lenders are likely to require equity capital from the developers, and not many are willing to put the required large sums at risk. In order to mitigate the upfront risks of geothermal development two approaches are possible: either the government takes full responsibility for the first three phases of project development or the risk of initial project phases is shared between government and the private sector [89]. The advantages of government responsibility include better access to financing options and the ability to mitigate geological risks by supporting studies of a portfolio of potential sites. Public and private sector's risk sharing approaches include (1) risk mitigation funds, operating as insurance schemes with subsidized premiums (2) independent power producers (IPPs), (3) separation of steam and power production, and (4) public–private joint ventures [89].

4.1.4. *Renewable, efficiently produced and used*

Renewability and sustained yield of energy resources is generally agreed to be a necessary but not a sufficient requirement for sustainable energy development [65].

4.1.4.1. Renewability. Although classified as a renewable source of energy, the renewable nature of geothermal energy is not unconditional, since the capacity of the geothermal reservoir to replenish itself can be compromised by such factors as high withdrawal rates or failure to reinject the geothermal fluids [89]. Whilst the usual lifespan for many geothermal power plants to date is 30–50 years, [90] a recent definition for sustainable utilization (sustained yield) has been proposed as utilization that can be maintained for 100–300 years, for any mode of production [91]. In 2010, a working group on Sustainable Geothermal Utilization in Iceland, brought together by the National Energy Authority and the Steering Committee of the Master Plan for Hydro and Geothermal Energy Resources, proposed definitions for the terms *Sustainable geothermal utilization* and *Sustainable yield* (production) [92]. The group proposes a sustainable lifespan of 100–300 years for geothermal resources. This timeframe is also referred to in the recent proposal for national energy policy [93]. A timescale for energy replacement for the resource, that is acceptable to technological or societal systems, has been proposed at 30–300 years [94].

Under New Zealand resource management policy, a strategy of "controlled depletion" is deemed acceptable, meaning that a geothermal system may be utilized in an excessive manner during a given period, leaving it depleted, assuming efforts are being made to develop other energy alternatives for future generations. Stepwise increasing production based on reservoir modeling is recommended, which considers the capacity of the whole geothermal system, promotes efficient management and use of the system and considers the "reasonably foreseeable needs of present and future generations" [95]. A timescale for resource lifetime is not specified beyond the term "present and future generations". Developing geothermal plants in steps is considered international best practice, and its implementation depends on the estimated resource potential and on the results of test drillings. For high temperature geothermal power projects, steps are commonly between 30 and 60 MW per power unit installed [96]. Examples of successfully managed stepwise developments include the Matsukawa plant in Japan [97] and Berlín plant in El Salvador [98]. Operating the initial plant for some years at a given level of production will provide valuable information about the reservoir's dependable potential and thereby facilitate viable fact-based planning for future expansions of the power facility [96]. Direct use applications should also be considered as a utilization mode. Sustainable production in low enthalpy systems for direct use, may be possible, even without reinjection. An example of this is the Laugarnes geothermal field, where increased production caused a pressure drop and enhanced recharge leading to the maintenance of a sustainable production level [99].

Due to the limited knowledge that may be gained about the resource characteristics and generating capacity before production commences, it is important that adequate monitoring and management be put in place for a single resource to avoid overexploitation and subsequent possible drastic drops in production [99]. Re-injection of produced geothermal water for pressure support is a common practice in geothermal field management. Pressure draw-down can lead to the intrusion of fluid from other aquifers into the geothermal reservoir. Reinjection counteracts this by providing an artificial water recharge. Choosing the location of the re-injection well and the rate of injection can be a challenging task. The goal of optimization of reinjection well location is to find one or more combinations of locations that will maximize the production and the pressure support at minimum cost and minimum temperature decrease [100]. Other parameters that should be considered for a successful reinjection process include disposal of waste fluid, cost, reservoir temperature and thermal breakthrough, reservoir pressure or production decline, temperature of injected fluid, silica scaling, chemistry changes in reservoir fluid, recovery of injected fluid and subsidence [100].

4.1.4.2. Efficiency. For geothermal resources, when it comes to ensuring resource longevity or renewability, achieving maximum exergetic efficiency may need to be balanced against maintaining resource health. For example, if reservoir pressure support is important, the power cycle would require that spent fluid be returned for reinjection, which may reduce the overall efficiency of the power plant.

4.1.5. *Equitable (readily accessible, available and affordable)*

For energy to be equitable, it must be available, accessible and affordable to all income groups [2]. Without readily available, affordable and sustainable energy services, it is estimated that by 2030 another 1.4 billion people are at risk of being left without modern energy [7]. Small geothermal developments, with lower maintenance costs, such as decentralized systems or minigrids may, in themselves have the potential to bring employment and wealth to local community, providing new skills and thus incentive for people to stay in the villages rather than work in the cities [17]. However too often, geothermal projects are not integrated within the local community and environment, meaning that its development and operation occurs largely in isolation from the local people and the local setting. It may happen that relatively few people gain skilled long-term employment (often it is based only on menial tasks) and the power primarily goes to city industries [17]. Barriers to electrification may exist in certain areas, and these must be assessed and if possible remedied in the early stages of the project. Poverty in communities may mean households cannot afford an initial connection fee. Sparsely populated areas may result in high installation costs due to the long distances needed for distribution lines. In some areas, residents may live in temporary dwellings unsuitable for electrification. Poor road network access and unfavorable terrain may drive up the costs of maintenance and be a barrier to supply and demand of electricity [16].

4.2. The need for a geothermal-specific indicator framework

Existing assessment frameworks for energy include the International Atomic Energy Agency's (IAEA) energy indicators for sustainable development (EISDs), the CSD's guidelines for energy indicator development, the International Hydropower Association's (IHA) Sustainability Assessment Protocol (SAP) or the Gold Standard Foundation's assessment framework for carbon projects and credits. While the review in Section 3 shows that these various sustainability assessment frameworks are useful for identifying certain themes and issues associated with any energy development, they lack specific coverage of issues relating to geothermal energy. For instance, the IAEA and CSD frameworks emphasize national self-examination of the sustainability of energy systems, but do not focus on individual projects or energy types. Frameworks or guidelines for assessing different types of renewable energy projects, such as bioenergy or wind also exist, but they do not make use of sustainability indicators as a measurement tool, relying only on qualitative assessment.

We have used the CSD thematic framework [9], rather than the PSR framework (Section 3.1.4) as a guideline for classifying the sustainability impacts of geothermal energy developments (Section 2.2), since its use of themes means it can be more easily connected to policy issues. We also look to the other frameworks mentioned for inspiration on possible sustainability issues that might need to be covered when considering geothermal energy developments. However, given the unique local circumstances for each geothermal project, extensive stakeholder consultation is required to produce a well-rounded set of sustainability indicators. No such consultation has been carried out to date with the aim of developing sustainability indicators relating to geothermal development. A comprehensive assessment framework tailored to geothermal projects, involving stakeholder input from diverse sectors and countries is required in order to effectively measure the project's impact on progress towards sustainable development at the local, regional and national level. A sustainability assessment framework for geothermal energy projects would consist of sustainability goals and a suite of sustainability indicators. The goals and indicators would be chosen in collaboration with a multi-disciplinary, international stakeholder group through an iterative indicator development process.

5. Conclusion

This paper has covered the main sustainability issues present in geothermal developments, and identifies the desirable characteristics of sustainable geothermal developments. Both positive and negative impacts are possible due to geothermal developments and in order for geothermal projects to be sustainable, these impacts must be managed so as to result in positive outcomes. The uniqueness of these issues and characteristics highlights the need for a sustainability assessment framework specifically for geothermal projects. Various tools for assessing sustainability of energy projects have been reviewed in this paper, in order to determine the best structure for a sustainability assessment framework for geothermal energy projects. The issues reviewed in this paper will be used as a foundation for creating a customized assessment framework for geothermal electricity generation developments, for which suitable sustainability indicators will be identified in collaboration with stakeholder groups in several countries.

Acknowledgments

We gratefully acknowledge the GEORG geothermal cluster as our project sponsor, without whom this project would not have been possible. This project had its beginnings in 2009 as a Master's thesis at the University of Iceland, which was generously sponsored by Orkustofnun (National Energy Authority of Iceland), Landsvirkjun Power. and RANNÍS (Icelandic Research Fund). We also acknowledge the support of University of Iceland, University of Auckland, Reykajvik Energy (Orkuveita Reykjavikur) and the Kenya Electricity Generating Company Ltd. (KenGen). Furthermore, the numerous stakeholders in Iceland, New Zealand and Kenya and the UNU Fellows that took part in our stakeholder process.

References

[1] UNDP. Energy for sustainable development: a policy agenda. New York: UNDP; 2002.
[2] International Atomic Energy Agency (IAEA). Energy indicators for sustainable development: methodologies and guidelines. International Atomic Energy Agency (IAEA), United Nations Department of Economic and Social Affairs (UNDESA). Vienna: International Energy Agency (IEA), Eurostat, European Environment Agency (EEA); 2005.
[3] Bertani Ruggero. Geothermal power generation in the world 2005–2010 update report. In: Proceedings of the world geothermal congress 2010. Bali: International Geothermal Association; 2010.
[4] Intergovernmental Panel on Climate Change. Renewable energy sources and climate change mitigation: special report of the intergovernmental panel on climate change. Intergovernmental panel on climate change. New York: Cambridge University Press, p. 9; 2012.
[5] Hunt Trevor M. Five lectures on environmental effects of geothermal utilization. Taupo, New Zealand: Institute of Geological and Nuclear Sciences, United Nations University, Geothermal Training Program; 2001.
[6] Pinfield G. Beyond sustainability indicators. Local Environ 1996;1(2):151–63.
[7] Modi V, McDade S, Lallement D, Saghir J. Energy services for the millenium development goals. Energy Sector Management Assistance Program, United Nations Development Program. New York: UN Millenium Project and World Bank; 2006.
[8] Alanne Kari, Arto Saari. Distributed energy generation and sustainable development. Renew Sustain Energy Rev 2006;10:539–58.
[9] United Nations. Indicators of sustainable development: guidelines and methodologies. 3rd ed.. New York: United Nations; 2007.
[10] Kagel A, Gawell K. Promoting geothermal energy: air emissions comparison and externality analysis. Electr J 2005;18(7):90–9.
[11] Prosini J, Anave S, Cala CL. Geothermal energy development as a medium toward total community development: the Phillipine example. In: Procedings of the world geothermal congress. Antalya; April 24–25, 2005.
[12] Inforse Europe. "Inforse Europe". Inforse Europe. 〈http://www.inforse.org/europe/pdfs/INFORSE-on-EU-energy-poverty_09.pdf〉; December 22, 2009 [accessed 20.01.14].
[13] Advisory Group on Energy and Climate Change (AGECC). Energy for a sustainable future. NY: The Secretary-General's Advisory Group on Energy and Climate Change (AGECC); 2010.
[14] International Energy Agency. Renewable energy into the mainstream. Sittard, Netherlands: International Energy Agency; 2002.
[15] Ormat Nevada. Factory integrated small geothermal power plants. Southern Methodist University. 〈http://smu.edu/geothermal/Oil&Gas/Thomsen_Modular%20geothermal%20power%20plant%20presentation%203.06%20SMU.pdf〉; 2006 [accessed 22.05.13].
[16] Achieng Ogola Pacifica. Brynhildur Davidsdottir and Ingvar BirgirFridleifsson, Lighting villages at the end of the line with geothermal energy in eastern Baringo lowlands, Kenya – steps towards reaching the millennium development goals (MDGs). Renew Sustain Energy Rev 2011;15:4067–79.
[17] Brotheridge Jane, Leniston Margaret, Christyono. Potential environmental and social impacts of small scale rural geothermal development. In: Proceedings of the world geothermal congress. Kyushu, Tohoku; 2000.
[18] Blue Lagoon. Blue Lagoon (geothermal spa). 〈http://www.bluelagoon.com/〉; 2013.
[19] World Health Organisation Regional Office for Europe Copenhagen. Air quality guidelines for Europe, 2nd ed. Copenhagen, Denmark: WHO Regional Publications, (European Series, No. 91); 2000.
[20] OECD. Analysis of H_2S – incidents in geothermal and other industries. Preliminary analysis of data. OECD WGCA steering group of analysis of H_2S incidents. Iceland: OECD; 2009.
[21] Noorollahi Younes. H_2S And CO_2 dispersion modeling for The Nesjavellir geothermal power plant, S-iceland and preliminary geothermal environmental impact assessment for the Theistareykir area, Ne-Iceland. Reykjavik, Iceland: UNU-GTP; 1999.
[22] Heath MJ. Environmental aspects of geothermal energy resources utilization. Lisse: Swets & Zeitlinger B.V.; 2002.
[23] Wetangula Gabriel. Assessment of geothermal waste water disposal effects, case studies: Nesjavellir (Iceland) and Olkaria (Kenya) fields. Reykjavik, Iceland: UNU-GTP, University of Iceland; 2004.
[24] Ray David. Wairakei power plant effects of discharges on the Waikato river. New Zealand: Contact Energy; 2001.

[25] Waikato Regional Council. ⟨http://www.waikatoregion.govt.nz/Environment/Natural-resources/Water/Rivers/Waikato-River/Wastewater-discharges/⟩; 2012 [accessed 31.10.12].
[26] Scheiber Julia. Personal communication. Soultz; July 17, 2013.
[27] Environmental Protection Agency. Geothermal energy production wastes. Radiation protection. ⟨http://www.epa.gov/radiation/tenorm/geothermal.html⟩; August 30, 2012 [accessed 14.05.13].
[28] Environmental Protection Agency. Health effects. ⟨http://www.epa.gov/radiation/understand/health_effects.html⟩; July 8, 2012 [accessed 14.05.13].
[29] World Health Organisation. Guidelines for community noise. Geneva, Switzerland: WHO; 1999.
[30] Becker HA, Frank Vanclay. The international handbook of social impact assessment: conceptual and methodological advances. Cheltenham, UK: Edward Elgar Publishing; 2003.
[31] All Africa. Kenya: Kengen buys 1700 acres for resettlement. ⟨http://allafrica.com/stories/201209230022.html⟩; September 22, 2012 [accessed 10.05.13].
[32] Barbara Farhar, Dunlevy Paul. Native American issues in geothermal energy. In: Annual meeting of the geothermal resources council. Morelia, Mexico: GRC Transactions; 2003.
[33] Mwangi-Gachau Elizabeth. Social aspects of geothermal development – a case of Olkaria geothermal project in Kenya. Reykjavik, Iceland: United Nations Unviersity Geothermal Training Program; 2011.
[34] Philippe Jousset. Seismic tomography and long-period earthquakes observation and modeling at the hengill geothermal volcanic complex, Iceland. In: Proceedings of the world geothermal congress. Bali; 2010.
[35] Majer Ernest L. The impact of injection on seismicity at The Geysers. California geothermal field. Int J Rock Mech Min Sci 2007;44:1079–90.
[36] Reykjavik Energy. Reykjavik energy annual report 2011. Reykjavik, Iceland: Reykjavik Energy; 2011.
[37] Shibaki M, Beck F. Geothermal energy for electric power: renewable energy policy project brief. Washington: Renewable Energy Policy Project (REPP); 2003.
[38] Kristmannsdóttir H, Ármannsson H. Environmental aspects of geothermal energy utilization. Geothermics 2003;32:451–61.
[39] Armansson H. CO_2 emissions from geothermal plants. In: Proceedings of the international geothermal conference. Reykjavik; September 2003.
[40] Valdez Salas Benjamin, Schorr Wiener Michael, Lopez Badilla Gustavo, Carrillo Beltran Monica, Zlatev Roumen, Stoycheva Margarita, et al. H_2S pollution and its effect on corrosion of electronic components, air quality–new perspective. Gustavo LopezDr. (edotor), InTech. Available from: ⟨http://www.intechopen.com/books/air-quality-new-perspective/h2s-pollution-and-its-effect-on-corrosion-of-electronic-components⟩.
[41] Department for Environment, Food and Rural Affairs. Construction code of practice for the sustainable use of soils on construction sites. London: Department for Environment, Food and Rural Affairs; 2009.
[42] Fridleifsson IB. Geothermal energy and the millennium development goals of the United Nations. Reykjavik, Iceland: United Nations University Geothermal Training Program; 2007.
[43] Mwangi Martin. Environmental and socio-economic issues of geothermal development in Kenya. Davis, CA: GRC Bulletin; 2010.
[44] Ogola FPA, Davidsdottir Brynhildur, Fridleifsson IB. Opportunities for adaptation-mitigation synergies in geothermal energy utilization – initial conceptual frameworks. Mitig Adapt Strateg Glob Change 2012;17(5):507–36.
[45] National Water Commission. Groundwater essentials. Australian Government: National Water Commission; 2012.
[46] Natural Standard. ⟨http://www.naturalstandard.com/index-abstract.asp?create-abstract=generic-thermalpollution.asp&title=Thermal%20pollution⟩; 2013 [accessed 12.12.13].
[47] Department for Environment. Food and Rural Affairs, Construction code of practice for the sustainable use of soils on construction sites. London: Department for Environment, Food and Rural Affairs; 2009.
[48] Boothroyd Ian KG. Ecological characteristics and management of geothermal systems of the Taupo Volcanic Zone, New Zealand. Geothermics 2009;38:200–9.
[49] Waikato Regional Council. Valuing uses of the Waikato regional geothermal resource. New Zealand: Waikato Regional Council; 2011.
[50] Dolor Francis M. Geothermal projects in national parks in the Philippines: the case of Mt. Apo geothermal project. PNOC Energy Development Corporation. San Salvador: UNU-GTP; 2006.
[51] UNDP. World energy assessment overview: 2004 update. New York, NY: United Nations; 2004.
[52] International Energy Agency. Contribution of renewables to energy security. Paris, France: International Energy Agency; 2007.
[53] Wind Energy Center, University of Massachusetts Amherst. Wind power: capacity factor, intermittency and what happens when the wind doesn't blow. ⟨http://www.umass.edu/windenergy/publications/published/communityWindFactSheets/RERL_Fact_Sheet_2a_Capacity_Factor.pdf⟩; January 20, 2014.
[54] US Department of Energy. Clean power for 21st century dollars from sense: the economic benefits of renewable energy. US Department of Energy: Office of Power Technologies. Washington, DC: US Department of Energy; 1997.
[55] International Association for Energy Economics. South and southeast asia pricing issue. vol. 9, Special issue, Cleveland, Ohio: International Association for Energy Economics; 1988.
[56] U.S. Department of Energy Geothermal Technologies Program. Buried treasure: the environmental, economic and employment benefits of geothermal energy. Washington, DC: U.S. Department of Energy; 2004.
[57] National Energy Authority. Meet Iceland – a pioneer in the use of renewable resources. Reykjavik, Iceland: National Energy Authority; 2009.
[58] Geothermal Energy Association. Green jobs through geothermal energy. Washington, DC: Geothermal Energy Association; 2010.
[59] Geoelec. Employment study: solutions on lack of skilled workers in the geothermal sector and results of the questionnaires. Geoelec; 2013.
[60] Stewart Carol. Effects on the environment – geothermal energy. ⟨http://www.teara.govt.nz/en/geothermal-energy/5⟩; March 2, 2009 [accessed 29.10.12].
[61] Bradshaw D, Faulkner R. Five Māori Trust Groups' perspectives on low temperature geothermal energy resources. GNS Science; 2011.
[62] de Jesus Agnes C. Social issues raised and measures adopted in Philippine geothermal projects. In: Proceedings of the world geothermal congress. Antalya; 2005.
[63] Sandia National Laboratories. Handbook of best practices for geothermal drilling. Oakridge, TN: US Department of Energy; 2010.
[64] International Finance Corporation. Summary of IFC EHS guideline – geothermal power generation. ES-Toolkit. ⟨https://www.estoolkit.com/⟩; 2014 [accessed 02.02.14].
[65] Prindle Bill, Eldridge Maggie, Eckhardt Mike, Frederick Alyssa. The twin pillars of sustainable energy: synergies between energy efficiency and renewable energy technology and policy. Washington DC: American Council for an Energy-Efficient Economy (ACEEE); 2007.
[66] IEA Renewable Energy Working Party. Renewable energy…into the mainstream. Sittard: International Energy Agency; 2002.
[67] Geothermal Energy Association. The state of geothermal technology part II: surface technology. Washington, DC: Geothermal Energy Association; 2008.
[68] Axelsson Guðni. Role and management of geothermal reinjection. Reykjavik, Iceland: United Naitons University; 2012.
[69] Hepbasli Arif. A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future. Renew Sustain Energy Rev 2008;12:593–661.
[70] Devuyst D, Hens L, Lannoy W. How green is the city? Sustainability assessment and the management of urban environments New York: Columbia University Press; 2001.
[71] Ness B, Urbel–Piirsalu E, Anderberg S, Olsson L. Categorising tools for sustainability assessment. Ecol Econ 2006;60(3):498–508.
[72] Jesinghaus J. A European system of environmental pressure indices, first volume of the environmental pressure indices handbook: the indicators. Part I: Introduction to the political and theoretical background Vol. 1. European Commision. Joint Research Center. Ispra, Italy: Institute for Systems, Informatics and Safety (ISIS); 1999.
[73] Planning and Compulsory Purchases Act. Planning and Compulsory Purchases Act (c.4). London: HMSO; 2004.
[74] Office of the Deputy Prime Minister. Sustainability appraisal of regional spatial strategies and local development: documents guidance for regional planning bodies and local planning authorities. London: ODPM Publications; 2005.
[75] Pinter Laszlo, Hardi Peter, Peter Bartelmus. Indicators of sustainable development: proposals for a way forward. New York, NY: IISD; 2005.
[76] OECD. Core set of indicators for environmental performance reviews. Paris, France: OECD; 1993.
[77] Bossel Hartmut. Indicators of sustainable development: theory, method, applications. A report to the Balaton group. Winnipeg, Manitoba, Canada: IISD; 1999.
[78] Hukkinen Janne. Sustainability scenarios as interpretive frameworks for indicators of human-environment interaction. In: Lawn Philip, editor. Sustainable Development Indicators in Ecological Economics. Cheltenham, UK: Edward Elgar; 2006. p. 291–316.
[79] International Hydropower Association. Sustainability Assessment Protocol; 2006.
[80] International Hydropower Association. IHA connect issue 3. no. 3; 2008.
[81] The Gold Standard Foundation. ⟨http://www.goldstandard.org/energy/certification-process⟩; September 7, 2014 [accessed 2014].
[82] The Gold Standard Foundation. The gold standard toolkit 2.2. Geneva: The Gold Standard Foundation; 2012.
[83] WWEA. Sustainability and due diligence guidelines. Bonn, Germany: WWEA; 2005.
[84] WWF. Sustainability standards for bioenergy. Frankfurt am Main, Germany: WWF; 2006.
[85] UN-Energy. Sustainable bioenergy: a framework for decision makers. New York, NY: UN-Energy; 2007.
[86] REPP-CREST. Geothermal resources. ⟨http://www.repp.org/geothermal/geothermal_brief_environmental_impacts.html⟩; 2012 [accessed 5.11.12].
[87] The World Bank. The world bank operations manual. World Bank. ⟨http://web.worldbank.org/WBSITE/EXTERNAL/PROJECTS/EXTPOLICIES/EXTOPMANUAL/0,menuPK:64142516~pagePK:64141681~piPK:64141745~theSitePK:502184,00.html⟩; May 2, 2013 [accessed 14.05.13].
[88] Geothermal Energy Association. A handbook on the externalities, employment, and economics of geothermal energy. Washington, DC: Geothermal Energy Association; 2006.
[89] World Bank. Drilling down on geothermal potential: an assessment for Central America. Washington DC: World Bank; 2012.

[90] Axelsson Guðni. Sustainable geothermal utilization. In: Proceedings of ICG 2013; March 2013.
[91] Axelsson Guðni, Gudmundsson A, Steingrimsson B, Palmason G, Armannsson H, Tulinius H, et al. Sustainable production of geothermal energy: suggested definition. IGA-News Quarterly; 2001. p. 1–2.
[92] National Energy Authority. Eðli Jarðhitans og Sjáflbær Nýting Hans: Álitsgerð faghóps um sjálfbæra nýtingu jarðhita. Reykjavik, Iceland: Orkustofnun; 2010.
[93] Ministry of Industries and Innovation. Orkustefna fyrir Ísland. Stýrihópur um mótun heildstæðrar orkustefnu; 2011.
[94] Axelsson Guðni, Stefánsson Valgardur, Björnsson Grímur, Liu Jiurong. Sustainable management of geothermal resources for 100–300 years. In: Proceedings of the world geothermal congress. Antalya, Turkey: International Geothermal Association; 24–29 April 2005.
[95] Waikato Regional Council. Waikato regional plan: chapter 7, Geothermal module. New Zealand: Waikato Regional Council; 2011.
[96] The World Bank Energy Sector Management Assistance Program. Geothermal handbook: planning and financing geothermal power generation. Washington DC: The World Bank; 2012.
[97] Hanano Mineyuki. Sustainable steam production in the Matsukawa geothermal field, Japan. Geothermics 2003;32:311–24.
[98] Rodríguez, José Antonio, Monterossa Manuel. Lecture 2 phased development at Ahuachapán and Berlín geothermal fields. In: Lectures on geothermal in Central America. Reykjavik: United Nations Geothermal Training Program; 2007.
[99] Axelsson Guðni, Stefánsson Valgardur, Björnsson Grímur. Sustainable utilization of geothermal resources for 100–300 years. In: Proceedings of the twenty-ninth workshop on geothermal reservoir engineering. Stanford, California; 2004.
[100] Uraz Irtek, Akin Serhat. Optimatization of reinjection in geothermal reservoirs. In: Proceedings of the twenty-eighth workshop on geothermal reservoir engineering. Stanford: International Geothermal Association; 2003.