# A Sustainability Assessment Framework for Geothermal Energy Developments

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Dissertation submitted in partial fulfillment of a
*Philosophiae Doctor* degree in Environment and Natural Resources

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# Abstract

With increasing global energy consumption, geothermal energy usage for electricity generation will increase significantly in the future. Since sustainable development calls for the use of sustainable energy systems and since geothermal developments may result in both positive and negative environmental and socio-economic impacts, the world's geothermal resources will need to be managed appropriately. Sustainability assessment tools are useful for informing decision-makers about the progress of policies towards sustainable development. This research provides a 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. A stakeholder-evaluated customized assesment framework of ten sustainability goals, 21 core and 18 optional indicators is produced, reflecting the priorities of stakeholder groups in Iceland, New Zealand, Kenya and the United Nations University Geothermal Training Program (UNU-GTP). The importance of the need to include a diversity of stakeholders when developing assessment tools is evidenced in the diversity of opinions between groups. Environmental management was a common concern among the Icelandic, New Zealand and Kenyan participants, whereas water usage was considered the most important environment-related issue for the UNU-GTP fellows. The Kenyan, New Zealand and the UNU-GTP groups rated economic management and profitability, along with research and innovation, highly, whereas the Icelandic group placed highest emphasis on resource renewability and also rated knowledge dissemination highly. The indicator choices of each group are also presented and discussed. The indicators were found to adequately cover the sustainability goals chosen by the stakeholders.

# Útdráttur

Með aukinni orkunotkun á heimsvísu er líklegt að nýting jarðvarma til rafmagnsframleiðslu muni aukast í framtíðinni. Sjálfbær þróun kallar á sjálfbæra nýtingu orkukerfa og þar sem nýting jarðvarma getur bæði haft jákvæð og neikvæð áhrif á sjálfbærni er mikilvægt að neikvæð áhrif séu lágmörkuð. Sjálfbærnigreiningar geta stuðlað að skilvirkari ákvarðanatöku þegar kemur að þróun orkukerfa og er markmið þessarrar rannsóknar að setja fram ramma sem og aðferðafræði til að meta áhrif nýtingar jarðvarma á sjálfbærni. Rannsóknin gefur yfirlit yfir helstu áhrif nýtingar jarðvarma á sjálfbæra þróun, sem og yfirlit yfir helstu ramma sem notaðir eru til mats á sjálfbærni. Matsrammi er síðan settur fram sem inniheldur 10 sjálfbærni markmið og 21 kjarnavísa, sem og 18 valkvæða vísa sem gefa til kynna hvort markmiðin séu uppfyllt. Rannsóknin sýnir framá mikilvægi þess að haghafar taki þátt í sjálfbærnigreiningum, en bæði vísarnir sem og markmiðin voru valin með þátttöku haghafa á Íslandi, í Kenýa og á Nýja Sjálandi sem og þátttöku fyrrum nemenda jarðhitaskóla SÞ. Munur var milli landa hvað haghafar töldu mikilvægt þegar kemur að sjálfbærri nýtingu jarðvarma. Umhverfisstjórnun var mikilvæg á Íslandi, Nýja Sjálandi og í Kenýa en áhrif á vatnsbúskap var taklið mikilvægt atriði af fyrrum nemendum Jarðhitaskóla SÞ. Íslenskir haghafar töldu endurnýjanleika auðlindarinnar mikilvægan sem og gegnsæi í upplýsingarflæði en haghafar í Kenýa og Nýja Sjálandi töldu skilvirka fjármálastjórn sem og rannsóknir og nýsköpun mikilvæg atriði. Rannsóknin dregur fram mun sem og líkindi milli haghafa í mismunandi löndum, en lokaafurð ritgerðarinnar er heildstæður rammi til að meta áhrif nýtingar jarðvarma á sjálfbæra þróun sem nýta má í mismunandi samfélögum um allan heim.

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# List of Papers

The thesis is based on three published papers, one book chapter and a submitted manuscript. The papers will be referred to in the text as chapters as follows:

### Paper I: Chapter 2

Shortall, R., Davidsdottir, B. & Axelsson, G. (2015). Geothermal energy for sustainable development: A review of sustainability impacts and assessment frameworks. *Renewable and Sustainable Energy Reviews 44*, 391–406. Elsevier.

### Paper II: Chapter 3

Shortall, R., Davidsdottir, B. & Axelsson, G. (2015). Development of a sustainability assessment framework for geothermal energy projects. *Energy for Sustainable Development 27*, 28-45. Elsevier.

### Paper III: Chapter 4

Shortall, R., Davidsdottir, B. & Axelsson, G. (2015). A sustainability assessment framework for geothermal energy projects: Development in Iceland, New Zealand and Kenya. *Renewable and Sustainable Energy Reviews 50*, 372-407. Elsevier.

### Book Chapter: Chapter 5

Shortall, R., Axelsson, G. & Davidsdottir, B. (2015) Assessing the Sustainability of Geothermal Utilization. In J. Dewulf, S. De Meester, R. Alvarenga (Eds.) *Sustainability Assessment of Renewables-Based Products: Methods and Case Studies.* Wiley, (in press).

# Abbreviations

| | |
|---|---|
| AGECC | Advisory Group on Energy and Climate Change |
| BOP | Bay of Plenty |
| CSD | Commission for Sustainable Development |
| dB | Decibel |
| DPSIR | Driving force-Pressure-State-Impact-Response |
| DSR | Driving force –State-Response |
| EBIDTA | Earnings Before Interest, Taxes, Depreciation and Amortization |
| EECA | Energy Efficiency and Conservation Authority |
| EIA | Environmental Impacts Assessment |
| EISD | Energy Indicators of Sustainable Development |
| ERC | Energy Regulatory Commission |
| EU | European Union |
| g | Gram |
| GDP | Gross Domestic Product |
| GHG | Greenhouse gases |
| $GWh_e$ | Gigawatt hour electric |
| Hr | Hour |
| IAEA | International Atomic Energy Agency |
| IGA | International Geothermal Association |
| IHA | International Hydropower Association |
| IHA-SAP | International Hydropower Association – Sustainability Assessment Protocol |
| IPCC | Intergovernmental Panel on Climate Change |
| IRR | Internal Rate of Return |
| kWh | Kilowatt hour |
| LOAEL | Lowest-Observed-Adverse-Effect-Level |
| $m^2$ | Meter squared |
| $m^3$ | Meters cubed |
| mg | Milligram |
| MW | Megawatts |
| MWe | Megawatts electric |
| $MW_e$ | Megawatts electric |
| NEA | National Energy Authority |
| NEMA | National Environmental Management Authority |
| NGO | Non-governmental Organization |
| NREAP | National Renewable Energy Action Plan |
| NWQMS | National Water Quality Management System |
| NZEECS | New Zealand Energy Efficiency and Conservation Strategy |
| OECD | Organisation for Economic Co-operation and Development |
| PNOC-EDC | Philippine National Oil Company - Energy Development Corporation |
| PSR | Pressure-State-Response |
| R&D | Research and Development |
| RMA | Resource Management Act |
| RPS | Regional Policy Statement |
| SA | Sustainability Appraisal |
| SEA | Strategic Environmental Assessment |
| SoE | State of the Environment |

| | |
|---|---|
| STAMP | Sustainability Assessment and Measurement Principles |
| UN | United Nations |
| UNESCO | United Nations Economic and Social Council |
| UNU-GTP | United Nations University Geothermal Training Program |
| UST | Umhverfisstofnun |
| WHO | World Health Organization |
| WRC | Waikato Regional Council |
| WRMA | Water Resources Management Authority |
| WWEA | World Wide Energy Association |
| WWF | World Wildlife Fund |
| Yr | Year |
| μ g | Microgram |

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*“Understanding means throwing away your knowledge”*
Thích Nhất Hạnh

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# 1 Introduction

Many countries around the world have geothermal resources that have as yet to be developed. Currently, geothermal energy is used in various forms including groundsource heat pumps, various direct uses, electricty generation from low and high temperature resources and from enhanced geothermal systems (EGS). For simplicity's sake, however, this research focusses on geothermal energy for electricity generation, although the findings also have relevance for other types of geothermal energy usage. Growing global energy demand and technological advances are likely to result in more geothermal energy sources being harnessed and geothermal energy will certainly be considered as a part of the energy mix in many countries. Work has already begun in many places to identify geothermal resources that could be exploited, e.g. in Canada (Richter, Ko & Thompson, 2012) and Norway (Midttømme et al., 2013). Since it is generally believed to be renewable and to have relatively low carbon emissions (Intergovernmental Panel on Climate Change, 2012), it is indeed an attractive option, particularly for settlements in remote areas. It is even more attractive when its low levelized cost (Matek & Gawell, 2014), high capacity factor, reliability (Shibaki & Beck, 2003) and flexibility (Matek & Schmidt, 2013) are taken into account.

Sustainable energy development is an emerging paradigm. It requires the reduction of negative impacts on health and the environmental, whilst concurently increasing access to affordable energy, as well as energy security and efficiency (Modi et al., 2006). Evidencing the move into this new paradigm, energy policy directives of various industrialized countries include common interests such as improving energy efficiency or reliability, security and diversity of supply, economic efficiency, support of research and development and regional partnerships for the development of more advanced technologies (Alanne & Saari, 2006). The need for a shift to a new energy paradigm has been stressed by the international community. The World Energy Assessment (WEA) report (United Nations Development Programme, 2000) compares the characteristics of a traditional energy paradigm to an emerging paradigm that will promote sustainable energy development. The geothermal sector, although relatively young, still displays some characteristics of the traditional paradigm. Table 1-1 outlines some of opportunities for the geothermal sector in moving into the new energy paradigm.

*Table 1-1: Opportunities for geothermal energy in the new energy paradigm*

| **Traditional Paradigm** | **Emerging Paradigm** | **Opportunities for Geothermal Energy** |
|---|---|---|
| Energy considered primarily as a sectoral issue | Greater consideration of social, economic, and environmental impacts of energy use | No current multi-dimensional assessment framework for geothermal energy development exists, suggesting that the industry focus is more on technical or resource issues at present. |
| Limitations on fossil fuels | Limitations on the assimilative capacity of the Earth and its atmosphere | Discourse currently tends to focus on geothermal's ability to displace fossil fuels rather than other types of impacts it may have, like any other energy resource. |
| Emphasis on expanding supplies of fossil fuels | Emphasis on developing a wider portfolio of energy resources, and on cleaner energy technologies | The role of geothermal in the wider energy mix needs to be further explored, in order to reduce the risk of over-reliance on and thus overexploitation of geothermal resources. |
| External social and environmental costs of energy use largely ignored | Finding ways to address the negative externalities associated with energy use | Whilst social and environmental assessments are common for geothermal projects and mitigation of impacts are sought, externalities still occur. |
| Economic growth accorded highest priority (even in prosperous countries) | Understanding of the links between economy and ecology, and of the cost-effectiveness of addressing environment impacts early on | Without multidimensional asssessment, there is a risk that only narrowly defined economic benefits of geothermal will be considered when planning new energy projects. |
| Tendency to focus on local pollution | Recognition of the need to address environmental impacts of all kinds and at all scales (local to global) | Geothermal may result in non-local impacts, such as long-range water pollution, acid rain or greenhouse gas emissions. In some cases these impacts remain unmitigated. |
| Emphasis on increasing energy supply | Emphasis on expanding energy services, widening access, and increasing efficiency | An increase in the use of geothermal energy is foreseen in the coming decades, despite the uncertainty and lack of knowledge of the capacity of geothermal resources. |
| Concern with ourselves and our present needs. | Recognition of our common future and the welfare of future generations | Examples exist where the sustained yield derived from geothermal resources is compromised, due to the need for short-term financial payback or poor planning. |

The motivation for this research arises in particular from the need for greater consideration of the simultaneous social, economic, and environmental impacts of energy development and use. Although the "pillars" of environment, economy and society, and sometimes institutions or well-being, have been commonly used to classify issues in sustainable development, a new method of classification has been proposed by the Commission on Sustainable Development (CSD). In their latest indicator publication, the CSD proposes that the multidimensional nature of sustainable development requires us to be more aware of the cross-cutting nature of impacts, and for this reason they move away from the traditional pillar approach, favouring a multidimensional thematic framework instead (United Nations, 2007). A multidimensional assessment framework for geothermal energy development will help to take account of negative externalities of geothermal energy usage, moving away from a focus only on profitability or economic gain, to a broader focus that takes into account varied cross-cutting environmental and social implications. As well as this, broader assessment will take into account the limits of capacity and unique characteristics of geothermal resources, which need to be understood and respected if usage is to be sustainable.

Past and current examples of geothermal developments show us that both positive and negative impacts can arise. The potential of geothermal energy to stimulate economic development and raise living standards in the Global South cannot be ignored, especially in countries sorely in need of additional generation capacity such as those in East Africa. Opportunities also exist for climate change mitigation and adaptation in vulnerable regions with geothermal energy (Ogola, Davidsdottir & Fridleifsson, 2012). At the same time, geothermal development can also have significant negative environmental, social and economic impacts across all sustainability themes (Shortall, Davidsdottir & Axelsson, 2015a) and increasing this usage in the future will increase the risk of these impacts. While geothermal power may provide access to much-needed energy in some countries, it may also result in unforeseen impacts in protected areas (Hunt, 2001), depletion of freshwater supplies for use in drilling or cooling (Mwangi, 2010) as well as dramatically influencing culture through stimulating migration to a region and providing household electricity (Mwangi-Gachau, 2011). Stimulating economic development can have implications for nature conservation efforts and tourism (Mariita, 2002). Care must be taken therefore to use geothermal resources in the best possible way for these regions, as well as those in the developed world. This research aims to further the cause of moving geothermal energy into the new sustainable energy paradigm, by taking the initial steps to properly consider the cross-cutting social, economic, and environmental impacts of its development and use.

The main research areas of this thesis consist of:

- Identification of the main sustainability issues associated with geothermal energy usage for electricity generation

- Design of appropriate methods to develop a sustainability assessment framework for geothermal energy development

- Development of a sustainability assessment framework for geothermal developments relying on case studies in Iceland, New Zealand and Kenya with the input of local and international stakeholder groups

## 1.1 Geothermal Energy in the New Energy Paradigm

Although the renewability and sustained yield of energy resources is imperative for sustainable energy systems (UNDP, 2002), the definition of sustainable energy development encompasses more than this alone. In line with the characteristics of the emerging sustainable energy paradigm (Table 1-1) and based on numerous definitions found in the literature, a sustainable energy system can be described as one that is cost-efficient, effective, and environmentally benign (Alanne & Saari, 2006), that generates enough power for everybody's needs at an affordable price and supplies clean, safe and reliable energy (Bonser, 2002). The sustainability perspective requires a much broader assessment of energy development that takes into account all of its associated multidimensional and cross-cutting impacts (International Atomic Energy Agency (IAEA), 2005).

Different energy sources have different types of impacts during their development and use. Pollution may take place at any point in the energy supply chain, often having serious impacts on health and the environment. Emissions and wastes may be also associated with any part of an energy projects' life cycle, including their manufacture or construction. However, the impacts differ widely. Fossil fuels are, for instance the main sources of air pollution in many areas, ocean acidification and climate change, whereas risks associated with nuclear power include radioactive waste storage or disposal and nuclear arms proliferation. Bioenergy production may contribute to desertification or biodiversity loss in some regions, as well as energy crop cultivation having significant impacts on food prices worldwide (International Atomic Energy Agency (IAEA) 2005). Other renewable energy sources such as hydro- and wind power have significant implications for land-use as well as important ecosystem and visual impact.

Geothermal energy has not until recently become an important source of electricity and heat, with exceptions in countries such as the USA, the Philippines, El Salvador, Iceland and Italy. In 2008, it was estimated that geothermal energy could fulfill around 3% of global electricity demand, as well as 5% of global heating demand by 2050. At this time, geothermal energy production reportedly contributed around 0.1% to the global energy supply (Intergovernmental Panel on Climate Change, 2012). In 2013, it was estimated that a geothermal resources provided approximately 600PJ (167 TWh) for electricity generation, direct heating and cooling purposes (REN21, 2014).

Geothermal energy development can have substantial sustainability implications. The possible impacts from geothermal development are listed in Table 1-2 (Shortall, Davidsdottir & Axelsson, 2015a). The impacts are grouped according to the relevant themes of the Commission on Sustainable Development (CSD) (United Nations, 2007) thematic indicator framework. Some specific examples of unsustainable management of geothermal projects clearly illustrate the need for better sustainability monitoring systems (Shortall, Davidsdottir & Axelsson, 2015b).

*Table 1-2: Summary of geothermal sustainability issues by theme*

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

Given the uniqueness of issues associated with geothermal energy projects and the current lack of suitable assessment tools for geothermal energy projects, a specialized assessment tool is required to ensure that geothermal projects will be properly guided into following best practices and result in positive impacts in all sustainability dimensions and themes.

## 1.2 Sustainability Assessment and Energy

Many international organizations, such as the United Nations Commission for Sustainable Development (CSD) (Pinfield, 1996), have made the case that indicators are needed to guide countries or regions towards sustainable energy development and the necessity of developing sustainability indicators is clearly set out in Agenda 21. After the UN Conference on Environment and Development (UNCED) held in 1992, the Agenda 21 action plan was draw up and states that:

*"Indicators of sustainable development need to be developed to provide solid bases for decision-making at all levels and to contribute to a self-regulating sustainability of integrated environment and development systems" (Agenda 21, Chapter 40).*

Sustainability assessment is a means of showing whether development projects contribute to a progress towards or away from sustainability. Sustainability assessments are used for many different types of projects, including energy developments. Various assessment tools, many of which involve the use of sustainability goals or criteria and indicators, exist from the national to local level (Pinter, Hardi & Bartelmus, 2005). Such criteria and indicators must provide a holistic view of sustainability, and thereby include all sustainability dimensions, and should not be rigid but take account of the local context as well as changes in opinions over time (Lim & Yang, 2009). In order to ensure this, broad stakeholder engagement is an essential part of the indicator development process (Fraser et al., 2006).

In general, an indicator provides information that measures and quantifies the characteristics or behavior of a system. Indicators simplify complex reality, thus enabling decision–makers to make better decisions (Jesinghaus, 1999). The information provided by indicators of sustainability promotes the understanding of the social, economic and ecological conditions that are critical for strategic and coordinated action for sustainable development, thus helping decision– and policy–makers to decide upon actions to take to help create more sustainable societies (Devuyst, Hens & Lannoy, 2001). As such, indicators have an important role in the policy cycle in providing decision support (Figure 1-1).

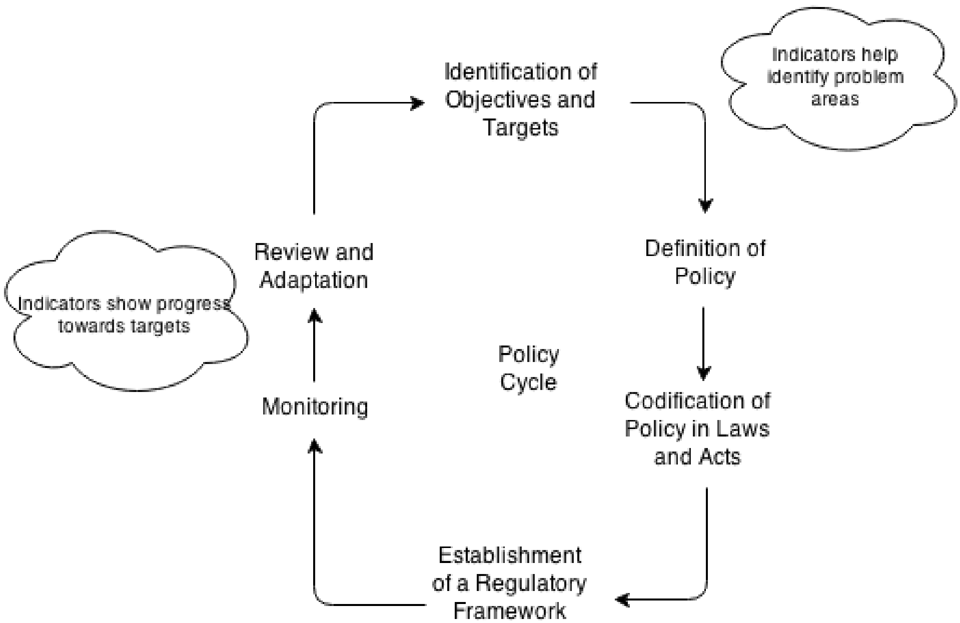


*Figure 1-1: Role of indicators in the policy cycle, adapted from Sheilds et al. (2002)*

While sustainability assessment tools have become increasinly popular in many sectors, their success in influencing actual policy varies (Pinter, Hardi & Bartelmus, 2005). It has been argued that indicators of sustainability may not necessarily always have an impact on decision-making or give rise to any policy changes (Moreno-Pires & Fidelis, 2012) and that the information provided to policy actors is seldom directly used to make decisions (Bauler, 2012).

# 1.3 Research Objectives

The objectives of this research are to:

- Review the literature on sustainability impacts of geothermal power development for electricity generation and thereby identify the most important issues of concern in 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 protocol.
- Develop a sustainability assessment framework for geothermal energy projects, through several iterations of the indicator development process, taking place in Iceland, New Zealand and Kenya, using diverse stakeholder input.

## 1.4 Geothermal Energy in Iceland, New Zealand and Kenya

Field work and case studies were carried out in Iceland, New Zealand and Kenya. These countries were chosen because each of them have geothermal power generation projects in operation and development. As well as this, it was hoped that due to the unique cultural and economic cirucmstances in each country, stakeholder consultation would result in a more well-rounded assessment tool. It was also hoped that stakeholders from these countries would provide valuable insights based on their experience with geothermal power.

Each of the countries studied has its own unique characteristics and a unique approach to geothermal development. Some relevant statistics are shown in Table 1-3. In New Zealand, the indigenous Maori people make up around 15% of the population and efforts are made to incorporate Maori views into resource management policy. In Kenya the relatively young population comprises numerous ethnic groups. Marked income inequalities exist, as well as vast differences between the lifestyles of rural and urban communities. It is not surprising therefore that conflicts have arisen between geothermal developers and local communities. In contrast, Iceland has a very small population and power developments often take place in sparsely populated areas.

Iceland and New Zealand are both countries with high levels of energy access and a longer history of geothermal energy usage than Kenya. The likely implications of increased geothermal developments in each of these countries differ according to predicted energy needs and socio-economic conditions. In 2013, electric power growth rates in Iceland stood at 3.22% (National Energy Authority, 2014) and in New Zealand electricity generation fell by 2.2% (Ministry of Business, Innovation and Employment, 2014a), whereas in Kenya, domestic electricity demand grew by 8% (Kenya National Bureau of Statistics, 2014). A detailed background of each country studied in this research is presented in this section.

*Table 1-3: Selected statistics for Iceland, New Zealand and Kenya*

| | **Iceland** | **New Zealand** | **Kenya** |
|---|---|---|---|
| GDP PPP/Capita (Int$) (International Monetary Fund, 2014) | 41,001 (2013) | 33,626 (2013) | 3,009 (2013) |
| Electricity consumption / population (MWh/capita) (International Energy Agency, 2014b) | 53.16 (2012) | 9.30 (2012) | 0.16 (2012) |
| $CO_2$ emissions (Mt of $CO_2$) * (International Energy Agency, 2014b) | 1.84 (2013) | 32.14 (2013) | 10.64 (2013) |
| Unemployment Rate (International Monetary Fund, 2014) | 4.44 (2013) | [no data] | 6.18 (2013) |
| General Government Net Debt (percentage of GDP) | 65.8% (2013) | 26% (2013) | 38.7% (2013) |
| Population below international poverty line of US$1.25 per day (%) (UNICEF, 2013) | - | - | 43.4 (2007 – 2011) |
| EDI** 2010 (Energy Development Index) | - | - | 0.10 (Rank 68 of 80) |
| **Energy access** (International Energy Agency, 2014a) | | | |
| Population without electricity (millions) | 0 | 0 | 35 |
| National electrification rate (%) | 100% | 100% | 20% |
| Urban electrification rate (%) | 100% | 100% | 60% |
| Rural electrification rate (%) | 100% | 100% | 7% |

* $CO_2$ Emissions from fuel combustion only. Emissions are calculated using IEA's energy balances and the Revised 1996 IPCC Guidelines (International Energy Agency, 2014b).

** The enhanced Energy Development Index (EDI) is a multi-dimensional indicator that tracks energy development country-by-country, distinguishing between developments at the household level and at the community level. In the former, it focuses on two key dimensions: access to electricity and access to clean cooking facilities. When looking at community level access, it considers modern energy use for public services (e.g. schools, hospitals and clinics, water and sanitation, street lighting) and energy for productive use, which deals with modern energy use as part of economic activity (e.g. agriculture and manufacturing). *Countries receive an EDI score between 0 and 1, with 1 indicating the highest level of energy development.* (International Energy Agency, 2014a).

### 1.4.1 Iceland

Iceland is a hotspot of volcanic activity, sitting on top of the Mid-Atlantic ridge, and one of the most tectonically active places on earth. Currently, the installed geothermal electricity generating capacity stands at 665 MWe (National Energy Authority, 2013) and geothermal plants are located mainly in the south-west or far north of the country.

Iceland has a population of around 325,000 people with the majority of the population living in the capital area (Statistics Iceland, 2014). Geothermal energy is used for the most part in space heating or electricity generation, with the remainder being used in such applications as swimming pools, snow melting, fish farming, greenhouses and other industry (National Energy Authority, 2013). Since the 1950s, Iceland has made the transition from being heavily dependent on fossil fuels to producing the majority of its energy from domestic, renewable resources. In 2013, around 99% of electricity produced in the country was from domestic and renewable energy resources, with approximately 29% of total electricity production from geothermal energy (National Energy Authority, 2013). In 2012 around 70% of gross energy consumption was from geothermal sources, with the largest proportion used for space heating, and in total around 87% of gross energy was produced domestically (Statistics Iceland, 2014). Forecasts for geothermal energy use predict an increase of 1.4% per year until 2030, with space heating, as before, taking the largest share of the total usage (Orkustofnun, 2003).

Currently there is no overarching energy policy in Iceland, although an energy master plan (Rammaáætlun) is in place (Ministry for Environment and Natural Resources, 2014). The master plan identifies eighty different development options for hydropower and geothermal power plants. The options have been listed and analyzed by expert groups, taking into account impact on nature, impact on economic sectors such as tourism and agriculture and socio-economic impact, as well as cost effectiveness of each option. The sites have been categorized as either acceptable for development, subject to further research or protected. The master plan has been accepted by the Icelandic Parliament and is currently in its third phase of analysis.

Although in Iceland geothermal energy originally acted as a replacement for fossil fuels, nowadays, Iceland has the highest ecological footprint (EF) in the world (Jóhannesson, 2010 as cited in Olafsson et al., 2014), belying the notion that the use of renewable energy automatically leads to national environmental sustainability. Around 80% of elecricity in Iceland is consumed by industry with 68% of total electricity produced being consumed by the aluminium industry (National Energy Authority, 2013). In 2010, 46.3% of Iceland's total $CO_2$eq emissions came from metals, in particular, aluminium reduction, in contrast to the 5% of total emissions that were emitted from geothermal sources (United Nations, 2009). In 2011, a total 16,900 GWh/a of power was used, supplied by the country's geothermal and hydropower resources. A further 13,100 GWh/a were available to exploit under the current master plan with another 9,100 GWh/a in the category awaiting further research (Stýrihópur um mótun heildstæðrar orkustefnu, 2011).

If in the future more energy is to be supplied to energy-intensive industry, further agressive exploitation of geothermal resources is likely. For energy needs this large, it would be necessary to simultaneously exploit numerous geothermal resources to power one smelter alone. However the productive operative lifespan of these geothermal fields, if exploited, is uncertain and each field is different. It is commonly recommended that geothermal resources be developed in steps, so that the resource capacity and behaviour can be determined, otherwise the developer risks prematurely depleting the resource to levels where the initial rate of production cannot be maintained, which can result in difficulties in meeting energy demands. Such has been the case at the Hellisheiði plant (Gunnarsson, Arnaldsson & Oddsdóttir, 2011), the largest geothermal combined heat and power plant in Iceland. Once a geothermal resource has been depeleted, it may take decades or centuries to replenish the natural energy flow (O'Sullivan, Yeh & Mannington, 2010; Pritchett, 1998), which means that the sustained yield of the resource may become compromised.

## 1.4.2 New Zealand

The country of New Zealand is comprised of two main islands with geothermal energy sources mainly on the North Island. Currently geothermal generation capacity stands at around 750 MWe. Six geothermal fields are currently in use, with most installed capacity within the Taupo Volcanic Zone. In Northland, there are 25 MWe installed at Ngawha (New Zealand Geothermal Association, 2009).

New Zealand has a population of around 4.5 million people, of which around 15% are indigenous Maori people. New Zealand is the country with the third highest renewables percentage of total primary energy supply (38%) in the OECD, Iceland having the highest (85%) and Norway (47%) the second highest. In 2013, 75% of electricity generation was from renewable sources. Geothermal energy makes up over half of the renewable energy supply in New Zealand and produces 14.5% of the country's electricity (Ministry of Business, Innovation and Employment, 2014b). By 2030, geothermal resources are predicted to be able to contribute at least 900 MWe of additional capacity, the equivalent to more than seven years of demand growth (Ministry of Economic Development, 2007). In all energy forecasts, the share of geothermal is shown to increase from 14% in 2012 to between 21% and 29% in 2040 (Ministry of Business, Innovation and Employment, 2013).

New Zealand has a unique regulatory framework for the management of natural resources, including geothermal resources, which consolidates most of its environmental legislation into a single statute, the Resource Management Act (1991). As well as this, the government has put in place a number of policies that aim for an increase in renewables and increasing efficiency. In New Zealand, the vast majority of the geothermal resources are managed by two regional councils, Waikato and Bay of Plenty.

Geothermal resources are of high importance to Maori in New Zealand, who still use geothermal resources for cooking, preserving, healing, ceremonial and bathing purposes. The Maori have their own approach to resource management and the Maori concepts of "Kaitiaki" (guardians) and "Kaitiakitanga" (stewardship) have been incorporated to some extent into legislation in New Zealand, particularly the Resource Management Act. As well as referring to stewardship, *Kaitiakitanga* also refers to the intergenerational and spiritual responsibility of all people to care for the environment by protecting the life supporting capacity of resources (Ministry for the Environment, 2010).

In New Zealand, the protection of geothermal resources has been incorporated into law, through the country's comprehensive legal framework for resource management. Plans to expand geothermal direct use and generation capacity are in place, to help increase energy security, replace fossil fuels and meet renewable energy targets (Ministry of Economic Development, 2011), however, expansion will only take place in certain geothermal fields, as some are classed as protected. There is only an estimated 1000 MW of geothermal energy that can be exploited in the future (Harvey & White, 2012). The majority of energy in New Zealand is consumed by the transport and industrial sectors (Ministry of Business, Innovation and Employment, 2014a). In 2012, Tiwai Point aluminium smelter counted for 13% of electricity demand, but the future of heavy industries like wood processing or aluminium production in New Zealand is uncertain and economic growth is expected to occur in less energy intensive sectors in the future (Ministry of Business, Innovation and Employment, 2013). Without long production histories, it is generally difficult to predict how long geothermal resources will last for electricity generation

(Gunnarsson, Arnaldsson & Oddsdóttir, 2011). Reflecting this, geothermal resource availability and cost, and the future of heavy industry, such as aluminium smelting, are cited as some of the key uncertainties for future electricity supply and demand in New Zealand (Ministry of Business, Innovation and Employment, 2013).

### 1.4.3 Kenya

Kenya's geothermal resources are located along the Rift Valley that runs through the country from north to south. In 2015, installed geothermal capacity for electricity generation stood at around 587 MWe[1], soon to be increased with the addition of new power plants (Ogola, 2015).

Kenya has an estimated population of 45 million people (CIA, 2014), with only around 23% of the population having access to electricity (Government of Kenya, 2011). Electricity accounts for only 9% of total primary energy consumption. The majority of the population relies on traditional or non-commercial fuels, such as wood fuel or biomass, which make up around 68% of total primary energy consumption (Omenda, 2012). Around 50% of electricity in Kenya is currently generated from hydropower sources, with geothermal sources contributing around 13% to the total electricity supply (Omenda, 2012). So far, developments have taken place in the Olkaria, Eburru and Menengai fields. The Rift Valley is an environmentally and culturally fragile region, home to a number of wildlife parks that draw many tourists (Mariita, 2002). The Olkaria Geothermal Project is located within the boundaries Hell's Gate National Park and near to Lake Naivasha, a Ramsar site. Geothermal resources of Eburru and Menengai are located within forest reserves (Mwangi-Gachau, 2012).

Geothermal energy is currently used mainly for electricity production in Kenya, but other uses are foreseen, with potential to aid climate change mitigation and adaptation strategies (Ogola, Davidsdottir & Fridleifsson, 2012). Current policies are mainly focussed on using energy to rapidly stimulate economic development, as Kenya urgently seeks to connect more households to the grid. The Kenyan government has the ambitious target of expanding geothermal generation capacity by an additional 5,000 MWe of electric power by the year 2030.

Around one fifth of the Kenyan population is pastoralist. Pastoralist communities are found in arid and semi-arid areas and live primarily by raising livestock, such as small ruminants, cattle and camels. These areas have variable rainfall and as a result the distribution of water resources and animal grazing areas is uncertain, yet pastoralists have adapted to these conditions by developing management systems based on strategic mobility. Such isolated, remote and underdeveloped areas are often conflict prone, lacking in food security, with little service provision and lower than average health and education standards (African Union, 2010). With the development of geothermal power, conflicts may arise over differing land and water uses in arid and semi-arid areas. For instance, land-related conflicts may arise between pastoralists and developers, as has happened in

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[1] Olkaria I (Old) 45 MW, Olkaria I Unit 4&5 (New) 140 MW, Olkaria IV Unit 1 &2 (New) 140 MW, Olkaria II 105 MW, Geothermal Well heads 45.7 MW, ORMAT (IPP) 108 MW, Oserian (IPP) 3.4 MW

Hell's Gate national park, ancestral Maasai land, with the construction of geothermal power plants and large scale flower farms on what are now government-owned lands (Mariita, 2002). The Maasai believe that land is a resource meant to support the human race and therefore should not be owned or sold as private property (Mariita, 2002). The need for stakeholder engagement when developing geothermal resources in Kenya has been demonstrated in recent years at Olkaria, where the power company, KenGen, had to implement a resettlement action plan to deal with the relocation of four Maasai villages (Mwangi-Gachau, 2011).

Kenya's Vision 2030 covers economic, social and political development, in particular, the goal for the social pillar is "a just and cohesive society enjoying equitable social development in a clean and secure environment" (Government of the Republic of Kenya, 2007). Achieving prosperity in Kenya will involve fulfilling the Millenium Development Goals (MDGs), which are goals for socio-economic development including the elimination of extreme poverty and hunger; the provision of universal primary education; gender equality; the reduction of child mortality; the improvement of maternal health; the lowering of HIV/AIDS and major disease incidence and the acheivement of environmental sustainability. However, to meet energy demand, various sources of energy, including fossil fuel, will be developed to achieve the vision's objectives. In the latest medium term plan the development of oil and other mineral resources is now included among the priority sectors, following the discovery of oil in commercial quantities in Kenya, as well as substantial deposits of coal, iron ore and rare earth minerals (Ministry of Devolution and Planning, 2013). Whilst developing geothermal energy resources are generally considered to be more benign than fossil fuels and have a positive impact by helping in the fulfillment of some of the Millienium Development Goals (Ogola, Davidsdottir & Fridleifsson, 2011), it may also result in unforeseen impacts in other areas (Shortall, Davidsdottir & Axelsson, 2015a).

The Kenyan government plans to harness the abundant high temperature geothermal resources found in the Rift Valley region. It has been estimated that over 10,000 MWe can potentially be exploited and there are plans to rapidly expand geothermal generation capacity up to 5,000 MW by the year 2030. This rapid expansion may potentially compromise long term extraction or sustainable yeild, and whilst it will add much needed power to the grid, other sustainability implications for power developments on this scale are likely to be considerable. Kenyan geothermal resources are located in an environmentally and culturally sensitive area. The additional electricity demand is predicted to come from households but also from manufacturing and other industries stimulated by the economic mulitiplier effect. The negative impacts that industrial development, horticulture and agricultural practices have had on the water levels and ecology of Lake Naivasha serve as a cautionary example of how increased economic activity may not always lead to sustainable outcomes (Awange et al., 2013). Further socio-economic impacts may arise increased migration to urban centers (Ogola, Davidsdottir & Fridleifsson, 2011) and further land-use and livelihood conflicts involving local Maasai are also a possibility (Mariita, 2002).

## 1.5 The Importance of Stakeholder Engagement

*"Disagreement is something normal"*
Dalai Lama

Stakeholders are generally defined as "persons or groups who are directly or indirectly affected by a development project, as well as those who may have interests in a project and/or the ability to influence its outcome, either positively or negatively" (International Finance Corporation, 2007). Stakeholder engagement is described as "the process used by an organization to engage relevant parties for a clear purpose to achieve accepted outcomes" (UK Institute of Social and Ethical Accountability, 2011) and is now also regarded as a type of accountability mechanism. Stakeholder engagement is important in developing tools for assessing sustainability since there tends to be an absence of scientific consensus on the components of sustainable development. As well as this, conditions for defining sustainable development tend to be context-specific and depend on the values of current as well as future human societies. The diversity of frameworks already available suggests an uncertainty or differences regarding the measurement of sustainable development in different regions or in different groups (Pinter, Hardi & Bartelmus, 2005; Meadows, 1998). Stakeholder engagement techniques have been used to address sustainability issues in diverse sectors, including mining (Azapagic, 2004), forestry (Sharma & Henriques, 2005), transportation (Mihyeon Jeon & Amekudzi, 2005), aviation (Amaeshi & Crane, 2006) and environmental management (Reed, 2008).

Developing indicators in collaboration with stakeholders can also result in indicators that are regarded as more salient, credible and legitimate (Cash et al., 2002), since they will be created drawing on both expert and grassroots knowledge and have a higher degree of consensus. As well as this the procedures used to create the indicators will be more likely to be viewed as fair and respectful of multiple viewpoints. Ideally, indicator selection works best with grassroots and expert participation, but this must be done carefully. Any indicators that have been chosen to assess sustainability should be rigorously checked by a panel of experts (Meadows, 1998). Sustainable development is a dynamic state, therefore stakeholder input will always be necessary in the assessment process to ensure that the most relevant issues are to be assessed for a given project. In order for stakeholder enegagement programs to be successful, they must clearly define the scope of the issue to be addressed, include an pre-approved decision making process, focus on stakeholder-relevant issues, encourage dialogue, use culturally appropriate methods, and be transparent, timely and adaptable (UK Institute of Social and Ethical Accountability, 2011).

Sustainability is transdisciplinary field, which requires knowledge of the social, economic and environmental impacts of a development. Yet often stakeholders from different fields have little interaction with each other, or little knowledge of other´s fields. In geothermal energy development, this is also the case. The wide-ranging topic of geothermal sustainability therefore requires the combined expert input of a varied group of experts or concerned parties, obtained by using an appropriate stakeholder engagement technique. For a geothermal project, stakeholders may include local communities, the geothermal industry, government authorities (local, regional or national), political and/or religious leaders, non-governmental organisations, academics, or other businesses, such as suppliers or those that may use the geothermal power.

# 1.6 Summary of Methods and Results

This section provides a summary of the research questions and methods used in each paper, as well as the resulting contribution to scientific knowledge, both practical and academic. A book chapter, which uses the same methods as described in the papers, is also summarized.

## 1.6.1 Paper I

Shortall, R., Davidsdottir, B. & Axelsson, G. (2015). Geothermal Energy for Sustainable Development: A Review of Sustainability Impacts and Assessment Frameworks. *Renewable and Sustainable Energy Reviews 44*, 391–406.[2]

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The first paper is motivated by the fact that until now, no framework exists that enables formal assessment of the sustainability of geothermal energy development and use. As geothermal energy usage is set to increase substantially in the future, it is important to ensure that geothermal exploitation is developed in a sustainable manner. Furthermore, the international community has called for the development of assessment tools or indicators to measure progress towards sustainable development.

The main research questions addressed by this paper are:

1. What are the most important issues of concern whilst assessing the sustainability of geothermal energy projects?
2. Can currently available assessment frameworks be used to assess geothermal projects?
3. Why is there a need for assessing sustainability in the geothermal energy sector and for the creation of a formal sustainability assessment protocol?

The paper therefore systematically reviews the unique multidimensional impacts of geothermal energy projects, grouping them into sustainability themes, using the CSD's thematic framework as a guideline, and demonstrates the need to create a customized framework to help correctly manage these impacts. The available sustainability assessment tools for energy developments, such as the IAEA Energy Indicators of Sustainable Development (EISDs) or the Sustainability Assessment Protocol of the International Hydropower Association (IHA-SAP) are also reviewed in order to determine the best structure for a geothermal sustainability assessment framework. Results of the review of literature on geothermal developments in many different countries show that the environmental and socio-economic impacts of geothermal developments can be substantial, varied and unique. Current literature tends to focus solely on the environmental impacts of geothermal development. This paper is therefore novel, as it acts

[2] The role of the doctoral student (Ruth Shortall) in this paper was to carry out all of the research activity. Dr. Brynhildur Davidsdottir and Dr. Guðni Axelsson guided the doctoral student during the research activity and writing process.

as a useful systemic reference on the multidimensional impacts of geothermal developments for decision-makers, which is useful in formulating policies towards sustainable geothermal resource management.

With regard to currently available assessment tools, it is found that although several frameworks exist for assessing the sustainability of energy projects generally, none of them are in themselves suited to assessing the unique aspects of geothermal development and thus a new assesment tool needs to be developed. The assessment frameworks reviewed in this paper, provide some basis for developing a new tool and can be built upon for this purpose. This paper contributes to existing knowledge by identifying the advantages and shortcomings of currently available assessment tools and also lays the foundation for the creation of a fully-fledged sustainability assessment framework for geothermal energy projects, which are further developed in subsequent papers.

### 1.6.2 Paper II

Shortall, R., Davidsdottir, B. & Axelsson, G. (2015). A Sustainability Assessment Framework for Geothermal Energy Projects. *Energy for Sustainable Development 27* ,28-45. Elsevier. [3]



The second paper is motivated by the need for a sustainability assessment tool specifically for geothermal energy projects, as identified in the first paper. The paper illustrates the first iteration of the process and methods used in establishing a stakeholder-qualified indicator framework, with a highly organized participatory process, through a case-study in Iceland.

The research questions addressed in this paper are:

1. What is an appropriate structure for an assessment framework for geothermal energy projects?
2. What steps are needed to develop an assessment framework for geothermal energy projects?

A sustainability assessment framework consists of a set of sustainability goals and indicators that allow monitoring of geothermal projects during their entire life cycle. Initially an extensive literature review of the impacts of geothermal energy projects on sustainable development was carried out (Paper I) in order to identify the most important sustainability issues in geothermal energy developments. Based on the review of the available assessment tools in Paper I, the most suitable structure for the framework was also decided upon. An initial set of potential goals and indicators was established by the authors, providing a starting point for seeking stakeholder input later in an iterative process with the intention of carrying out iterations in a number of different geographical locations.

[3] The role of the doctoral student (Ruth Shortall) in this paper was to carry out all of the research activity. Dr. Brynhildur Davidsdottir and Dr. Guðni Axelsson guided the doctoral student during the research activity and writing process.

The system boundaries of the assessment framework were conceptualized within the dimensions of sustainable development (social, environmental, economic) and then further broken down into a number of sustainability themes, guided by the sustainability themes of the CSD. These themes guided the classification of sustainability issues relating to geothermal development in the literature review. Stakeholders were selected to take part in the indicator development process via a pre-engagement World Café workshop and online Delphi survey. The stakeholder group consisted of participants from diverse backgrounds, from government to industry to NGOs.

The World Café workshop technique was used as a starting point or pre-engagement method for this Icelandic case-study. The purpose of this workshop was to present the research project to the stakeholder group, informing them of their role in the process; as well as to elicit an initial response to a list of sustainability indicators only during the literature review period. The responses of this stakeholder group would then be incorporated into a more in-depth engagement process in the form of a Delphi survey. Participants voted and commented on a list of indicators during the workshop. For convenience, the indicators were divided into three dimensions: Environment, society (including institutional indicators) and economy. The classification of impacts into these dimensions was not continued throughout the rest of the research, since the use of themes similar to those of the CSD was preferred.

The Delphi technique was deemed the most appropriate method to use in this study in order to elicit knowledge from a group of stakeholders with widely divergent opinions or backgrounds, using a structured communication and feedback format. A Delphi survey was carried out with the Icelandic stakeholders consisting of three rounds in total. A diverse group of Icelandic stakeholders, as well as some international stakeholders from the United Nations Geothermal Training Program, were chosen from various sectors to take part.

In Round 1, participants were presented with an initial set of indicators and asked to rate and comment on each one. In this instance, indicators had already been suggested in the pre-engagement workshop as a starting point for the Delphi survey. Stakeholders were asked to suggest sustainability goals themselves in Round 1. Participants were also given the opportunity to suggest new indicators in the comments section. After Round 1, the facilitators modified the list based on their own judgement, item scores and synthesized comments. Comments on reference values or perceived relevance of indicators were taken into account. New goals and indicator suggestions were also incorporated into the modified list. In Round 2 and 3, participants were requested to rate the modified list and make comments if they desired. After each round, the facilitators modified the list as before. After Delphi Round 3, the final indicator list was taken to represent the collective opinion of the participants on the most appropriate goals and indicators. Scores were allocated by participants on a scale of 1-5 according to the perceived relevance of the sustainability goal or indicator.

Guiding principles known as the Bellagio STAMP principles were incorporated into the entire development process. An initial set of sustainability goals and indicators are produced as a result of this first iteration with the stakeholders.

The stakeholder engagement process had a very good level of participation, with representatives from diverse sectors, including the energy industry, non-governmental organisations, government, academia and businesses, taking part. The results provide insights into Icelandic stakeholder views, as well as their level of knowledge, on sustainability issues relating to geothermal energy projects. Notably, environmental and economic indicators were regarded as more relevant than social or institutional indicators in the pre-engagement workshop, which produced in total 38 indicators as a starting point. Subsequently, the Delphi survey revealed the top three priority sustainability goals for Icelandic stakeholders as renewability, water resource usage and environmental management, with the top five indicator choices (which relate to resource reserve capacity, utilization efficiency, estimated productive lifetime of the geothermal resource and air and water quality) reflecting these goals. Conversely, the bottom three sustainability goals related to energy efficiency, energy equity and energy security and the the bottom five indicator choices related to average income in project-affected communities, the project EBITDA ratio, household expenditure on energy, company R&D expenditure, and the percentage of renewables in the national energy supply. The number of indicators reduced from 38 at the beginning of the Delphi down to 24 at the end of the third Delphi survey round. Response rates also decreased between the first and last Delphi survey rounds.

The results of implementing the methods illustrated in this paper are of practical value for policy and decision-makers wishing to carry out indicator development through a participatory process. The action of involving stakeholders in the indicator development process can lend additional political credibility to the information that is produced for monitoring policy progresses, as well as facilitating the exchange of more relevant information between scientists and policy-makers or the general public. By documenting the experiences of the indicator development process, this paper contributes to knowledge on indicator development by introducing an innovative process that incorporates and builds on elements of internationally recognised frameworks using comprehensive stakeholder engagement techniques. The results of this study also provided insight into how the process could be improved in subsequent iterations (Paper III). This first iteration of the process was a starting point for the further development of an assessment framework for geothermal development in other countries. Further iterations (Paper III) were later carried out in Kenya and New Zealand to further refine the indicator set and reveal its suitability in these regions.

### 1.6.3 Paper III

Shortall, R., Davidsdottir, B. & Axelsson, G. (2015). A Sustainability Assessment Framework for Geothermal Energy Projects: Development in Iceland, New Zealand and Kenya. *Renewable and Sustainable Energy Reviews 50,* 372-407. Elsevier. [4]



The third paper builds on the first and second papers, by completing the indicator development process through case studies in three countries: Iceland, New Zealand and Kenya with extensive stakeholder engagement.

[4] The role of the doctoral student (Ruth Shortall) in this paper was to carry out all of the research activity. Dr. Brynhildur Davidsdottir and Dr. Guðni Axelsson guided the doctoral student during the research activity and writing process.

This paper describes the entire process of developing a sustainability assessment framework for geothermal energy projects in the three countries. Three iterations of the indicator development process were carried out in total. Each iteration constitutes a separate, yet interconnected, case study. Using the methods outlined in detail in the second paper, as well as insights gained from implementing the first iteration, this study continues the iterative indicator development process through further case studies in New Zealand and Kenya. A set of sustainability goals and indicators were produced to form an assessment framework for geothermal energy projects that has been critically evaluated by a wide range of stakeholders.

The results highlight the importance of including diverse stakeholder views when developing assessment frameworks. A significant diversity of opinion was observed between stakeholder groups. For instance, with regard to goals of sustainable geothermal developments (Appendix A), environmental management was a common concern among the Icelandic, New Zealand and Kenyan participants, whereas water usage was considered the most important environment-related issue for the UNU-GTP fellows, which may be due to the fact that participants come from water scarce countries. The Kenyan, New Zealand and the UNU-GTP groups rated economic management and profitability, along with research and innovation, highly, whereas the Icelandic group placed highest emphasis on resource renewability and also rated knowledge dissemination highly. The Icelandic focus on renewability may be due to recent cases relating to the management of certain geothermal plants in the south of Iceland, that has led to reduction in energy production. The results of the Delphis survey showed a definite increase in the level of consensus among the participants by the end of the third round.

The indicator choices (Appendix B and C) of each group also varied, but it was found that the stakeholder groups regarded some of the indicators as universally relevant (common or core indicators), leaving a subset of indicators that were only considered relevant by some groups. It was decided that the indicators in this subset should be considered as optional indicators, to be used at the discretion of the end-user. These indicators have potential relevance, depending on the circumstances. More optional indicators could be produced in the future, with further stakeholder input, in particular in the light of new knowledge on goethermal sustainability issues. The indicators were found to adequately cover the sustainability goals chosen by the stakeholders, in that all of the goals had at least one corresponding indicator, and indicators were also found to cover the CSD sustainability themes as outlined in Paper I.

The methods illustrated and tested in this paper are of practical value to policy and decision-makers in the context of developing indicators using a participatory process. The action of involving stakeholders in the indicator development process can facilitate the provision of more plausible and relevant information between scientists and policy-makers or the general public. As well as this, given that it has been qualified and evaluated by a diverse range of international stakeholders, the framework can be said to have increased political credibility in the eyes of the public, since it merges different societal and political norms.

In terms of its academic contribution, by documenting the experiences in three different countries of the stakeholder-driven indicator development process, this paper not only contributes to academic knowledge on the methods of development of indicators of energy sustainability in general, but also regarding their development across national borders and cultures, which is increasingly acknowledged as a necessity in this field. When its coverage is compared to other known similar frameworks, it provides evidence of the need to consider and incorporate a diversity of opinion when measuring sustainability progress and therefore the need for more advanced and inclusive forms of local stakeholder engagement methods in all types of development projects.

### 1.6.4 Book Chapter

Shortall, R., Axelsson, G. & Davidsdottir, B. (In Press) Assessing the Sustainability of Geothermal Utilization. In J. Dewulf, S. De Meester, R. Alvarenga (Eds.) *Sustainability Assessment of Renewables-Based Products: Methods and Case Studies.* Wiley. [5]

While much has been written about sustainable geothermal utilization, renewability and sustained yield of energy resources are generally agreed to be necessary, but not sufficient, requirements for sustainable energy development. A broader viewpoint must be adopted to account for the wider social, economic and environmental implications of geothermal energy developments. This book chapter aims to introduce a multi-dimensional sustainability assessment framework for geothermal energy.

The chapter introduces the concept of sustainable energy development and the place of geothermal energy within this paradigm. The concept of sustainable geothermal utilization is introduced from a technical perspective and the issues of sustainable production or yeild and timeframes are discussed. Case histories of geothermal resources with long production histories are presented to illustrate the behaviour of geothermal resources in response to exploitation over time. Techniques for simulating the main features in the structure and nature of geothermal systems and their response to production is also explained. The necessity for broader sustainability assessment is then argued in the following section, where a multidimensional assessment framework is introduced. The development of the framework, as outlined in papers II and III is described, and the final resulting assessment framework, consisting of sustianability goals and indicators, is presented.

[5] The role of the doctoral student (Ruth Shortall) in this book chapter was to edit and contribute to the parts of the chapter text on the multidimensional assessment of geothermal energy development whereas Dr. Guðni Axelsson contributed to the text on technical aspects of geothermal utilziation, the concept of sustainable geothermal utilization and sustained yield and the case studies. Dr. Brynhildur Davidsdottir edited the entire text and provided guidance for the writing process.

# 2 Paper I: Geothermal Energy for Sustainable Development: A Review of Sustainability Impacts and Assessment Frameworks

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

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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**



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## 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<br>– Increase in salaries<br>– Social development initiatives<br>– Affordable energy supply<br>– Higher living standards<br>– Improved food security<br>– Access to drinking water | – Rising property prices<br>– Community displacement |
| Health | – Improved sanitation<br>– Improved medical facilities<br>– Lower indoor air pollution<br>– Therapeutic uses | – Odor nuisance<br>– Toxic gas emissions<br>– Water contamination risk<br>– Noise pollution |
| Education | – Improved education facilities<br>– Improved school attendance | – Sudden or unprecedented cultural change |
| Natural hazards | | – Induced seismicity<br>– Subsidence<br>– Hydrothermal eruptions |
| Demographics | – Positive social change<br>– Increased tourism | – Negative cultural impacts<br>– Resettlement<br>– Livelihood displacement |
| Atmosphere | – Displacement of greenhouse gas emissions from other energy sources | – Greenhouse gas emissions<br>– $H_2S$ pollution<br>– Toxic gas emissions |
| Land | – Small land requirements relative to other energy sources | – Habitat loss<br>– Soil compaction<br>– Conflict with other land uses |
| Forests | – Replacement of traditional biomass | – Deforestation<br>– Ecosystem loss |
| Freshwater | – Low lifecycle water consumption relative to other energy sources | – Conflict with other energy uses<br>– Contamination of shallow aquifers and other water bodies |
| Biodiversity | | – Habitat loss or disturbance<br>– Loss of rare geothermal ecosystems |
| Economic development | – Increased energy security<br>– Low climate dependence<br>– High capacity factor<br>– 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<br>– Risk of overexploitation<br>– 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 over-exploitation 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.

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# 3 Paper II: Development of a Sustainability Assessment Framework for Geothermal Energy Projects

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# Development of a sustainability assessment framework for geothermal energy projects

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ABSTRACT

With the increasing global energy consumption, geothermal energy usage is set to increase in the future. Geothermal developments may result in both positive and negative environmental and socio-economic impacts. Sustainability assessment tools are useful to decision-makers in showing the progress of energy developments towards sustainability. Due to the unique characteristics of geothermal energy projects, a customized framework for assessing their sustainability is required. This paper presents the development of an appropriate indicator assessment framework, through a case-study in Iceland. The results reveal Icelandic stakeholder views on sustainability issues relating to geothermal energy projects. Environmental and economic indicators were regarded as more relevant than social or institutional indicators. A Delphi survey revealed that the priority sustainability goals for stakeholders were related to renewability, water resource usage and environmental management. The top five indicator choices were related to resource reserve capacity, utilization efficiency, estimated productive lifetime of the geothermal resource and air and water quality.


## Introduction

### Geothermal energy and sustainable development

Energy usage worldwide is increasing. It has been predicted that global energy will increase by over one-third by 2035 and fossil fuels are still dominating the global energy mix (International Energy Agency, 2012), but the use of alternatives such as geothermal energy is set to increase, since the world has only a finite supply of fossil fuels. Furthermore, in order to combat climate change and fulfill international agreements, low carbon energy sources such as geothermal energy are now being tapped on a larger scale. 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 (Intergovernmental Panel on Climate Change, 2012).

While energy is needed for economic growth and sustainable development, energy development also has environmental and social impacts. Like any other energy source, geothermal energy developments can result in positive as well as negative socio-economic and environmental impacts (UNDP, 2002). For example, geothermal projects can result in socio-economic benefits particularly in developing countries and rural communities by improving infrastructure, or stimulating local economies. They can also act as a good source of base-load power for a region's energy system. However, certain issues need to be addressed as many geothermal energy developments result in negative social or environmental impacts (Shortall et al., 2015).

The wide variety of available sustainability assessment frameworks in existence today highlights the ambiguity surrounding the meaning of sustainability for different user groups, cultures and regions or organizations. As shown by the county pilot studies undertaken using the CSD indicator set, for example, customized indicator sets were often developed to suit local conditions (Pinter et al., 2005). Given the unique issues associated with geothermal energy projects, a specialized assessment tool is required to ensure that geothermal projects will be properly guided into following best practices and result in positive impacts in all sustainability dimensions: environmental, social and economic.

### Objective

The purpose of this paper is to

1. Review the literature on means of developing sustainability indicators for energy developments.
2. Describe the steps needed to develop an assessment framework for geothermal energy projects, with highly organized participatory processes, through a case-study in Iceland.

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The paper will illustrate the methods used in establishing a stakeholder-qualified indicator framework in the Icelandic context and reflect on the learning process therein. The framework may then be applied in Iceland and elsewhere. The paper concludes with recommendations for the development process of the assessment framework. The Icelandic case study presented in this paper represents the first iteration of the indicator development process. Further iterations are to be carried out in Kenya and New Zealand to further refine the indicator set and reveal its suitability in these regions.

## Background

Many international organizations, such as the United Nations Commission for Sustainable Development (CSD) (Pinfield, 1996), have made case that indicators are needed to guide countries or regions towards sustainable energy development and the necessity of developing sustainability indicators is clearly set out in Agenda 21. There have also been further calls in the literature for the use of sustainability indicators as a means to measure sustainability (Bell and Morse, 2008). Sustainability assessment is a means of showing if development projects contribute to a progress towards or away from sustainability. Sustainability assessments are used for many different types of projects, including energy developments. Various assessment tools, many of which involve the use of sustainability indicators, exist from the national level, to the local level (Pinter et al., 2005). Such indicators must provide a holistic view of sustainability, and thereby include all sustainability dimensions. Furthermore, as well as indicators, sustainability criteria or goals are also important for sustainability measurement. Such criteria and indicators should not be rigid but take account of the local context as well as changes in opinions over time (Lim and Yang, 2009). In order to ensure this, broad stakeholder engagement is an essential part of the indicator development process (Fraser et al., 2006).

Assessment frameworks range from overarching guidelines, such as the Bellagio STAMP principles to specific sustainability indicator development approaches, such as the Pressure-State-Response (PSR)/Driving Force-State-Response (DSR) framework or the theme based approach (Shortall et al., 2015). The most widely used development approach, especially for national indicator sets, is theme-based. In such frameworks, indicators are grouped according to sustainability issue-areas or themes, which are chosen based on their policy-relevance. Theme-based indicator sets allow decision-makers to link indicators to policies or targets (United Nations, 2007). While the various impacts of geothermal projects have been discussed in depth by the authors (Shortall et al., 2015), some examples of unsustainably management of geothermal clearly illustrate the need for better sustainability monitoring systems.

The Hellisheidi geothermal power plant is the largest combined heat and power plant in Iceland. Turbines were brought online in a series of phases between 2006 and 2011. Decisions on how large the Hellisheidi Power Plant should be were made before enough steam had been proved by drilling. No production data was available and therefore the decisions were based on the initial state of the reservoir alone. By 2040, the draw down and cooling of the geothermal field will most likely render production uneconomic, leaving the resource with a total productive lifetime of only 34 years. A total of 66 production wells will need to be brought online by the end of 2040 (Gunnarsson et al., 2011). In the Icelandic context, this is at odds with the acceptable resource lifetime of at least 100–300 years (National Energy Authority, 2010). It is predicted that pressure will return in 60–80 years if all production is terminated by 2040, but temperature could take up to 1000 years to recover. This could have been avoided by using more appropriate resource management strategies (Gunnarsson et al., 2011).

A further example of unsustainable management can be seen with the Wairakei power plant in New Zealand where separated geothermal water and cooling water are discharged into the section of the Waikato river between Lake Taupo and Ohaaki Bridge (Ray, 2001). The arsenic level in the Waikato River has more than doubled since the station opened in the 1950s and now exceeds drinking water standards (Waikato Regional Council, 2012).

In Iceland, assessment of the impacts of geothermal projects on sustainable development is mainly limited to the pre-development phase. An energy Master Plan has been proposed in Iceland that ranks the desirability of potential energy projects according to a number of environmental, social and economic criteria. Environmental impact assessments are done for proposed geothermal projects, as for any major development, yet the outcome of these assessments can vary significantly. While routine environmental monitoring is carried out by various agencies nationally, no specific requirements to monitor the environmental, social and economic impacts of geothermal projects are currently specified in legislation for the sustainable management of geothermal projects.

### *Sustainability indicators and energy*

As has been illustrated (Shortall et al., 2015), the impacts of geothermal energy developments have significant implications for sustainable development, and require specific monitoring tools to ensure the impacts are managed in a sustainable manner. Several indicator frameworks exist to measure sustainable development in the context of energy developments. While they are not all suited to assessing geothermal projects in themselves, they can be used as guidelines to further the development of a framework to assess geothermal energy developments. These frameworks and the methods used to create them are described below. For a more in-depth discussion of such frameworks, please refer to the author's previous work.

#### *International atomic energy agency energy indicators of sustainable development*

In 2005 the International Atomic Energy Agency (IAEA) created a set of energy indicators for sustainable development (EISDs) (International Atomic Energy Agency (IAEA), 2005) 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.

The EISD indicators are intended for use at a national level and cover many different types of energy usage. For this reason, they are unsuited to assessing individual geothermal projects, but their conceptual framework provides some basis for the design of a framework for geothermal energy assessment in particular.

#### *International hydropower association sustainability assessment protocol*

The International Hydropower Association has developed a sustainability assessment tool for hydropower projects (IHA-SAP) (International Hydropower Association, 2006). Although not based on indicators as such, the IHA-SAP assesses various strategic and managerial aspects of proposed or operational hydropower projects (International Hydropower Association, 2008).

#### *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 (The Gold Standard Foundation, 2012). The Gold Standard is an accreditation system for greenhouse gas (carbon dioxide ($CO_2$), methane ($CH_4$) and nitrous oxide ($N_2O$) only) reduction projects, whose eligibility is evaluated under a number of criteria such as the project scale or location (The Gold Standard Foundation, 2012). The Gold Standard indicators are general and therefore not specifically tailored to geothermal projects. As a result, they are not suitable to be used themselves to carry out geothermal assessments, since they do not deal with all of the unique sustainability issues associated with geothermal development projects.

*Other frameworks*

The Commission for Sustainable Development (CSD) provides guidelines for developing national level sustainability indicators, including energy indicators (United Nations, 2007). In the EU, these indicators were incorporated into a monitoring framework, to monitor the implementation of the main EU directives and other policies relating to sustainable energy development (European Commission, 2005).

This framework exists at the national level and is not specific enough and thus not suitable as a geothermal assessment tool, but the themes of the CSD conceptual framework are useful for categorizing geothermal sustainability issues that should be assessed (Shortall et al., 2015). The CSD thematic framework can therefore be taken further by applying additional stakeholder engagement methods to develop indicators for geothermal developments.

The Energy Sustainability Index, developed by the World Energy Council, looks at the impact of energy policies of different countries and ranks them in terms of energy sustainability based on the three dimensions of energy security, social equity, and environmental impact mitigation. The index uses two types of indicator, energy performance indicators, covering supply and demand, affordability and access; and contextual indicators, covering broader issues such as living standards and the economic and political conditions (World Energy Council, 2011). This index uses national-level information for its indicators, therefore is not suited to assessing individual energy projects but nonetheless highlights important issues that should be considered in sustainable energy 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 (WWEA, 2005), 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 (WWF, 2006) 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 (UN-Energy, 2007). However no indicators exist for assessing the sustainability of geothermal power.

## Development method

*Overview of the development process*

A sustainability assessment framework consists of a set of sustainability goals and indicators that allow monitoring of geothermal projects during their entire life cycle.

This section describes the methods used to carry out the first iteration of the indicator development process. Initially an extensive literature review of the impacts of geothermal energy projects on sustainable development (Shortall et al., 2015) was carried out in order to identify the most important sustainability issues in geothermal energy developments. An initial set of potential indicators and goals was established by the authors providing a starting point for which further stakeholder input would be sought later in the process in an iterative process (Davidsdottir et al., 2007) with the intention of carrying out iterations in a number of different geographical locations. Each iteration constitutes a separate, yet interconnected, case study. The purpose of the iterative approach is to allow the progressive refinement of the indicator set following each iteration.

Once the sustainability goals were established, the boundaries of the system that the framework would assess were defined. The system boundaries were conceptualized within the dimensions of sustainable development (social, environmental, economic) and then further broken down into a number of sustainability themes (Shortall et al., 2015). Following the literature review, stakeholders were selected to take part in the development process via a pre-engagement World Café workshop and online Delphi survey. In the pre-engagement workshop, stakeholders rated and commented on the draft list of indicators, presented to them by the authors, which were then reduced in number based on stakeholder input. Some new indicators were also suggested at this stage. Later, in the Delphi survey, this list of indicators was refined further and the draft list of sustainability goals was also reviewed and refined. The refined sustainability goals and indicators were then calculated in a trial assessment, using data from the Nesjavellir geothermal power project. It should be noted that the results of this trial assessment are beyond the scope of this paper. At the end of this process, it was possible to evaluate the indicators for suitability to their purpose using the set of criteria shown in the section on Iterative indicator development method. Guiding principles known as the Bellagio STAMP (Box 3-1) were incorporated into the entire development process.

*Iterative indicator development method*

An iterative approach, shown in Fig. 3-1 (Davidsdottir et al., 2007) to indicator development was chosen because it lends itself well to the trialing of the indicator set in several countries, allowing refinement of the indicators, after each iteration, and to account for regional specificities. This was also intended to reduce country or stakeholder biases, which could arise if stakeholders in only one country were consulted.

The method consists of the following steps, which may be repeated as necessary, in an iterative fashion.

1. Definition of sustainability goals;
2. specification of dimensions;
3. selection of themes and sub-themes;
4. selection of indicators;
5. selection of aggregation function;
6. selection and calculation of weights (if needed);
7. calculation of indicators; and
8. reporting of indicators.

The first four steps of the iterative process (Fig. 3-1) required stakeholder input, which in this case was obtained through pre-engagement "World Café" workshops (World Café workshop section) and the Delphi technique (The Delphi technique section). These methods are explained in detail in the next section.

During the first four steps, following the literature review, the facilitators' personal expert judgment and stakeholder input were used to determine sustainability goals, dimensions and themes and the best and most suitable indicators, using as a guidance the suitability criteria shown below. Once indicators were chosen, they were then calculated in a trial assessment on the existing Nesjavellir geothermal energy project in Iceland. By carrying out trial calculations, issues such as lack of data, the suitability of reference values or responsiveness of the indicator were identified. The indicators were again evaluated for their suitability to their purpose against the following suitability criteria (OECD, 1993; United Nations, 2007):

- clear and unambiguous and able to show trends over time;
- responsive to changes in the environment and related human activities;
- relevant to assessing sustainable development progress;
- provide a basis for international comparisons;
- have a threshold or reference value against which to compare it so that users are able to assess the significance of the values associated with it;

**Box 3-1**
List of Bellagio STAMP principles.

1. Guiding vision
   Assessing progress towards sustainable development is guided by the goal to deliver well — being within the capacity of the biosphere to sustain it for future generations.
2. Essential considerations
   Sustainability assessments consider the following:
   - The underlying social, economic and environmental system as a whole and the interactions among its components.
   - The adequacy of governance mechanisms.
   - Dynamics of current trends and drivers of change and their interactions.
   - Risks, uncertainties, and activities that can have an impact across boundaries.
   - Implications for decision-making, including trade-offs and synergies.
3. Adequate scope
   Sustainability assessments adopt the following:
   - Appropriate time horizon to capture both short and long-term effects of current policy decisions and human activities.
   - Geographical scope ranging from local to global.
4. Framework and indicators
   Sustainability assessments are based on the following:
   - A conceptual framework that identifies the domains that core indicators have to cover.
   - The most recent and reliable data, projections and models to infer trends and build scenarios.
   - Standardized measurement methods, wherever possible, in the interest of comparability.
   - Comparison of indicator values with targets and benchmarks, where possible.
5. Transparency
   The assessment of progress towards sustainable development:
   - Ensures the data, indicators and results of the assessment are accessible to the public.
   - Explains the choices, assumptions and uncertainties determining the results of the assessment.
   - Discloses data sources and methods.
   - Discloses all sources of funding and potential conflicts of interest.
6. Effective communication
   In the interest of effective communication, to attract the broadest possible audience and to minimize the risk of misuse, sustainability assessments:
   - Use clear and plain language.
   - Present information in a fair and objective way, that helps to build trust.
   - Use innovative visual tools and graphics to aid interpretation and tell a story.
   - Make data available in as much detail as reliable and practical.
7. Broad participation
   To strengthen their legitimacy and relevance, sustainability assessments should:
   - Find appropriate ways to reflect the views of the public, while providing active leadership.
   - Engage early on with users of the assessment so that it best fits their needs.
8. Continuity and capacity
   Assessments of progress towards sustainable development require the following:
   - Repeated measurement.
   - Responsiveness to change.
   - Investment to develop and maintain adequate capacity.
   - Continuous learning and improvement.

- theoretically well founded in technical and scientific terms;
- based on international standards and international consensus about its validity to the extent possible;
- lend itself to being linked to economic models, forecasting and information systems;
- use data which is readily available or made available at a reasonable cost/benefit ratio; and
- use data which is updated regularly or adequately documented and of known quality.

The assessment is not designed to result in one final value and weights were not assigned to the indicators in this study, as it was felt that the aggregation of the indicators into one number would result in loss of important insights provided by individual indicators.

*Overarching guidelines: the Bellagio STAMP*

To guide the process of developing a sustainability assessment framework, the principles of the Bellagio group, known as the Bellagio STAMP were used as overarching guidelines. The International Institute of Sustainable Development's Bellagio STAMP principles are a set of guiding principles designed to be applied when improving sustainability assessment systems and have been widely adopted (IISD, 1997). The Bellagio STAMP was developed with the aim of addressing the shortcomings of indicator schemes recognized by the research community; harmonizing indicator sets internationally; and improving co-ordination among measurement and assessment processes (IISD, 2012). The principles are intended to guide the choice and design of indicators, their interpretation and their communication. While the Bellagio STAMP principles seek to promote desirable characteristics of sustainability assessment tools, they do not offer a detailed methodological approach required for the development of an indicator set.

*Stakeholder engagement methods*

The meaning of sustainable development depends on a group or society's opinions and values regarding issues that are important to them. These values will determine which goals should be pursued and what should be measured (Meadows, 1998; Shields et al., 2002). The wide-ranging topic of geothermal sustainability therefore requires the combined expert input of a varied group of experts, obtained by using an appropriate stakeholder engagement technique.

*General description of engagement methods*

Stakeholder engagement is “the process used by an organization to engage relevant parties for a clear purpose to achieve accepted outcomes” (UK Institute of Social and Ethical Accountability, 2011) and is now also regarded as a type of accountability mechanism. In order for stakeholder engagement programs to be successful, they must clearly define the scope of the issue to be addressed, include an pre-approved decision making process, focus on stakeholder-relevant issues,

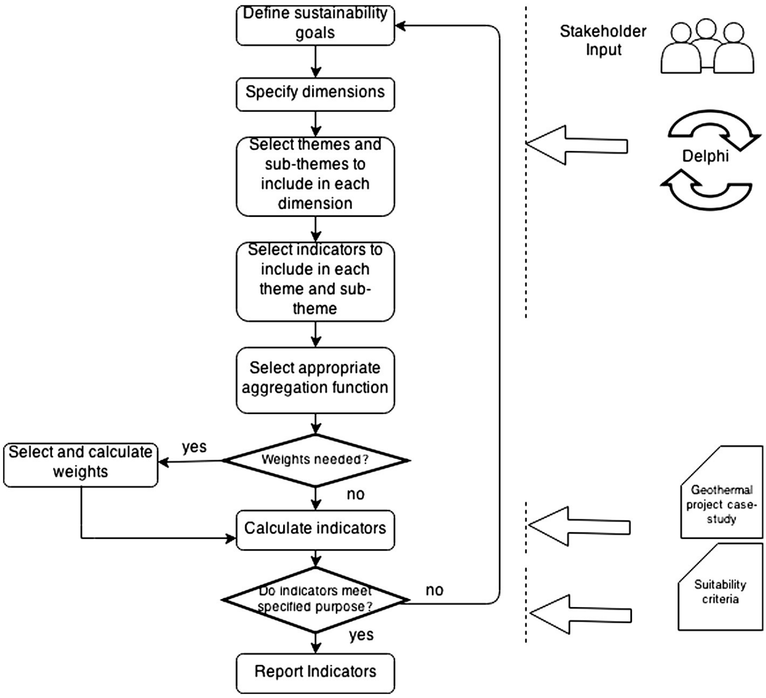


**Fig. 3-1.** Iterative indicator development process.
Diagram modified from Davidsdottir et al. (2007).

encourage dialogue, use culturally appropriate methods and be transparent, timely and adaptable (UK Institute of Social and Ethical Accountability, 2011). Stakeholder engagement techniques have been used to address sustainability issues in diverse sectors, including mining (Azapagic, 2004), forestry (Sharma and Henriques, 2005), transportation (Mihyeon Jeon and Amekudzi, 2005), aviation (Amaeshi and Crane, 2006) and environmental management (Reed, 2008).

*Stakeholder mapping.* Stakeholders are generally defined as “persons or groups who are directly or indirectly affected by a development project, as well as those who may have interests in a project and/or the ability to influence its outcome, either positively or negatively” (International Finance Corporation, 2007). Another definition of stakeholders is as follows:

> Stakeholders are not just members of communities or non-governmental organisations. They are those individuals, groups of individuals or organisations that affect and/or could be affected by an organisation's activities, products or services and associated performance with regard to the issues to be addressed by the engagement.
>
> [UK Institute of Social and Ethical Accountability, 2011, p. 10]

For a geothermal project, stakeholders may include local communities, the geothermal industry, government authorities (local, regional or national), political or religious leaders, non-governmental organizations, academics, or other businesses, such as suppliers or those that may use the geothermal power.

A stakeholder mapping exercise was carried out before the engagement process to identify individuals or organizations that would potentially be impacted by or have an interest or impact in the sustainable operation of geothermal projects. Stakeholders were chosen based on a number of characteristics, as recommended by the Australian government stakeholder engagement practitioner handbook (Australian Government, 2008):

- Responsibility: people to whom a hypothetical geothermal development would have responsibility to, such as the local community or general public, community representatives or NGOs, environmental organizations, local businesses, future generations.
- Proximity: those people who would have most interaction with a hypothetical geothermal project, such as the following: the geothermal industry itself, researchers, governments, local communities.
- Dependency: those who depend directly or indirectly on a geothermal project, such as the following: power companies, financiers, potential users of the energy, the local community, local businesses.
- Representation: those people that represent a constituency impacted by geothermal projects, such as the following: NGOs representing the environment or “voiceless” things such as landscape, geothermal features, delicate ecosystems, forests and so on; indigenous peoples representatives, other community group representatives such as local authorities, trade unions, or local leaders.
- Policy and Strategic intent: those people to whom geothermal projects (or companies) address their policy or value statements, such as the following: NGOs, activists, community groups, financiers.

The chosen stakeholders then interacted in a world café workshop and during a Delphi process.

*World Café workshop.* The World Café is described as “a powerful social technology for engaging people in conversations that matter” and is based on the understanding that conversation is the core process that drives personal, business, and organizational life (Brown and Isaacs, 2005). The method has the advantage of being flexible and easily adapted to suit the needs of the group. Generally, participants meet in a Café style setting, seated at tables where they hold conversations exploring a particular question, moving between tables at prescribed time intervals (Brown and Isaacs, 2005). In this way, the method allows diverse information to be gathered as well as the sharing of ideas and insight. Participants learn collectively, allowing the group to find solutions to the given question, based on their new insights (Brown and Isaacs, 2005).

The disadvantages of using the World Café technique, as for any type of stakeholder group meeting (Thompson, 2007), include the potential for conflict in a group setting, due to differences in opinion of stakeholders. The success of the World Café will depend on the participants present. Furthermore, the cost of organizing and facilitating the workshop may be prohibitive and participants may need to travel long distances to reach the location. Few studies using the World Café method exist in the literature, however the method has, for example, been applied in social science research in order to help develop a culture of enquiry among practitioners in social service (Fouché and Light, 2011). Further examples of its use appear in fields such as nursing (Brooma et al., 2013).

*The Delphi technique.* The Delphi technique is used for policy, decision, and goal setting, when consensus is required from a group of stakeholders with widely divergent opinions or backgrounds (Lim and Yang, 2009). The technique uses a structured format to elicit opinions and potential consensus among a group of stakeholders or experts in their field. As a result, the method has become increasingly popular and widely used in technology, education and other fields (Lim and Yang, 2009), and has been used successfully in developing indicators of sustainability in diverse fields such as road infrastructure projects (Lim and Yang, 2009), ecotourism (Barzekar et al., 2011) and communities (Hai et al., 2009).

For the Icelandic Delphi 70 stakeholders were invited for the survey. This would have been too large a group to facilitate the effective extraction of opinions in a short time frame. It would also have been difficult and costly to arrange repeated face-to-face meetings with the number of people involved. Even though a pre-engagement World Café workshop was organized, it was not possible to arrange similar meetings for all three Delphi rounds. Furthermore, the Icelandic stakeholder group consisted of members of government and other institutions with differing views. Since Iceland is a small community, the Delphi technique was chosen as a way to circumvent political differences that could arise in a group setting.

*Implementation of engagement methods*

As per the recommendations of the Bellagio STAMP (IISD, 2012), a diverse group of stakeholders was selected to contribute to the process of developing the sustainability assessment framework. The group consisted of participants from diverse backgrounds, from government to industry to NGOs. As can be seen from Fig. 3-1, stakeholder engagement is an integral part of the iterative indicator development process. Stakeholders have an influence through their comments during the pre-engagement "World Café" workshop and the Delphi process, from the choice of sustainability goals and indicators (Fig. 3-1). Their input also defines the scope of the assessment itself by identifying the most important sustainability issues that will be considered.

The World Café workshop technique was used as a starting point or pre-engagement method. The purpose of this workshop was to present the research project to the stakeholder group, informing them of their role in the process; as well as to elicit an initial response to a list of sustainability indicators only during the literature review period. The responses of this stakeholder group would then be incorporated into a more in-depth engagement process in the form of a Delphi. Before the workshop, emails were sent to participants with explanatory information, along with a list of indicators that they would be required to comment on. The workshop involved having participants seated in small groups around tables, where they were provided with lists of indicators. They were asked to deal with each indicator on the list systematically, discussing and voting as a group and making comments individually on sheets of paper. Participants voted by show of hands. For convenience, the indicators were divided into three themes: Environment, Society (including Institutional indicators) and Economy. Table hosts were seated at each table and remained at the same table throughout the workshop. Participants were put into groups of 5–6 and moved from one table to the next after each thematic round. Once all participants had covered the three dimensions, the main opinions of each group were presented and discussed as a group. Comment sheets were then gathered from table hosts and participants. The table hosts also took note of the overall opinion of each group for each indicator and noted any prominent discussion topics at each table regarding the indicators. Following the World Café in Iceland, the following steps were taken to refine the initial sustainability indicator set:

- Discard indicators which were voted to have low or no relevance (attempt to have less indicators overall).
- Discard indicators that are hard to understand, even with supplementary information.
- Include new indicator suggestions, if they fulfill the criteria for good indicators.

The Delphi technique was the main stakeholder engagement method used in the study. The main steps taken by the facilitators in the Delphi technique (Linstone and Turoff, 2002; Barzekar et al., 2011; Lim and Yang, 2009) are as follows:

1. Assemble/choose participants.
2. Present list of goals and indicators to be rated and added to by the group through an online survey.
3. Rate and comment on each item.
4. Record each participant's ratings and modify the list based on ratings or comments (may involve adding or eliminating items).
5. Return the statistics to all participants.
6. Rate and comment on items again.
7. Repeat the process (steps 3–6) for three rounds.
8. Select the highest rated goals and indicators (those with the highest mean score) to use in final assessment framework.

The Icelandic Delphi consisted of three rounds in total. In Round 1, the participants were presented with an initial set of indicators and asked to rate and comment on each one. In this instance, indicators had already been suggested in the pre-engagement workshop as a starting point for the Delphi. Stakeholders were asked to suggest sustainability goals themselves in Round 1. The participants were also given the opportunity to suggest new indicators in the comments section. After Round 1, the facilitators modified the list based on ratings and synthesized comments. Comments on reference values or perceived relevance of indicators were taken into account. New goals and indicator suggestions were also incorporated into the modified list. In Rounds 2 and 3, the participants were requested to rate the modified list and make comments if they desired. After each round, the

**Table 3-1**
Scoring system for Delphi survey.

| Score | Relevance |
|---|---|
| 1 | Irrelevant |
| 2 | Somewhat irrelevant |
| 3 | Neither relevant not irrelevant |
| 4 | Somewhat relevant |
| 5 | Extremely relevant |

**Table 4-1**
Types of stakeholders, Iceland.

| Organization type | World Café | Delphi |
|---|---|---|
| Energy industry | 6 | 9 |
| Other business | 5 | 7 |
| Non-governmental | 2 | 2 |
| Government | 7 | 5 |
| Academia | 3 | 10 |
| Total | 23 | 33 |

facilitators modified the list as before. After Round 3, the final list was taken to represent a broader consensus of the participants on the most appropriate goals and indicators. Scores were allocated by participants on a scale of 1–5 (Table 3-1), according to the perceived relevance of the sustainability goal or indicator.

In general, items with a mean score below 3 were discarded. Items with a low score but high standard deviation were resubmitted to the next round if there was evidence that more information or a modification could result in a different score.

Indicators were discarded if they clearly did not fulfill the criteria for good indicators, e.g. if there was a difficulty finding a reference value for them, for example, with newly suggested indicators, or if they were unsuitable in the opinion of the facilitators (e.g. not clearly understandable to the general public, or clearly missing the point of the exercise). For example, there was no reference value for the total number of cases lost in the Supreme Court by the energy company per year. The same was true for the area of land used due to geothermal energy project. The indicators for odor experience from $H_2S$ gas and acidifying air pollutants were discarded because stakeholders considered these issues to be covered already by the air quality indicator.

## Results

The stakeholder engagement process was designed according to the Bellagio principles (Box 3-1), in order to obtain as diverse a range of views as possible regarding the choice of sustainability goals and indicators. The results of the stakeholder engagement process for the Icelandic iteration of the indicator development process are described below.

### *Stakeholder participation*

The group of stakeholders listed in Table 4-1 agreed to take part in the indicator development process in Iceland.

### *Pre-engagement workshop (World Café)*

Although time was a limiting factor for the workshop, the participants still managed to provide insightful comments on many of the indicators presented to them by the authors, which helped the facilitators to refine the list further before the Delphi process. Results of group voting and comments on the individual indicators are presented in the Appendix A. The economic indicators received quite high votes overall (Appendix A). Comments suggested that economic costs and benefits for the project-affected community should be measured by the indicators, with less emphasis on the financial performance of the energy company. Measures of economic diversity such as the Hackman index or Shannon–Weiner index were not understood by most stakeholders.

**Table 4-3**
Sustainability goals with scores after each Delphi round.

| Goal | Score after Round 2 | Score after Round 3 |
|---|---|---|
| Goal 1 — Renewability | 4.72 | 4.55 |
| Goal 2 — Water resource usage | 4.68 | 4.09 |
| Goal 3 — Environmental management | 4.65 | 4.45 |
| Goal 4 — Efficiency | 4.18 | 3.64 |
| Goal 5 — Economic management & profitability | 4.12 | 4.09 |
| Goal 6 — Energy equity | 4.04 | 3.64 |
| Goal 7 — Energy security & reliability | 4.12 | 4.00 |
| Goal 8 — Community responsibility | 4.5 | 4.00 |
| Goal 9 — Research and innovation | 4.4 | 4.18 |
| Goal 10 — Dissemination of knowledge | 4.4 | 4.27 |

The indicator measuring the difference between change in average national and municipal house prices and income levels was also unclear to some people. The institutional indicators (Appendix A) achieved few votes overall. Comments generally questioned the relevance, clarity or methods of the institutional indicators and called for less R&D indicators. The comments suggested that almost all of the environmental indicators (Appendix A) were considered relevant. There were a few suggestions for combining some of the environmental indicators. For instance, the indicators on odor from $H_2S$ gas and acidifying air pollution were considered to be already covered by the air quality indicator and were therefore eliminated. The social indicators received a mixed vote overall. In many cases, stakeholders called for more information on the rationale behind certain indicators, while low relevance to sustainability for developed countries was cited in other cases. For example, the indicators on life expectancy at birth and number of unlicensed teachers in the project-affected area were only considered relevant in developing countries by the stakeholders. The participants put forward a number of suggestions for new indicators, which are shown in the Appendix A, categorized into dimensions of sustainability. Not all of these suggestions were suitable for use as indicators for various reasons. Table hosts recorded any notable comments from discussion at each table. Further comments were provided by individual participants on comment sheets or post-its, which were collected afterwards (see Appendix A). Based on the results of the World Café, it became clear how the indicator set would need to be refined for this iteration. The comments of the stakeholder groups were taken into account and a number of steps were taken to improve the indicator set, taking into account the suitability criteria for indicator selection shown in the section on Iterative indicator development method. It also became clear that modifications would also be necessary regarding how the indicators were presented. The following tasks were therefore required:

- Rearrange indicators into more meaningful clusters/themes/sub-themes, for certain user groups.
- Reduce the number of indicators where possible or simplify by condensing or combining indicators.
- Classify indicators more clearly according to phase and scope.
- Improve and distribute supplementary information for all of the indicators where necessary.
- Clarify the future use focus of the indicators according to the following:

a. scale: project/local/regional/national;
b. project phase: assessment vs. monitoring;

**Table 4-2**
Response rates of Delphi participants.

| | Invited | Response rate | Responded (partial/complete) |
|---|---|---|---|
| Round 1 | 70 | 47% | 33 (11/22) |
| Round 2 | 70 | 23% | 16 (3/13) |
| Round 3 | 70 | 16% | 11 (2/9) |

**Table 4-4**
Highest scoring goals — Icelandic Delphi.

| Goal | Mean score |
|---|---|
| Goal 1 — Renewability | 4.55 |
| Goal 3 — Environmental management | 4.45 |
| Goal 10 — Dissemination of knowledge | 4.27 |

**Table 4-5**
Lowest scoring goals — Icelandic Delphi.

| Goal | Mean score |
|---|---|
| Goal 4 — Efficiency | 3.64 |
| Goal 6 — Energy equity | 3.64 |
| Goal 7 — Energy security | 4 |

c. scope: direct or indirect impact from project, inclusion of cascaded uses;
d. focus: developer company, government or other groups;
e. economy type: developed vs. developing countries;
f. project type: high heat (electricity) or Low heat (other uses) projects; and
g. project size: small or large projects.

*Delphi results*

As stated before stakeholders in Iceland were invited to take part in an online Delphi, beginning in March 2013 and ending in August 2013.

*Response rates*

It should be noted that during the Delphi, invitations were sent out to a pool of seventy potential participants for all three rounds. In each round a portion of this pool responded, but the same people did not necessarily respond each time. The response rates of participants are shown in Table 4-2.

*Sustainability goals*

Once sustainability goals were suggested by stakeholders in the first Delphi round, in Round 2 the participants were requested to award a score between 1 (irrelevant) and 5 (extremely relevant) to each item on the list of sustainability goals (Table 4-3). Since the participants suggested goals in the first round, they could only rate the goals in the second and third rounds. The number of goals remained the same during the course of the Delphi.

*Agreement and consensus: goals.* At the end of three rounds, there was a general consensus between the stakeholders on the most relevant and least relevant goals. Tables 4-4 and 4-5 show the highest and lowest scoring goals in the Delphi.

The standard deviation serves as a measure of agreement between participants on the relevance on a given item. After the final Delphi round for Iceland, the scores with the highest standard deviation were those of Energy Equity and Efficiency. These, as expected, were also among the lowest scoring goals in terms of perceived relevance. The scores with the lowest standard deviation were those of Renewability and Environmental Management. These goals were also the highest scoring in terms of perceived relevance. Fig. 4-1 shows the change in standard deviation for the sustainability goals between Rounds 2 and 3.

For all the goals in the Icelandic Delphi, the standard deviation decreased between Round 2 and Round 3, indicating an increased agreement between participants on the relevance of these goals.

*Sustainability indicators*

The number of indicators reduced from 38 to 24 after three Delphi rounds. Table 4-6 shows the change in indicator numbers after each round.

As with the sustainability goals, the participants were requested to award a score between 1 (irrelevant) and 5 (extremely relevant) to each item on the list of initial sustainability indicators. The scores received by the indicators after each round are shown in Table 4-7. Indicators that were eliminated during the Delphi are not shown in this table. These indicators are discussed later.

Some indicators were added after Round 1 based on suggestions of the stakeholders and therefore have an “n/a” score. Indicators that were eliminated after a round also have an “n/a” score in the next round. The five highest scoring indicators after three Delphi rounds are shown in Table 4-8. These are the indicators that the participants considered most relevant to geothermal sustainability.

The five lowest scoring indicators are shown in Table 4-9. These are the indicators that the participants considered least relevant to geothermal sustainability.

*Agreement and consensus: indicators.* The standard deviation for the lower scoring indicators was generally wider than for the higher scoring ones, indicating less agreement on these indicators between stakeholders. Tables 4-10 and 4-11 show the indicators with the five highest and lowest standard deviations for the Delphi.

The standard deviation decreased for the majority of indicators between Round 1 and Round 3 (Fig. 4-2), indicating a higher level of agreement between the Icelandic Delphi participants.

*Elimination of indicators.* The Delphi facilitators used personal expert judgment and stakeholder input to determine the best and most suitable indicators. Indicators were also calculated from the available data

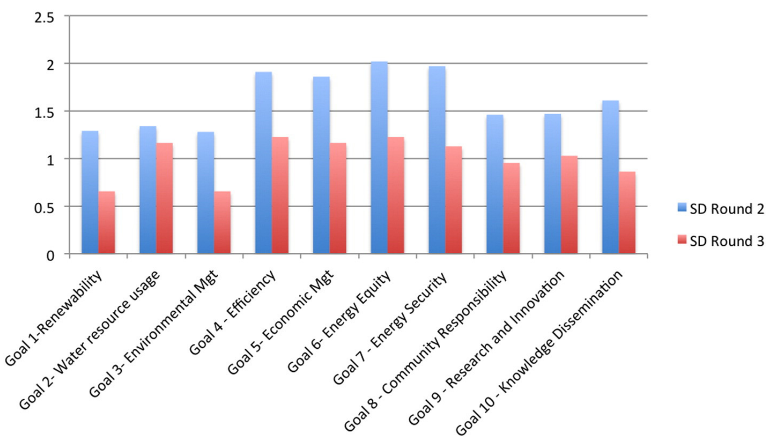


**Fig. 4-1.** Sustainability goals Iceland — comparison of standard deviation between Round 2 and Round 3.

**Table 4-6**
Change in indicator numbers after each Delphi round.

| Round | Number of indicators before | Number of indicators after | % increase/decrease |
|---|---|---|---|
| Round 1 | 38 | 24 + 2 new | −32% |
| Round 2 | 26 | 24 | −8% |
| Round 3 | 24 | 24 | 0% |

**Table 4-8**
Highest scoring indicators after Round 3.

| Indicator | Mean score |
|---|---|
| Resource reserve capacity ratio of the geothermal resource | 4.22 |
| Utilization efficiency | 4.22 |
| Estimated productive lifetime of geothermal resource | 4.56 |
| Water quality | 4.67 |
| Air quality | 4.78 |

and evaluated for suitability after this. Indicators were eliminated based on facilitator judgments and stakeholder comments on their suitability. An indicator was eliminated if it could clearly not fulfill all of the suitability criteria shown in Box 3-1. In most cases, the indicator's score would also reflect its suitability. Otherwise, if a modification of the indicator would mean it fulfilled the criteria, then this modification was suggested in the next round and stakeholders scored the indicator again. Table 4-12 shows the indicators that were eliminated during the Delphi, along with the reasons for elimination.

## Discussion

In this section the following questions regarding the effectiveness of the indicator development process are addressed:

- Was the stakeholder process effective and valid?
- Is the framework suited to its intended purpose?
- What modifications should be made based on the experience gained?

### *Effectiveness and validity of the stakeholder process*

The stakeholder process was designed to obtain as broad ranging set of views as possible. Stakeholders from a wide range of sectors participated in the process. The World Café and Delphi Technique were the dominant methods used to gain stakeholder input during the indicator development process. Their validity and effectiveness is discussed below.

*Pre-engagement World Café workshop*

The World Café workshop had a high attendance with a broad range of stakeholders.

This showed the interest of the participants in the topic and a willingness to be involved in the process. The high attendance may also have been due in part to the fact that many of the people invited already work in the Reykjavik area and the fact that Reykjavik is a small and easily navigable city. The participants found that they did not have enough time in some cases to complete the voting on each dimension of the indicators as well as suggest new indicators. Furthermore a convergence in the voting was observed when "show of hands" voting was used in the groups, suggesting a possible "bandwagon" effect. Not all participants provided comments on their answer sheets. The knowledge of participants regarding indicators in general also varied significantly, although this was to be expected and even desirable (Fraser et al., 2006). However the pre-engagement workshop did serve to provide many useful ideas regarding the modification of the indicator set, as well as putting suggestions for new indicators forward. It also provided local insights and qualitative information, which although not directly useful for indicator development, did help to highlight important issues regarding geothermal development in the Icelandic context. The facilitators modified the list of initial indicators based on the workshop outputs and used this list for the first round of the Delphi process.

*Delphi process*

Proponents of the Delphi technique propose that a successful Delphi must provide a more accurate result than would otherwise be achieved

**Table 4-7**
Comparison of mean scores for indicators between Delphi rounds.

| Indicator | Mean R1 | Mean R2 | Mean R3 |
|---|---|---|---|
| Air quality in the surrounds of the geothermal power plant | 4.28 | 4.36 | 4.78 |
| Average income levels in project-affected communities | 2.32 | 2.72 | 3.33 |
| Direct and indirect local job creation over lifetime of project | 3.09 | 2.93 | 3.44 |
| Duration of plant power outages per year | 3.07 | 3.36 | 3.89 |
| EBIDA ratio per project | n/a | 3.04 | 3.33 |
| Estimated productive lifetime of geothermal resource | 4.48 | 4.68 | 4.56 |
| Expenditure on heat and electricity as a percentage of household income | 3.09 | 3.25 | 3.33 |
| Impact on important or vulnerable geothermal features | 3.47 | 4.20 | 4.00 |
| Imported energy as a percentage of total (national level) | 3.13 | 3.43 | 3.56 |
| Income-to-expenditure ratio for project-affected municipalities | 3.22 | 3.43 | 3.56 |
| Initial phase capacity as a percentage of estimated total capacity | 2.35 | 3.0 | n/a |
| Level of induced seismicity per year | 3.22 | 3.61 | 3.67 |
| Noise levels in working, recreation and residential areas in the surrounds of the geothermal power plant. | 3.66 | 3.71 | 4.22 |
| Number of accidents leading to work absence in the energy company per year | 2.93 | 3.65 | 4.22 |
| Percentage of community residents that must be relocated due to energy project | 3.73 | 3.75 | 3.89 |
| Percentage of energy company expenditure given to R&D per year | 3.04 | 3.79 | 3.33 |
| Percentage of protected area removed/affected due to geothermal project | 4.27 | 4.04 | 4.11 |
| Percentage of renewables in total energy supply nationally | 3.66 | 4.22 | 3.33 |
| Project internal rate of return (IRR) | 3.61 | 3.68 | 3.67 |
| Rate of subsidence in the geothermal field | 3.26 | 3.97 | 4.11 |
| Ratio of average male income to female income for the project-affected area | 2.25 | 3.65 | 3.89 |
| Ratio of reinjection to production | n/a | 4.00 | n/a |
| Resource reserve capacity ratio of the geothermal resource | 4.04 | 4.22 | 4.22 |
| Tons of greenhouse gas emissions resulting from geothermal operations | 3.76 | 4.04 | 4.11 |
| Utilization efficiency for the geothermal power plant | 4.04 | 4.25 | 4.22 |
| Water quality | 4.13 | 4.54 | 4.67 |

**Table 4-9**
Lowest scoring indicators after Round 3.

| Indicator | Mean score |
|---|---|
| Average income levels in project-affected communities | 3.33 |
| EBITDA ratio per project | 3.33 |
| Expenditure on heat and electricity as a percentage of household income | 3.33 |
| Percentage of energy company expenditure given to R&D per year | 3.33 |
| Percentage of renewables in total energy supply nationally | 3.33 |

by individuals or interacting groups. The Delphi technique may avoid the interpersonal conflict of groups, or the domination of a group by perceived powerful personalities (Powell, 2003). The main advantages of the Delphi technique are said to be its ability to be used in areas of uncertainty as well as its relatively low cost. Through its feedback mechanism, it can expand the knowledge of participants and stimulate new ideas. It is also a way of gathering a broad range of direct expert knowledge into a decision-making process, with few geographical limitations (Powell, 2003). Conversely, disadvantages may include a high time commitment; hasty decisions by participants; the risk of producing a "watered down" opinion; the risk of lack of accountability for opinions due to anonymity; or the potential for low response rates (Powell, 2003). In addition, the facilitators may unintentionally influence opinions and there the level of expertise among participants may vary greatly (Hsu and Sandford, 2007). Furthermore, clustering at the high end of the scale may occur when category scales are used to score items, making it difficult to interpret the result (McGeary, 2009).

Indicators of sustainability are only likely to be effective if they provide users and the public with meaningful information they can relate to. Users like policy- and decision-makers will be in a better position to set attainable policy goals if they understand environment–society interactions well, and this is all the more likely to happen if indicators are derived from a participatory process, as they will reflect the objectives and values of the public (Shields et al., 2002). In this iteration of the indicator development process, both the sustainability goals and indicators were chosen by stakeholders, so the list should prove useful to useful to future users, such as policy-makers or regulators in the Icelandic context. In order to be influential, consensus must exist among policy actors that the indicators are legitimate, credible and salient (Cash et al., 2003). This means that the indicators must not only answer questions that are relevant to the policy actor, but also provide a scientifically plausible and technically adequate assessment. To be legitimate, the indicators must be perceived to be developed through a politically, socially and ethically acceptable procedure. The results of the Delphi show a definite increase in the level of consensus among the participants by the end of the third round. This is evident from the change in the standard deviation for the majority of the goals and indicators between rounds (Figs. 4-1 and 4-2). We suggest that the Delphi process used in this study lends legitimacy, credibility and saliency to goals and indicators that were produced.

Although the range of stakeholders used in this study was extremely diverse, including both experts and non-experts, this did not necessarily

**Table 4-10**
Indicators with highest standard deviations after Round 3.

| Indicator | Mean Score | Standard Deviation |
|---|---|---|
| Imported energy as a percentage of total (national level) | 3.56 | 1.26 |
| Project internal rate of return (IRR) | 3.67 | 1.33 |
| EBIDA ratio per project | 3.33 | 1.33 |
| Percentage of energy company expenditure given to R&D per year | 3.33 | 1.33 |
| Expenditure on heat and electricity as a percentage of household income | 3.33 | 1.49 |

**Table 4-11**
Indicators with lowest standard deviations after Round 3.

| Indicator | Mean score | Standard deviation |
|---|---|---|
| Tons of greenhouse gas emissions resulting from geothermal operations | 4.11 | 0.57 |
| Air quality in the surrounds of the geothermal power plant | 4.78 | 0.63 |
| Noise levels in working, recreation and residential areas in the surrounds of the geothermal power plant | 4.22 | 0.63 |
| Utilization efficiency for the geothermal power plant | 4.22 | 0.63 |
| Water quality | 4.67 | 0.67 |

pose a problem, since inclusion of non-expert or local participants can lead to community empowerment as well as providing detailed local knowledge to the experts in the group, which in turn can lead to community support for future policies (Fraser et al., 2006). As well as having varying degrees of influence on policy making, developing indicators alone can have an influence by stimulating social learning (Lehtonen, 2013). Social learning takes place between actors in a social network through social interactions or processes. It can be said to occur when a change in understanding took place in the individuals involved and the change went beyond the individual to be embedded in a wide social unit or community (Reed, 2010).

While it is difficult to precisely measure whether group learning or social learning occurred as a result of the Delphi, without doing a post-Delphi survey, it can be assumed that participants most likely came away from the Delphi with a greater understanding of the issues surrounding sustainable geothermal developments, as well as an increased understanding of the functioning of indicator frameworks and the design of effective indicators. The stakeholder input for this Delphi was also very useful to the authors in designing better indicators generally, as problems with the theory behind certain indicators or reference values were pointed out. Thus, the authors will be better prepared for future Delphis and save time in the indicator evaluation stage.

If we look only at the overall result of a Delphi, we may neglect the minority views that are present. Where minority views are not taken into account, the participant may be tempted to drop out of the Delphi, leading to a "false consensus" in the final result. The Delphi must therefore "explore dissension" (Linstone and Turoff, 2002).

The results show that for the majority of items, both goals and indicators, that the standard deviation reduced between rounds, suggesting an increased consensus by the end. Although, the mean score for items reduced in some cases, this can be attributed to new stakeholders joining the Delphi after the first or second round and rating items with lower scores. In spite of this, consensus levels still increased in the final round for the majority of items. More consensus existed on certain issues than others. Regarding the sustainability goals, those dealing with energy equity and efficiency had the highest standard deviation in the final round, whereas renewability and environmental management had the lowest standard deviation. The comments, such as those show in Boxes 5-1 and 5-2 throw some light on the reasons for the consensus levels, and we suggest that these comments be used to inform policy- or decision-makers further.

Among the Icelandic Delphi participants, some mentioned a lack of free time as a reason for not completing the survey, or completing it later than the allocated time. Response rates reduced significantly between the first and third rounds (Table 4-2), suggesting diminishing interest or burnout on the part of the stakeholders. Incentives in the form of prizes were offered in an attempt to boost the Delphi response rate. In future Delphis, giving participants more time will be considered as a measure for boosting response rates. Score clustering did occur to some extent, suggesting that a different score allocation system may have been more appropriate (McGeary, 2009). However, In order to maintain consistency of research methods, the same scoring system

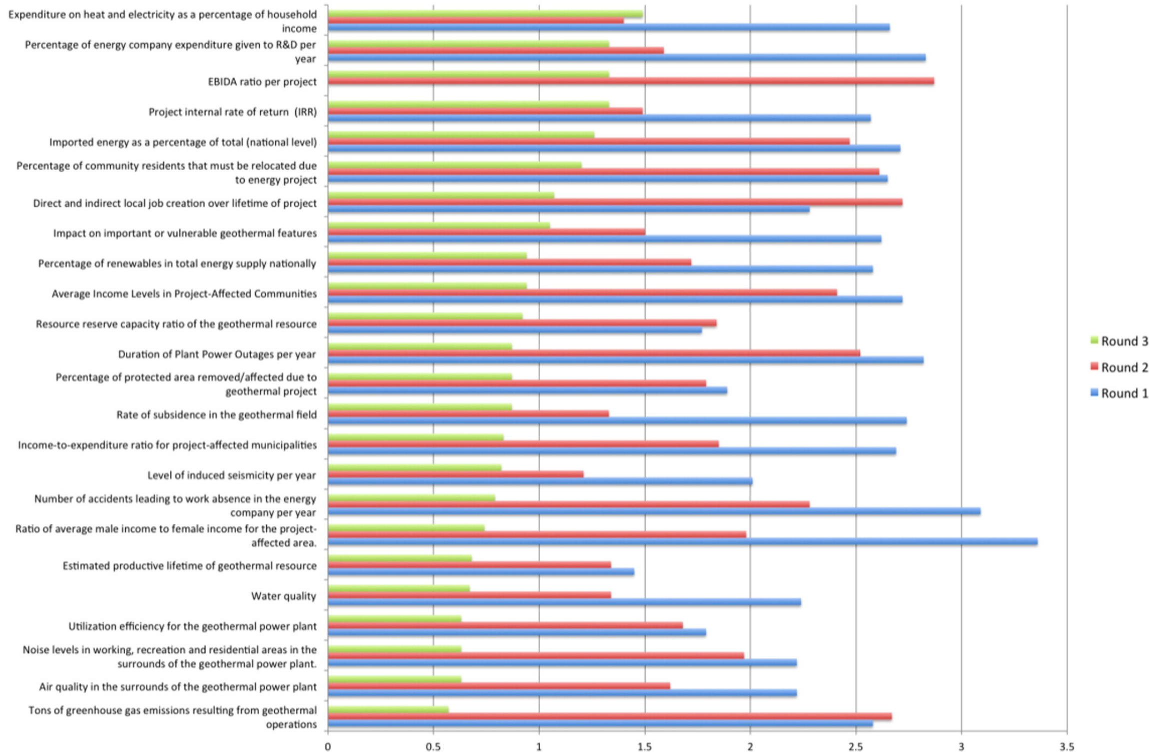


**Fig. 4-2.** Changes in standard deviations between rounds for indicators.

will need to be used in subsequent Delphis. The participants were obliged to give each Delphi item a score in the survey, but comments were optional. This meant that the reasons for giving indicators a particular score were not always clear. It also meant that the participants may have rushed through the survey without giving much thought to their responses in some cases. The participants also tended to score items based on their relevance in the Icelandic context, even though the item may have had relevance in other contexts. This was to be expected and for that reason, further iterations of the indicator development process will be carried out in other countries.

*Suitability for intended purpose*

The list of indicators produced in this first iteration has been critically evaluated through a stakeholder engagement process in Iceland and also against a set of theoretical criteria to determine their suitability to

**Table 4-12**
Indicators eliminated during Delphi.

| Indicator | Final score | Round eliminated | Reason for elimination |
|---|---|---|---|
| Total cases lost in supreme court by energy company per year | 1.57 | Round 1 | No clear reference value available |
| Ratio of rate of change in housing prices to rate of change in income levels (housing affordability) | 1.9 | Round 1 | Indicator not easily understandable |
| Housing value in the area compared to national average | 2.1 | Round 1 | Not considered relevant to geothermal sustainability |
| Initial phase capacity as a percentage of estimated total capacity | 3.00 | Round 2 | No clear reference value available |
| Percentage of satisfied workers in the energy company per year | 2.4 | Round 1 | Not considered relevant to geothermal sustainability |
| Percentage of females with university education in local energy company | 2.4 | Round 1 | Not considered relevant to geothermal sustainability |
| Unemployment rate in project affected areas | 2.43 | Round 1 | Already covered by the employment indicator (double counting) |
| Income equity in project-affected communities | 2.48 | Round 1 | Not considered relevant to geothermal sustainability |
| Energy diversity index for project-affected regions | 2.76 | Round 1 | Not considered relevant to geothermal sustainability |
| Make-up holes as a function of time | 2.79 | Round 1 | Indicator not easily understandable |
| Ratio of reinjection to production | 4.00 | Round 2 | No clear reference value available |
| Percentage of population with access to commercial energy in project-affected area | 2.98 | Round 1 | Not considered relevant to geothermal sustainability (in Iceland) |
| Area of land used due to geothermal energy project (including infrastructure) | 3.04 | Round 1 | No clear reference value available |
| Economic diversity of project-impacted areas | 3.16 | Round 1 | No clear reference value available |
| Odor experience from $H_2S$ gas in residential or recreational areas near the power plant | 3.65 | Round 1 | Already covered by air quality indicator (double counting) |
| Tons of acidifying air pollutants ($H_2S$, $SO_2$) emitted as a result of geothermal operations | 4.3 | Round 1 | Already covered by air quality indicator (double counting) |

**Box 5-1**
Example comments for a goal with high level of consensus.

Goal 1 — renewability:
In order to ensure the geothermal resource remains replenishable, sustainable production* should be the goal in all geothermal projects.
*For each geothermal area and each mode of production there exists a certain maximum level of production, E0, so that with production below E0 it is possible to sustain steady energy production from the system for at least 100–300 years. If the level of production exceeds E0 it is not possible to sustain steady production from the system for so long. Geothermal production that is less than or equal to E0 is defined as sustainable production but production exceeding E0 is not sustainable.
Comments (in support)
"Is geothermal renewable? i.e. high enthalpy areas?"
"If possible, even longer production periods should be looked at."
"We build our society on having access to the energy we need — electrical and thermal. It is a basis for the function of our society. One obligation of today is to ensure the possibility of this access in the future as well — ethically — but also (and this is usually what creates the strongest urgency) to maintain the foundation for the future economy in Iceland. If we use up everything now, then what will be built on in the future? "Þetta reddast?""
"If this is not fulfilled then the extraction is not sustainable in other words."

their purpose. However, the development process has also highlighted other advantages and drawbacks of developing the assessment framework. The indicators may be used to measure performance against some target value, such as national or international standards or benchmarks. However, while many of the links between human–environmental interactions are well understood, many other complex issues remain to be studied. Therefore, performing an assessment using these indicators is never guaranteed to provide a fully integrated view of the entire system we wish to assess. The value of supplementary or qualitative information should not be ignored when reporting the indicators in an assessment. For example, with subsidence, it may be necessary to state whether or not the subsidence is likely to impact negatively on residential areas, which is a qualitative judgment. Another example might be income-to-expenditure ratio for project-affected municipalities, which may be higher or lower due to other factors that should be explained clearly with supplementary information. In the early phases of a geothermal project, especially, qualitative information will be very important, since some indicator data will not yet be available. In such cases, predictions about the sustainability of a future project may need to be made based on the available information. Assessments using indicators alone may not be sufficient and other types of investigation, such as a detailed socio-economic analysis, may need to be done. The list of indicators produced by this one study is not prescriptive, in that it is entirely possible to find alternative metrics for any of the indicators produced using the methods described in this paper. For example, the social benefits of geothermal energy projects may differ significantly from country to country and the Icelandic stakeholder group rejected indicators that would be considered relevant in developing countries, such as access to energy or the percentage of females with university education.

It was decided not to create a composite index from the indicators or add weights, as it was felt that too much information would be lost due to the "information iceberg" effect (Molle and Mollinga, 2003) if the indicators were to be aggregated. As well as this, the choice of weights is a politically sensitive and value-laden process, prone to arbitrariness and inconsistency (Bohringer and Jochem, 2007). The framework could form the basis, however, for the calculation of an index that uses weights, but careful consideration would need to be given to the themes that would be aggregated as well as the units used. It was felt that assigning weights at this point was inappropriate as the weightings of each theme or issue-areas are likely to differ depending on the region or country. The stakeholder process in Iceland was intended only to result in the choice of an initial set of goals and indicators. Stakeholders were not involved in any actual assessment using the indicators. The results of any trial assessment using the indicators are beyond the scope of this paper.

**Box 5-2**
Examples comments for a goal with low level of consensus.

Goal 4 — efficiency:
Geothermal utilization shall be managed in such a way as to maximize the utilization of exergy available where practical at sustainable production levels. The desired maximum efficiency for electricity generation should be based on the theoretical maximum efficiency for converting heat to electrical energy (Carnot efficiency).
Comments (in support)
"Efficiency is an important goal, but I think it might be phrased better, more simply and "where practical" who decides where it is practical to maximize the utilization. Is it possible to put a specific percentage of efficiency?"
"What means where practical? If sustainable usage, and renewability suffers from electricity production then the exergy optimisation may be devastating."
"As long as the theoretical maximum efficiency is defined within sustainable utilization, I agree with this, otherwise not."
"This is the whole point of striving towards sustainability — fulfilling the energy (electrical & thermal) while at the same time using the primary resource as sparingly as possible."

*Modifications and further research*

Based on this first iteration of the indicator development process in Iceland, it is clear that inevitably, each geothermal energy project will face unique sustainability challenges, due to the differing environmental and socio-economic setting in which it is found. We suggest that qualitative information be supplied alongside the reported indicators in order to provide the end user with site-specific information. By carrying out further iterations of the indicator development process, we suggest that the final assessment framework produced will be more likely to take into account the diverse and unique circumstances surrounding geothermal developments. Further iterations of the indicator development process will also produce better, more refined indicators and further study may reveal issues that may have been neglected previously. It should be possible to produce a framework of goals and indicators, with in-built flexibility of indicator choice. However we suggest that it would also be beneficial to have an associated stakeholder input process that runs simultaneously with a sustainability assessment in order to ensure that the indicators reflect the evolving nature of sustainable development. Such stakeholder inclusion methods should be culturally appropriate and agreed to by all parties before they are implemented (Meadows, 1998). The lessons learned from this iteration in the Icelandic context will be applied to further iterations in New Zealand and Kenya. Following these iterations, more insights on the assessment framework will become apparent and allow for a more comprehensive evaluation of its suitability.

## Conclusion

This paper describes the first steps in the development of a sustainability assessment framework for geothermal energy projects, using the input of an Icelandic stakeholder group and internationally recognized methods. The first iteration of the indicator development process has been completed in Iceland illustrating that the process can be applied elsewhere. As a result, further iterations will be carried out in New Zealand and Kenya before a finalized set of goals and indicators is produced.

## 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 Masters thesis at the University of Iceland, which was generously sponsored by Orkustofnun (National Energy Authority of Iceland), Landsvirkjun Power and RANNIS (Icelandic Research Fund). We also acknowledge the support of the University of Iceland, University of Auckland, Reykjavik Energy (Orkuveita Reykjavikur) and the Kenya Electricity Generating Company Ltd. (KenGen). Furthermore, we sincerely thank the numerous stakeholders in Iceland, New Zealand and Kenya and the UNU Fellows that took part in our stakeholder process.

## Appendix A. Results of pre-engagement World Café workshop in Iceland

**Table A-1**
Indicator list with corresponding comments and votes.

| Indicator | Main comments | Group vote |
|---|---|---|
| N-1 Land area used by plant and infrastructure | Applies to high-temperature only.<br>The amount of area used is not a good indicator. Consider the quality of land and surroundings — i.e. land-use and possibility. | 56% |
| N-2 Percentage of forested areas in the region removed due to energy project | What about wetland? Forest not applicable in Iceland.<br>Include soil erosion.<br>Consider previous use of land, for instance, agriculture and whether these kind of activities are being displaced. | 89% |
| N-3 Highest Icelandic *verndaflokkur* protected area classification rating of the location of structures or infrastructures | Political classification. Not relevant.<br>Ok if categorizing is done on trustworthy basis and agreement (i.e. a more transparent scale than this needs to be developed).<br>Visual effects rather than verndaflokkur.<br>Consider using view-shed analysis results. | 100% |
| N-4 Type of impact of ground subsidence (positive or negative) | Should be assessed in preparation phase. | 100% |
| N-5 Concentration (ppb) of $H_2S$ in recreational and inhabited areas around power plant | Not a problem in Iceland generally.<br>Consider using only when $H_2S$ is an issue. | 100% |
| N-6 Concentration of mercury (Hg) gas in vicinity of power plant | May be repeating N-7, could be combined with effluent indicators.<br>Not heard of in Iceland. | 87.5% |
| N-7 Concentration of metals (Hg, Cr, Cu, As, Pb, Zn, Ni, Cd, etc.) in effluents released from power plant | Local indicator. | 100% |
| N-8 Amount in tonnes of acidifying air pollutants ($SO_2$, Nox and $H_2S$) emitted from power plant per year | Repeats N-5. | 100% |
| N-9 pH of effluent released from power plant into the environment | | 100% |
| N-10 Concentration of chlorides and sulphides released in effluent from power plant | Have one single indicator for "effluent". | 100% |
| N-11 Temperature of hot water released from power plant into the environment | Look at temperature AND quantity of water. | 100% |
| N-12 Noise levels (dB) in the area surrounding the geothermal energy project | Occupational vs. ambient. | 100% |
| N-13 Concentration of $H_2S$ gas in the areas around the geothermal energy project | The same as N5.<br>Measure "experience" — use "odor" instead of "concentration" in the indicator description (experience of discomfort). | 74% |
| N-14 Likelihood of impact on biodiversity hotspots in vicinity of power plant, construction area or infrastructure | Yes. Usually increased (i.e. algae in the Blue Lagoon).<br>Biodiversity can increase and decrease (whether this is good or bad depends on the situation). | 100% |
| N-15 Likelihood of impact on threatened species in vicinity of power plant, construction or infrastructure | Link to use of land.<br>Needs a lot of research — depends on existing data. | 100% |
| N-16 Status of rivers and lakes in vicinity of power operations according to EU Water Framework Directive | Look at combining with effects of effluents on ground water.<br>Yes. Compared to fossil fuels.<br>Would work well with a baseline assessment.<br>Misleading to say "disturbance" — instead consider water quality.<br>Rephrase this better and single out relevant part of measurement. | 84% |
| N-17 Annual national greenhouse gas emissions ($CO_2$ eq) from geothermal energy | Context can be confusing, misleading.<br>Combine into one indicator for gas releases.<br>Could compare to emissions from fossil fuel plants. | 100% |
| N-18 Productive lifetime of geothermal resource | Significant controversy surrounding this indicator.<br>Use "estimated" productive lifetime.<br>Consider scale.<br>100 years currently gets 100%. Maybe too short. High temperature and low temperature resources may differ.<br>Should be 300 years. 30 years is too short.<br>Yes. Also depends on the geothermal field.<br>Very difficult to predict.<br>Resource vs. reserve measurement: define clearly. | 100% |
| N-19 Concentrations of dissolved chemicals ($SiO_2$ and Cl) indicating | Pressure decline, water table — status of geothermal resource. | 100% |

**Table A-1** (*continued*)

| Indicator | Main comments | Group vote |
|---|---|---|
| cooling | Flawed — first observe pressure lowering in both high and low temp and then changing chemicals. | |
| N-20 Utilization efficiency of geothermal plant | Energy quality levels. | 100% |
| N-21 Level of micro-seismic activity | Should be taken into account in regards to social effects of power plant — positive here but negative for society.<br>Distinguish between good for the resource and negative for the people.<br>Consider induced seismicity.<br>Earthquakes should be in social indicators. | 100% |
| N-22 Years to recovery of resource pressure and heat after exploitation | Depend on a lot of factors and the type of field.<br>Very site specific.<br>Many systems operate with constant temperature, like Svartsengi. So the indicator will say it is inexhaustible.<br>Needs more reliable data.<br>Yes but can be difficult to obtain information based on facts — now models that need more work, based on probabilities.<br>Combine with N18 as lifetime performance indicator. | 74% |
| E-1 Government foreign debt ratio | Political. Project ownership important.<br>Government responsibility — hard to interpret.<br>How is that interpreted in context with sustainability? | 80% |
| E-2 Percentage of future energy needs fulfilled by project | Varies when talking about high temp or low temp area.<br>Ok, but Is bigger better?<br>Define needs. Public or industry?<br>Is it related to energy policy?<br>Future energy demand — how to predict? | 70% |
| E-3 Ratio of social and environmental costs of operations to value of economic transactions for the project (Cost benefit analysis) | Define better.<br>Is cost–benefit analysis the only method?<br>Difficult to put monetary value on environmental and social costs.<br>Limited, future value — economic view. | 100% |
| E-4 Impact on hydrological features or hot springs | Should this be in the economic or environmental dimension?<br>Yes, reduced activity of hot springs e.g. Waireiki or increased impact of hot springs on water use conflicts with other use. Tourism. Water pollution by geothermal.<br>Define/explain relevance better. | 82% |
| E-5 Percentage of total water usage for the area used by energy project | Consider moving into the social dimension.<br>Depends on location and population.<br>Consider combining with E-3.<br>For developing countries, use access to water.<br>Difference between developed and developing countries. Access to fresh water. Needs indicators which take into account future use, such as fish farming, Blue Lagoon, etc. Extra gains. | 80% |
| E-6 Utilization Efficiency | Same as N-20 environmental indicator. | 100% |
| E-7 Percentage of transmission loss annually | E7 to E10 deal with national aspects, if looking at individual power plant then this should be skipped.<br>(a question of scale) | 70% |
| E-8 Percentage of distribution loss annually | As above.<br>E-6 is the most important as more directly related to the project. | 70% |
| E-9 Imported energy as a percentage of total energy | Price volatility of fuels.<br>A previous study will show the impact of the establishment and development of the geothermal power plant over the energy needs and the mix. | 100% |
| E-10 Renewable energy share in total energy production | Better definition. | 100% |
| E-11 Ratio of predicted future flows of geothermal energy to predicted production or consumption patterns | Unclear.<br>Too difficult to define.<br>Similar issues to E-2. | 53% |
| E-12 Reserve capacity ratio nationally | Define “reserve” better. Clarify this indicator.<br>Is it viable energy? Considering technology, natural preservation. | 94% |
| E-13 Reserve capacity for greater volcanic system | | 94% |
| E-14 Shannon–Weiner index of energy diversity | Unclear. | 70% |
| E-15 Duration of power outages per year | | 100% |
| E-16 Return on assets of developer company | Political issues.<br>Does production exceed needs? | 100% |
| E-17 Short term debt to total debt ratio of developer company | Combine E17–E21.<br>E17–E21: ownership and risk. Social duty/obligation of power companies vs. Ownership of resources. Fulfill needs of the community (heating, electricity, plumbing, etc.) first. | 100% |
| E-18 Owner company leverage ratio | Combine E17–E21. | 100% |
| E-19 Balance sheet effects of exchange rate changes | Combine E17–E21. | 80% |
| E-20 Level of financial risk associated with energy project | Combine E17–E21. | 100% |
| E-21 Unhedged foreign currency exposure of owner company | Combine E17–E21. | 80% |
| S-1 Income to expenditure ratio for project-affected municipalities | Unclear.<br>The municipality's obligations should be clear.<br>Government responsibility as cost.<br>Municipality may have sharp increase in expenditure during construction. | 100% |

(*continued on next page*)

**Table A-1** (*continued*)

| Indicator | Main comments | Group vote |
|---|---|---|
| S-2 Percentage of unlicensed teachers in region compared to national average | Not relevant or applicable in Iceland, maybe in developing countries. | 8% |
| S-3 Local unemployment rate compared to regional or national average | No because if it hard to measure and differentiate from other effects. (indirect impact) | 100% |
| S-4 Percentage of full-time project workers residing in Iceland Percentage of full-time project workers based locally | Include national and regional numbers, direct vs indirect employment.<br>Matters most during construction phase.<br>Should be looked at for long term.<br>Locally trained workers?<br>Annual work of service industry instead?<br>Look at energy company employees. | 76% |
| S-5 Average income levels for project-affected municipalities compared to regional income levels | Only if change in income levels is brought about by the geothermal project.<br>Use only for smaller communities.<br>Applicable for larger geothermal projects only. | 100% |
| S-5 Average income levels for project-affected regions compared to national income levels | As above.<br>Energy company workforce.<br>The number of jobs created in the geothermal sector is less than other industries (direct impact on employment is small). | 62% |
| S-6 Difference between change in average national and municipal house prices and income levels | Unclear, needs to be rephrased.<br>Property value?<br>Better as an economic indicator?<br>Needs to be confirmed that they are related and impacted by a project. | 86% |
| S-7 Percentage of population below poverty line in project affected municipality compared to regional percentage | Not applicable to Iceland, more for developing countries. | 85% |
| S-7 Percentage of population below poverty line nationally compared to global average | Too many variables enter this on a global scale.<br>Hard to compare vastly different societies. | 62% |
| S-8 Hackman economic diversity index or Shannon–Weiner index | Unclear or unfamiliar index. | 57% |
| S-9 Level of education in developer company compared to level of education regionally/nationally | Not applicable in Iceland.<br>The education of employees when hired e.g. BSc and MSc industrial degree or education and training within the company — could increase knowledge/know-how in the area.<br>Use experience rather than education if talking about energy company.<br>Change in level of education since being employed by energy company? | 24% |
| S-10 Level of education of least educated 20% of project workforce compared to municipality and national population | Should be in context with the locality or region since geothermal projects will be done with qualified people anyway. | 43% |
| S-11 Icelandic *verndaflokkur* rating of project-affected areas | Define better.<br>Will newly discovered cultural treasures replace/amount to those destroyed?<br>No, development sites in Iceland are usually in uninhabited areas.<br>Badly defined word (verndaflokkur) — political, not rational.<br>Too political. | 86% |
| S-12 Percentage of population with access to high quality energy | Define high quality. | 86% |
| S-13 Expenditure on energy as percentage of lowest income household disposable income | | 100% |
| S-14 Gini coefficient for energy use between income groups | | 67% |
| S-15 Ratio of male energy use to female energy use | Relevant in developing countries.<br>Define use better — maybe “access” is better? | 38% |
| S-16 Gini coefficient | | 63% |
| S-17 Ratio of average female to male income in project staff compared to municipality and national ratios | | 67% |
| S-18 Percentage of females with university education in developer company compared to percentage of females with university education locally | Also technical trade education e.g. Truck drivers, electrician, etc.<br>Does this relate to sustainability? | 56% |
| S-19 Percentage of females with university education in developer company compared to percentage of females with university education nationally | Micro economy in power companies.<br>Does this relate to sustainability? | 75% |
| S-20 Percentage of satisfied workers in developer company | Define satisfaction.<br>Measurement of life quality and other factors? | 57% |
| S-21 Infant mortality rates in project-affected area and nationally | Developing countries.<br>Regional development should have benchmark of the state of the area to begin with. | 76% |
| S-22 Life expectancy at birth in project-affected area and nationally | Developing countries. | 81% |
| S-23 Percentage of community residents that must relocated due to energy project | Not such a problem in Iceland as sparsely populated. | 44% |
| S-24 Number of accident fatalities due to energy projects | | 100% |
| S-25 Degree of public participation during environmental impact assessment in relation to legal requirements | Doubts about method.<br>General participation — not enough to count the participants of cases. | 100% |
| I-1 Time taken to complete cases in government agencies | Quality of public administration.<br>Important for permitting process. | 30% |
| I-2 Level of customer satisfaction for developer company | Unclear. | 25% |
| I-3 Value of fines or number of sanctions for regulatory non-compliance of developer company | Hard to measure, hard to interpret. | 30% |
| I-4 Average education level of staff in developer company | Experience rather than education.<br>Should this be in the social dimension? | 35% |
| I-5 Presence of environmental management system | Include quality management. | 55% |

**Table A-1** (*continued*)

| Indicator | Main comments | Group vote |
|---|---|---|
| | Certification rather than presence.<br>Presence of an EMS does not imply good management. | |
| I-6 Percentage of GDP spent on environmental protection | Unclear.<br>Better to use as % of project expenditure rather than GDP. | 0% |
| I-7 Transparency International corruption perceptions index | | 30% |
| I-8 Total cases in supreme court involving developer company per year | Use cases lost instead. | 10% |
| I-9 Freedom House democracy levels | Rather emphasis governance. | 10% |
| I-10 Percentage of voter turnout | Does not work in practice. | 0% |
| I-11 Percentage of developer company expenditure given to R&D | Not directly linked to a project.<br>Define R&D better.<br>R&D training. | 55% |
| I-12 Percentage of total geothermal energy R&D staff nationally funded by developer company | R&D training. | 24% |
| I-13 Percentage of research personnel employed in geothermal energy theme in public institutions. | What about multinational corporations.<br>Combine with other R&D indicators. | 47% |
| I-14 Percentage of total national R&D expenditure contributed by government sources (public institutions) | Look at combining and simplifying all R&D indicators.<br>Define R&D clearly. | 0% |

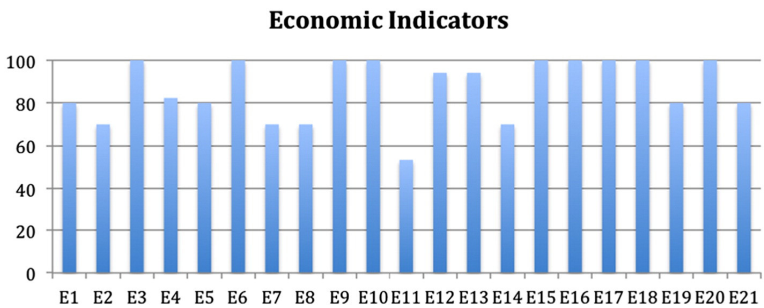


**Fig. A-1.** Voting scores (%) for economic indicators.

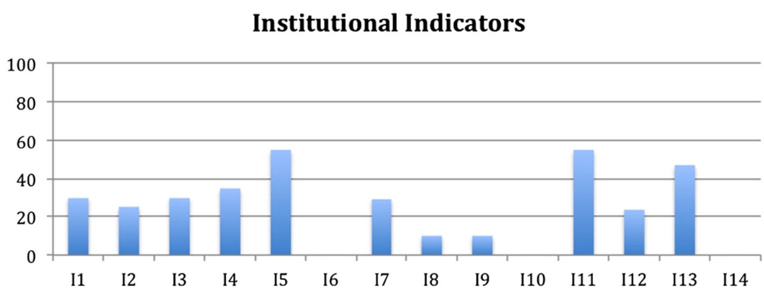


**Fig. A-2.** Voting scores (%) for institutional indicators.

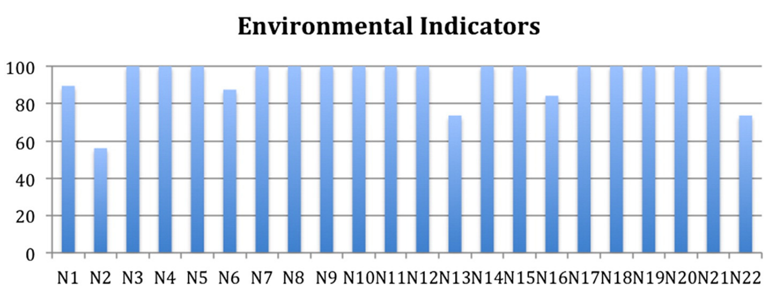


**Fig. A-3.** Voting scores (%) for environmental indicators.

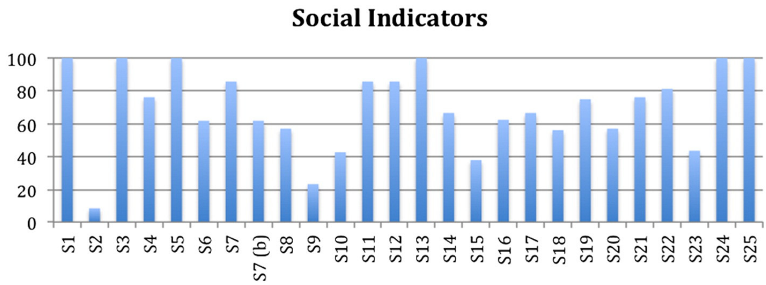


**Fig. A-4.** Voting scores (%) for social indicators.

**Table A-2**
New indicator suggestions from stakeholders.

| Social | Economic/institutional | Environmental |
|---|---|---|
| Ownership of the resource | Staff to energy output | % lava removed (is protected in Iceland) |
| Look at effects from cascaded use/by-products | Direct and indirect jobs | % protected area removed/affected |
| More indicators to show economic benefits or costs to society | Quality jobs for long term | Visibility (view-shed) |
| Minor seismic activity. | Government keeping of set time goals | Make-up holes as a function of time |
| Number of accidents/mishaps leading to work absence | Initial phase capacity as a % of estimated total capacity | Wetlands/visibility/vegetation/species endangered |
| Change in literacy level (phase 3) | Housing value in the area compared to national | Soil erosion in the area |
| Opportunities provided by energy companies for training and adult education | Percentage of females with university education in local energy company | Access to fresh water (in developing countries) |
| Future use of water — how it is impacted by project. E.g. fish farming Blue lagoon — added gains (cascaded use) | An indicator to measure economic benefits of a new plant in a greater surrounding with a broader view than only developer — linked to social impacts | Indicators that replace a cost benefit analysis |
| Indicator to take account of quality of the land and surroundings, the possible land uses that would be impacted (e.g. agriculture) | Quantity of hot water | Indicator for induced seismicity to make it clearer when seismicity is harmful |

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# 4 Paper III: A Sustainability Assessment Framework for Geothermal Energy Projects: Development in Iceland, New Zealand and Kenya

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# A sustainability assessment framework for geothermal energy projects: Development in Iceland, New Zealand and Kenya

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ABSTRACT

With increasing global energy consumption, geothermal energy usage is set to increase in the future. There is potential for geothermal developments in many countries all over the world, where geothermal resources are located. Geothermal developments may result in both positive and negative environmental and socio-economic impacts. Sustainability assessment tools are useful to decision-makers in showing the progress of energy developments towards sustainability, and the international community has called for the development of indicators to steer countries or regions into sustainable energy development.

Stakeholder engagement is important in developing tools for assessing sustainability since there tends to be an absence of scientific consensus on the components of sustainable development. As well as this, conditions for defining sustainable development tend to be context-specific and depend on the values of current as well as future human societies. The input of a wide variety of stakeholders in different countries is crucial for minimizing biases in the assessment framework. Due to the unique issues associated with geothermal energy projects in different locations, a customized framework for assessing the sustainability of such projects is required.

In order to develop an effective framework for sustainability assessment, several iterations of the indicator development process are required. This paper describes the development of a sustainability assessment framework for geothermal energy projects in Iceland, New Zealand and Kenya using the input of international multi-stakeholder groups and internationally recognized methods. In Iceland, stakeholders from the United Nations University Geothermal Training Program (UNU-GTP) were also consulted. The importance of the need to include diverse stakeholder views is shown in the diversity of opinions between groups. The priorities of the stakeholders regarding the goals of sustainable geothermal developments are presented. Environmental management was a common concern among the Icelandic, New Zealand and Kenyan participants, whereas water usage was considered the most important environment-related issue for the UNU-GTP fellows. The Kenyan, New Zealand and the UNU-GTP groups rated economic management and profitability, along with research and innovation, highly, whereas the Icelandic group placed highest emphasis on resource renewability and also rated knowledge dissemination highly. The indicator choices of each group are also presented and discussed.



**Contents**



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## 1. Introduction

### 1.1. Need for an effective sustainability assessment framework development for geothermal developments

The international community has called for the development of indicators to steer countries or regions into sustainable energy development. The need for the development of sustainability indicators is clearly set out in Agenda 21 and has been acted on by the United Nations Commission for Sustainable Development (CSD) [37]. There have been further calls in the literature for the use of sustainability indicators as a means to measure sustainability [5], due to their usefulness in informing decision-makers about the progress of certain policies [12].

With increasing global energy consumption, geothermal energy usage is set to increase in the future. There is potential for geothermal developments in many countries all over the world, where geothermal resources are located. Geothermal developments may result in both positive and negative environmental and socio-economic impacts. Sustainability assessment tools are useful to decision-makers in showing the progress of energy developments towards sustainability. Due to the unique issues associated with geothermal energy projects in different locations, a customized framework for assessing the sustainability of such projects is required. The need for such a sustainability assessment tool has been established following a review of the available sustainability assessment frameworks, which are found to be unsuited to assessing the unique characteristics of geothermal projects [42]. The methods used in this paper have already been illustrated in detail by the authors in a paper describing the steps for developing an assessment framework for geothermal energy projects, through a case-study in Iceland [43].

### 1.2. Objective

The objective of this paper is to present and describe the development of a fully developed sustainability assessment framework for geothermal energy projects. The paper describes several iterations of the indicator development process (Fig. 3-1) [43] taking place in Iceland, New Zealand and Kenya. Each iteration involves stakeholder engagement techniques and a detailed study of a geothermal development in each of the countries. In Iceland, a group of stakeholders from the United Nations University Geothermal Training Program was also consulted. The fully developed framework, which takes into account the views of all stakeholder groups, is then presented and the effectiveness of the methods discussed.

## 2. Background

In a response to the need for a customized sustainability assessment framework for geothermal energy projects [42], a set of sustainability goals and indicators for the assessment of geothermal energy projects was developed in a first iteration of the indicator development process, carried out in Iceland [43]. By carrying out the first iteration, the authors identified ways to improve the indicator development process for the next iterations. Experience in developing more effective indicators and reference values, with the help of stakeholder comments and through a group learning process, was gained. Stakeholder insights also helped to identify sustainability issues around geothermal developments that were previously not considered.

Further iterations of the indicator development process are required to ensure that the framework is tested in diverse conditions and receives adequate input and criticism from stakeholders in different countries. By carrying out several iterations with input from stakeholder in different countries, a diverse range of knowledge about sustainable geothermal developments can be tapped into. With an international perspective, there is a reduced likelihood of the assessment framework having a particular country bias. This is important since geothermal developments can take place in countries with differing levels of economic development and hence different priorities for their societies. Knowing the different priorities of different stakeholder groups allows the creation of a more flexible assessment tool for geothermal projects. The participation of international stakeholders also lends more credibility to the development process, which is important for the future acceptance of the assessment framework.

## 3. Method

We propose a sustainability assessment framework consisting of a set of sustainability goals and indicators that allow monitoring of geothermal projects during their entire life-cycle. A literature review of the impacts of geothermal energy projects on sustainable development [42] was carried out in order to determine the most important sustainability issues associated with geothermal energy assessments. A previous paper offers are more detailed description of the methods used to develop the assessment framework [43].

The goals and indicators in this framework were developed using an iterative process (Fig. 3-1) for thematic indicator development [11], which included stakeholder participation and testing of the indicators on an existing geothermal project. Stakeholder participation was integrated into the process because it widely acknowledged that social learning can take place during the development of indicators as well as discovering the values and priorities of the stakeholder group [31]. Guiding principles known as the Bellagio STAMP were incorporated into the entire development process [43].

One iteration consists of choosing sustainability goals and indicators with stakeholder input; collecting indicator data in a trial assessment of an operational geothermal project (also known as implementing the indicator set) and finally evaluating the indicators for suitability. The purpose of the iterative approach is to allow the progressive refinement of the indicators following each iteration. A geothermal project was chosen in each country and evaluated by implementing the indicator set produced at the end of each iteration. In this paper, only the steps of the iteration process up until the implementation will be described. Stakeholder engagement methods used during the iterative process included pre-engagement "World

**Table 3-1**
Stakeholder participation for workshops and Delphis

| Country | No. Participants (Workshop/Delphi[a]) |
|---|---|
| Iceland | 23/33 |
| New Zealand | –/30 |
| Kenya | 5/13 |

[a] Total number of participants that completed at least one Delphi round.

**Table 3-2**
Breakdown of stakeholders by sector.

*Total numbers and types of stakeholders participating in each Delphi[a] (excludes UNU-GTP fellows)*

| | Energy Industry | Other Business[b] | Government | NGOs | Academia | Total |
|---|---|---|---|---|---|---|
| Iceland | 9 (27%) | 7 (21%) | 5 (15%) | 2 (6%) | 10 (30%) | **33** |
| New Zealand | 1 (7%) | 7 (50%) | 3 (21%) | n/a (0%) | 3 (21%) | **14** |
| Kenya | 4 (19%) | 4 (19%) | 6 (29%)[c] | 5 (24%) | 2 (5%) | **21** |
| **All Countries** | **14** | **18** | **14** | **7** | **15** | |

[a] Stakeholders that completed at least one round are included in the count.
[b] Includes any other industry apart from energy (e.g. tourism, consulting, financing).
[c] Includes two intergovernmental organizations.

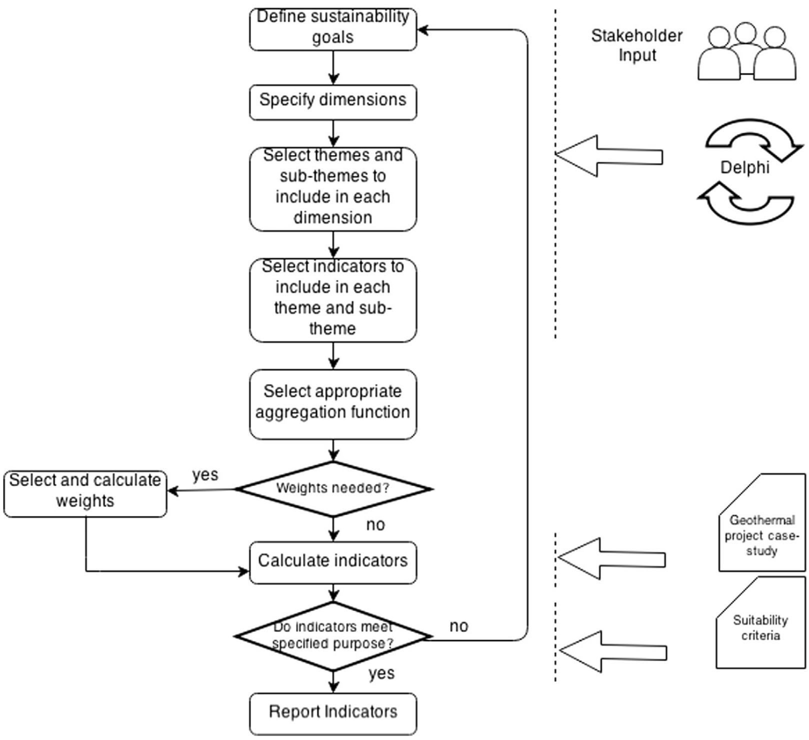


**Fig. 3-1.** Iterative indicator development process, modified from [11]. See also [43].

**Table 3-3**
Scoring system for Delphis.

| Score | Relevance |
|---|---|
| 1 | Irrelevant |
| 2 | Somewhat irrelevant |
| 3 | Neither relevant not irrelevant |
| 4 | Somewhat relevant |
| 5 | Extremely relevant |

**Table 4-1**
World Café workshop outcomes.

| Location | Attended | Outputs |
|---|---|---|
| Iceland (Dec 2012) | 23 | Indicator list (38 indicators) |
| Kenya, (Nov 2013) | 5 | Indicator list (42 indicators) |

Café" workshops and the Delphi technique (Fig. 3-1). The Icelandic case study represented the first iteration of the indicator development process. Three further iterations were carried out in New Zealand, Kenya and with an international group of United Nations University fellows.

### 3.1. Stakeholder engagement methods

As per the recommendations of the Bellagio STAMP principles [21], a diverse group of stakeholders was selected to contribute to the process of developing the sustainability assessment framework. The group consisted of participants from diverse backgrounds, from government to industry to NGOs. Stakeholders had an influence through their comments during pre-engagement "World Café" workshops and the Delphi process, from the choice of sustainability goals and indicators (Fig. 3-1). Their input also defined the scope of the assessment itself by identifying the most important sustainability issues to be considered.

#### 3.1.1. World Café method

The World Café workshop technique was used as a starting point or pre-engagement method in Iceland and Kenya, in order to gather stakeholder input on potential sustainability goals and indicators for geothermal energy projects, as well as to make adjustments according to the cultural climate, before holding a full-fledged Delphi process. Where it was not possible to do a World Café workshop, information sessions were held instead. The workshops and information sessions also served to inform the participants about the goal of the research project and the subsequent Delphi process. The participation for the workshops and Delphis is shown in Table 3-1. A full and detailed description of the running of a World Café workshop method is illustrated, using the Icelandic case-study, in the author's previous work [43].

#### 3.1.2. Delphi in Iceland, New Zealand, Kenya and at the United Nations Geothermal Training Program

The predominant stakeholder engagement method used in the country studies was the Delphi technique. The Delphi technique was chosen as the main stakeholder engagement method as it was considered the best technique to use given the circumstances. A full description of this technique and rationale for its use is available in the author's previous paper [43]. The Delphis for each country were held online using customizable survey tools. See Table 3-2 for the types and number of stakeholders that participated. UNU-GTP fellows are not included in this count. As it was not possible to hold a World Café in New Zealand or for the UNU-GTP stakeholders, the initial indicator list, with 38 indicators,

**Table 4-2**
Response rates for Delphis (Full or partial response).

| Delphi | Invitations sent | Round 1 | Round 2 | Round 3 |
|---|---|---|---|---|
| Iceland | 70 | 47% (33/70) | 23% (16/70) | 16% (11/70) |
| New Zealand | 33 | 24% (8/33) | 24%(8/33) | 30% (10/33) |
| Kenya | 60 | 20% (12/60) | 22% (13/60) | 12% (7/60) |
| UNU-GTP | 95 | 24% (23 / 95) | 16% (15/95) | 9% (9/95) |

produced from the Icelandic World Café was used as a starting point for those Delphis.

Each Delphi consisted of three rounds in total. In Round 1, participants were presented with an initial set of indicators and asked to rate and comment on each one. They were also asked to suggest sustainability goals for geothermal developments. The stakeholders rated the items for relevance to geothermal sustainability, by awarding scores between 1 and 5 as shown in Table 3-3.

After Round 1, the facilitators modified the list based on the average score of each item and synthesized comments. Comments on reference values or perceived relevance of goals and indicators were taken into account. New goals and indicator suggestions were also incorporated into the modified list. In Round 2 and 3, participants were requested to rate the modified list and make comments if they desired. After each round, the facilitators modified the list as before. After Round 3, the final list was expected to represent a broader consensus of the participants on the most appropriate goals and indicators.

In general, indicators with a mean score below 3 were discarded. Indicators with a low score but high standard deviation, signifying a higher level of disagreement between the participants, were resubmitted to the next round if there was the possibility that more information or a modification could result in a different score. In addition, after each round, indicators were discarded if they clearly did not fulfill the criteria for good indicators [43,35,48] e.g. if there was a difficulty finding a reference value for them, for example, with newly suggested indicators, or if they were unsuitable in the opinion of the facilitators (e.g. not clearly understandable to the general public).

A Delphi was also done with participants from the United Nations University Geothermal Training Program (UNU-GTP) in Reykjavik. Although this does not constitute a full iteration of the indicator development process, the results are nonetheless valuable and will be presented in this paper. This group had 23 active participants and consisted of a number of different nationalities, mainly from developing countries. A World Café was not held at the United Nations University because of the high workload of the current students and the fact the past fellows had left Iceland and were scattered around the globe. Similarly, a World Café was not held in New Zealand due to the large geographical distances between participants. However a number of information sessions in different locations were held instead before the online Delphi was started.

## 4. Results

The results of the indicator development process are presented in this section for the three country studies and the UNU-GTP group's Delphi.

### 4.1. Pre-engagement workshops

Two pre-engagement "World Café" workshops were held in Reykjavik, Iceland and Nairobi, Kenya. The list of indicators

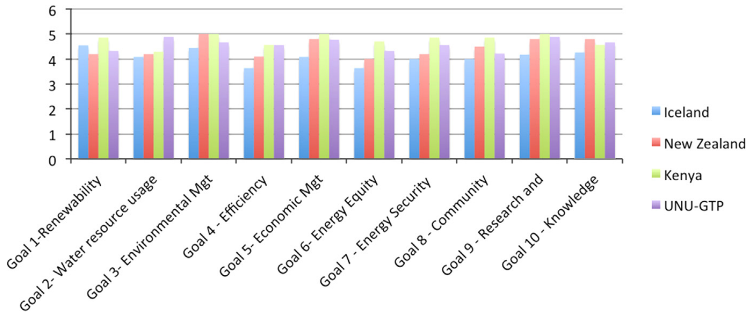


**Fig. 4-1.** Comparison of scores for sustainability goals after final Delphi round.

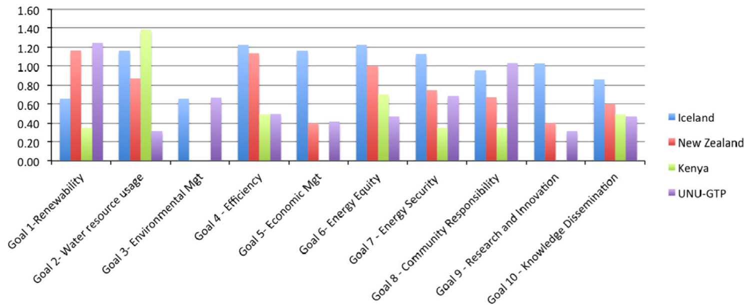


**Fig. 4-2.** Comparison of standard deviations for goals after final Delphi round.

**Table 4-3**
Number of indicators after each round for each Delphi.

| Delphi | Initial | Round 1 | Round 2 | Round 3 |
|---|---|---|---|---|
| Iceland | 38 | 26 | 24 | 24 |
| New Zealand | 38 | 30 | 24 | 24 |
| Kenya | 42 | 36 | 34 | 34 |
| UNU | 38 | 32 | 30 | 30 |

produced after the workshops were used as a starting point for the subsequent Delphi process (Table 4-1).

## 4.2. Delphi surveys

Invitations to take part in an online Delphi were sent to stakeholders in Iceland, New Zealand and Kenya. Invitations were also sent to current and past fellows of the United Nations Geothermal Training Program (UNU-GTP). Tables 4-2 shows response rates for the Delphis. Agreement or consensus between the participants can be measured by the standard deviation of the scores assigned by the participants. A high standard deviation indicates a lower level of consensus or agreement whereas a low standard deviation indicates a higher level of consensus or agreement for that item.

## 4.3. Sustainability goals

Stakeholder input in the form of the online Delphi was sought in order to guide the choice of a set of sustainability goals that would in turn guide the choice of sustainability indicators.[1] The final set of goals produced from the results of all Delphis is shown in Appendix A. Scores were allocated by participants on a scale of 1–5 (Table 3-3), according to the perceived relevance of the sustainability goal. The final scores allocated to the list of goals by each stakeholder group are shown in Fig. 4-1. The scores for the highest and lowest scoring goals are shown in Appendix B.

### 4.3.1. Agreement between participants on relevance of sustainability goals

Fig. 4-2 shows the standard deviation for sustainability goals after the final Delphi round. For example, in the Icelandic Delphi, the goals of Energy Equity and Efficiency had the highest standard deviation or least consensus, whereas Renewability and Environmental Management had the lowest standard deviation or greatest consensus. Overall, there was a high consensus on the relevance of the goal of Environmental Management among the majority of the Delphi participants.

## 4.4. Sustainability indicators

Each iteration of the indicator development process produced a set of sustainability indicators, reflecting the views of the stakeholder group in that particular country. In each Delphi, the number of indicators was reduced by the final round, shown in Table 4-3. This was a desirable consequence because indicator sets with many indicators are more difficult to manage.

### 4.4.1. Overall scores for sustainability indicators

Appendix C shows the final lists of indicators and their scores and some examples of the comments produced from the Delphis for each country as well as the UNU-GTP fellows. For example in the Icelandic Delphi, the indicator *Air quality in the surrounds of the geothermal power plant* received an average score of 4.28 out of a possible 5.00 ("Extremely Relevant") in the first Delphi round (R1). Since this was a highly scoring indicator, it was not discarded. In the second Delphi round (R2), this indicator received an average score of 4.36 and was

[1] In New Zealand, stakeholders were presented with an initial set of goals in Round 1 and the resulting comments were used to modify the goals. This was not done for the other Delphis, in which participants were asked to suggest the goals themselves in Round 1.

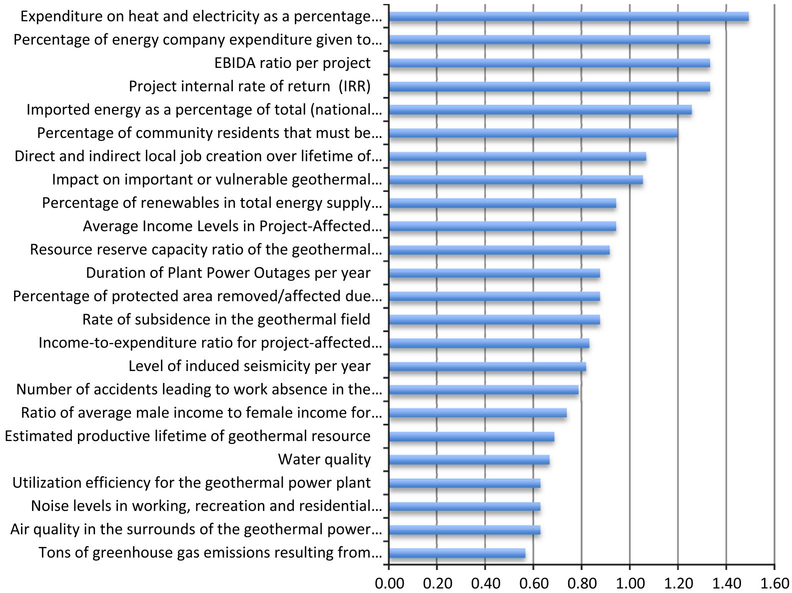


**Fig. 4-3.** Icelandic Delphi – standard deviations for all indicators after Round 3.

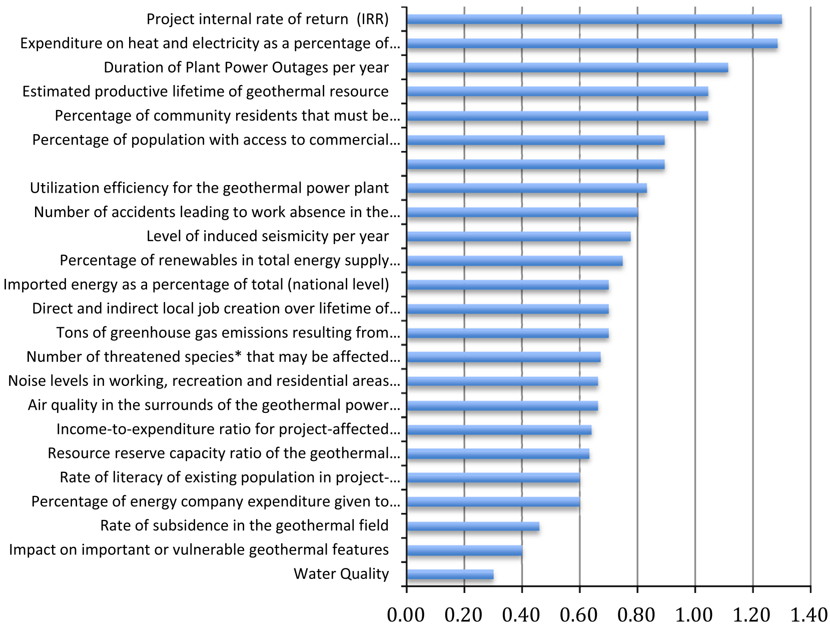


**Fig. 4-4.** New Zealand Delphi – standard deviations for all indicators after Round 3.

therefore kept until Round 3 (R3) where it received a final score of 4.78. Certain indicators were eliminated during each Delphi, and the reasons for their elimation are provided. A more detailed description of the indicators, including their metrics or reference values is provided in Appendix D.

#### 4.4.2. *Agreement between participants on relevance of sustainability indicators*

Figs. 4-3–4-6 show the standard deviations for each indicator after Round 3 of each Delphi. For example, in the Icelandic Delphi, the lowest consensus was observed the indicator "*Expenditure on*

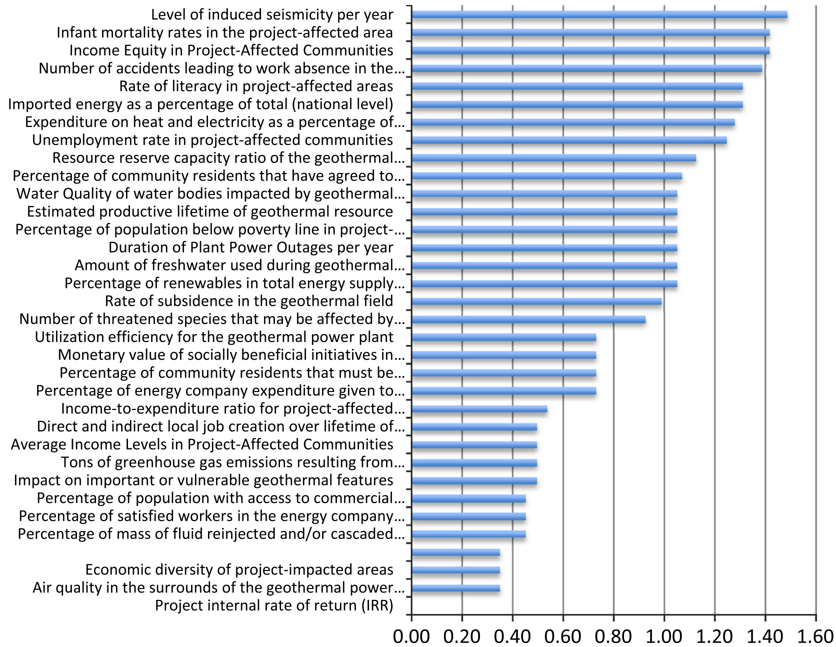


**Fig. 4-5.** Kenyan Delphi – standard deviations for all indicators after Round 3.

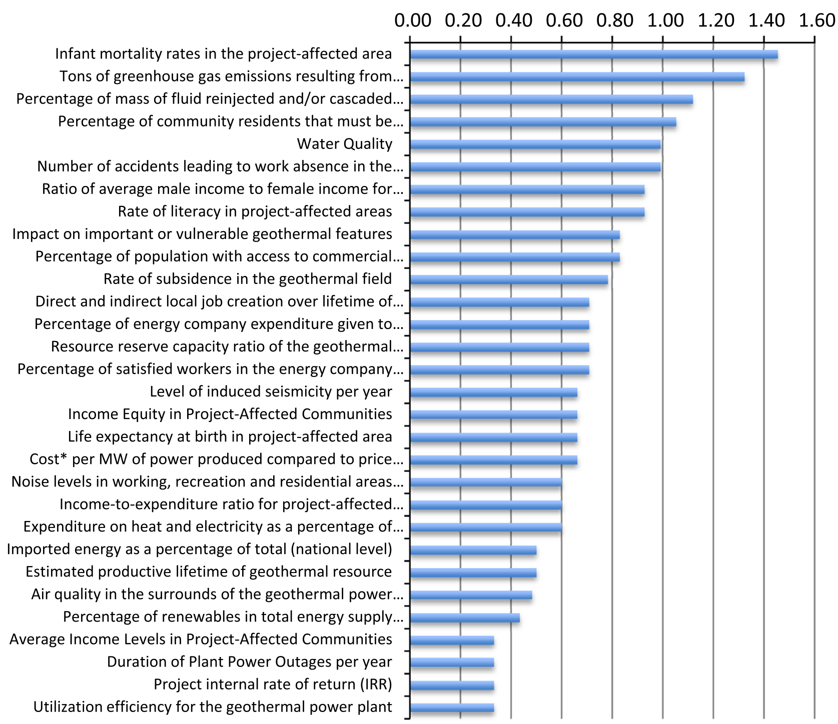


**Fig. 4-6.** UNU-GTP Delphi – standard deviations for all indicators after Round 3.

**Table 4-4**
Common indicators chosen by all stakeholders.

| |
|---|
| Air quality in the surrounds of the geothermal power plant |
| Average Income Levels in Project-Affected Communities |
| Direct and indirect local job creation over lifetime of project |
| Duration of Plant Power Outages per year |
| Estimated productive lifetime of geothermal resource |
| Expenditure on heat and electricity as a percentage of household income |
| Impact on important or vulnerable geothermal features |
| Imported energy as a percentage of total (national level) |
| Income-to-expenditure ratio for project-affected municipalities |
| Level of induced seismicity per year |
| Noise levels in working, recreation and residential areas in the surrounds of the geothermal power plant. |
| Number of accidents leading to work absence in the energy company per year |
| Percentage of community residents that must be relocated due to energy project |
| Percentage of energy company expenditure given to R&D per year |
| Percentage of renewables in total energy supply nationally |
| Project internal rate of return (IRR) |
| Rate of subsidence in the geothermal field |
| Resource reserve capacity ratio of the geothermal resource |
| Tons of greenhouse gas emissions resulting from geothermal operations |
| Utilization efficiency for the geothermal power plant |
| Water Quality of water bodies impacted by geothermal power plant operations |

**Table 4-5**
Supplementary indicators and their presence in each Delphi group.

| Indicator | Iceland | New Zealand | Kenya | UNU-GTP |
|---|---|---|---|---|
| EBIDTA ratio per project | ✓ | | | |
| Percentage of protected area removed/affected due to geothermal project | ✓ | | | |
| Number of threatened species that may be affected by the geothermal project. | | ✓ | ✓ | |
| Rate of literacy of existing population in project-affected areas | | ✓ | ✓ | ✓ |
| Cost per MW of power produced compared to price per MW from other sources | | | | ✓ |
| Income Equity in Project-Affected Communities | | | ✓ | ✓ |
| Infant mortality rates in the project-affected area | | | ✓ | ✓ |
| Life expectancy at birth in project-affected area | | | | ✓ |
| Percentage of mass of fluid reinjected and/or cascaded compared to total extracted fluid mass | | | ✓ | ✓ |
| Percentage of satisfied workers in the energy company per year | | | ✓ | ✓ |
| Ratio of average male income to female income for similar jobs for the project staff | ✓ | | | ✓ |
| Percentage of population with access to commercial energy in project-affected area | | ✓ | ✓ | ✓ |
| Amount of freshwater used during geothermal development (exploration, construction or operation activities) as a percentage of available freshwater in the project area | | | ✓ | |
| Monetary value of socially beneficial initiatives in project-affected communities as a percentage of total project expenditure | | | ✓ | |
| Percentage of community residents that have agreed to potential culture-changing activities relating to the energy project | | | ✓ | |
| Unemployment rate in project-affected communities | | | ✓ | |
| Percentage of population below poverty line in project-affected area | | | ✓ | |
| Economic diversity of project-impacted areas | | | ✓ | |

*heat and electricity as a percentage of household income"*, whereas the highest consensus existed on the indicator *"Tons of greenhouse gas emissions resulting from geothermal operations"*. Overall, there were marked differences between the levels of consensus on the relevance certain indicators between Delphis, in particular between the developed and developing countries.

### *4.4.3. Commonalities and differences in indicator choices*

Based on the combined results of all the Delphis, indicators that were commonly relevant to all stakeholders could be identified. A set of 21 core (Table 4-4) and 18 supplementary or satellite indicators (Table 4-5) could therefore be derived from the results of all Delphis. The core indicators are those indicators that were agreed to be relevant in any sustainability assessment by all stakeholders. The supplementary indicators are those that are applicable in some but not all situations, depending on the local conditions. Table 4-5 also shows in which Delphi each of the supplementary indicators were present.

### *4.5. Coverage of sustainability themes and goals*

Sustainability issues arising from geothermal developments can be classified according to themes following the Commission for Sustainable Development (CSD) Framework [48,42]. In order to determine if the assessment framework produced in this research adequately covered the relevant sustainability issues relating to geothermal energy development, its coverage was analyzed using the CSD thematic framework (Tables 4-6 and 4-7) and found to cover all themes to some degree. As well as this, the "internal" coverage of the framework was considered in the context of the sustainability goals that were chosen by the stakeholders (Table 4-8 and 4-9). In the tables, a darker shaded box signifies a greater degree of coverage of that theme or goal by an indicator.

Tables 4-8 and 4-9 show that although some goals appear to receive more coverage than others through the chosen indicators, all of the goals have at least one corresponding indicator, either common or optional. The fact that certain goals that have greater representation through the indicators, such as environmental management, economic management and community responsibility, may signal

**Table 4–6**
Linkages of common indicators to CSD sustainability themes.

**Sustainability Theme**

| Common Indicator | Poverty | Health | Education | Natural Hazards | Demographics | Atmosphere | Land | Freshwater | Biodiversity | Economic Development | Consumption and Production | Global Economic |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Air quality in the surrounds of the geothermal power plant | | ▒ | | | | ■ | | | ░ | | | |
| Average Income Levels in Project-Affected Communities | ■ | ░ | | | | | | | | ▒ | | |
| Direct and indirect local job creation over lifetime of project | ▒ | | | | ░ | | | | | ■ | | |
| Duration of Plant Power Outages per year | | | | | | | | | | ▒ | ■ | |
| Estimated productive lifetime of geothermal resource | | | | | | | | ▒ | | ■ | ■ | |
| Expenditure on heat and electricity as a percentage of household income | ■ | ░ | | | | | | | | | ▒ | |
| Impact on important or vulnerable geothermal features | | | | | ░ | | | | ▒ | ■ | | |
| Imported energy as a percentage of total (national level) | ░ | | | | | | | | | ■ | ░ | ░ |
| Income-to-expenditure ratio for project-affected municipalities | ░ | | | | | | | | | ■ | | |
| Level of induced seismicity per year | | | ░ | ■ | | | | | | | | |
| Noise levels in working, recreation and residential areas in the surrounds of the geothermal power plant | | ■ | | | | | | | ▒ | | | |
| Number of accidents leading to work absence in the energy company per year | | ■ | | | | | | | | | | |
| Percentage of community residents that must be relocated due to energy project | ▒ | | | | ■ | | | | | | | |

| Common Indicator | Poverty | Health | Education | Natural Hazards | Demographics | Atmosphere | Land | Freshwater | Biodiversity | Economic Development | Consumption and Production | Global Economic Partnership |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Percentage of energy company expenditure given to R&D per year | | | ▒ | | | | | | | ■ | | ▒ |
| Percentage of renewables in total energy supply nationally | | | | | | ■ | | | | | ▒ | |
| Project internal rate of return (IRR) | | | | | | | | | | ■ | | |
| Rate of subsidence in the geothermal field | | | | ■ | | | ▒ | | | ░ | | |
| Resource reserve capacity ratio of the geothermal resource | | | | | | | | | | ▒ | ■ | |
| Tons of greenhouse gas emissions resulting from geothermal operations | | ░ | | | | ■ | | | ▒ | ▒ | | ▒ |
| Utilization efficiency for the geothermal power plant | | | | | | | | | | ▒ | ■ | |
| Water Quality of water bodies impacted by geothermal power plant operations | | ▒ | | | | | ▒ | ■ | ▒ | | ░ | |

that these issues are of particular importance to the stakeholders, or alternatively that it was easier to chose the indicators for these goals. In order to ascertain which was the case it would be necessarily to divide or break down these goals into a number of more specific sub-goals for greater clarity, for instance, the goal of community responsibility could be broken up into categories of direct or induced impacts.

For some goals, it may be the case that it was rather difficult for the stakeholders to find indicators to measure a given goal. For instance, the goal of research and innovation, although rated as highly relevant by most groups, receives sparse coverage by indicators. Without clear examples of policy targets for some goals, the task of assigning reference values became more difficult. For other goals with little coverage, such as water resource usage, it may simply make more sense to combine two goals, e.g. the goal of water resource usage could be included in the goal relating to environmental management as a sub-goal. For this reason, we advise against assigning weights to any of the goals, as one would perhaps do for themes in other assessment frameworks, because it is clear that the goals were chosen by stakeholders without reflecting on their relative importance or weight.

The goal of efficiency did not receive many indicator suggestions, nor was it rated as highly relevant by most groups, which is interesting, since efficiency is often cited as a key tenet of sustainable energy development [47]. This suggests that using efficiency as an indicator of sustainable energy development without placing it in context may not be appropriate for this framework. Increasing the efficiency of geothermal energy sources may in fact be at odds with other criteria for sustainability, such as sustained yield, e.g. where fluid is cascaded and not reinjected. It may therefore be necessary to examine the efficiency of power production strictly within a systemic context.

With regard to the sattelite or optional indicators, the goals of Research and Innovation and Knowledge Dissemination do not receive any coverage by the chosen indicators, again showing the unwillingness of the stakeholders to come up with metrics for these goals. Efficiency is still sparsely covered. Environmental management, economic management, energy equity and community responsibility are again the best covered goals by the optional indicators, with energy equity receiving more attention in the optional indicators than in the common ones. The goal of energy equity was considered among the least relevant in nearly all of the groups, which is perhaps unexpected, given that many participants come from countries in which energy equity is a concern, such as Kenya, where it has already been pointed out that only around 23% of the population have access to electricity [17].

**Table 4-7**
Linkages of Satellite indicators to sustainability themes.

| Sattelite Indicator | Sustainability Theme: Poverty | Health | Education | Natural Hazards | Demographics | Atmosphere | Land | Freshwater | Biodiversity | Economic Development | Consumption and Production | Global Economic |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EBIDTA ratio per project | | | | | | | | | | ■ | | |
| Percentage of protected area removed/affected due to geothermal project | | | | | | | ▒ | | ■ | | | |
| Number of threatened species that may be affected by the geothermal project. | | | | | | | | | ■ | | | |
| Rate of literacy of existing population in project-affected areas | ▒ | | ■ | | | | | | | ▒ | | |
| Cost per MW of power produced compared to price per MW from other sources | | | | | | | | | | | ■ | |
| Income Equity in Project-Affected Communities | ▒ | | | | | | | | | ■ | | |
| Infant mortality rates in the project-affected area | | | | | | | | | | | | |
| Life expectancy at birth in project-affected area | ■ | ■ | | | | | | | | | | |
| Percentage of mass of fluid reinjected and/or cascaded compared to total extracted fluid mass | | | | ░ | | | | | ░ | | ■ | |
| Percentage of satisfied workers in the energy company per year | | ■ | | | | | | | | | | |
| Ratio of average male income to female income for similar jobs for the project staff | █ | | | | | | | | | | | |
| Percentage of population with access to commercial energy in project-affected area | ■ | ■ | ▒ | | ░ | | | | | ▒ | | |
| Amount of freshwater used during geothermal development as a percentage of available freshwater in the project area | | ▒ | | | | | | ■ | ▒ | | | |
| Monetary value of socially beneficial initiatives in project-affected communities as a percentage of total project expenditure | ▒ | ▒ | ▒ | | | | | | | ■ | | |
| Percentage of community residents that have agreed to potential culture-changing activities relating to the energy project | | | | | ■ | | | | | | | |
| Unemployment rate in project-affected communities | ■ | | | | | | | | | ▒ | | |
| Percentage of population below poverty line in project-affected area | ■ | ▒ | | | | | | | | ▒ | | |
| Economic diversity of project-impacted areas | | | | | | | | | | ■ | | |

## 5. Discussion

This research set out to create a tool for decision-makers for assessing the sustainability of geothermal energy projects. Three iterations of the indicator development process were carried out in Iceland, New Zealand and Kenya, as well as an additional Delphi process involving the UNU-GTP fellows in Reykjavik. The results revealed differences in priorities of stakeholders from different economic backgrounds and cultures, highlighting the role social values have in shaping the definition of sustainable development. The insights from the stakeholder groups were key in creating an assessment framework that takes account of differences in cultures and priorities.

Based on the results of all of the Delphis, a suggested framework of ten sustainability goals (Appendix A) measured by 21 core (Table 4-4) and 18 optional indicators (Table 4-5) was derived. It was found that the Delphi groups considered some of the indicators universally relevant (common or core indicators), leaving a subset of "optional" or "sattelite" indicators that were only considered relevant by some groups and that could therefore be chosen at the discretion of the end-user. This section discusses the findings of the four iterations of the indicator development process[2], in particular in relation to stakeholder priorities and agreement as well as the validity and effectiveness of the development process.

### 5.1. Stakeholder priorities

The perceived relevance of each sustainability goal and indicator was reflected in the mean scores awarded by the stakeholders for each item during the Delphi processes. In most cases, an item's mean score after each round would reflect its suitability.

#### 5.1.1. Icelandic group

In the Icelandic group the goals perceived to have most relevance to the sustainability of geothermal developments were focused on resource renewability, environmental management and the dissemination of knowledge. Reflecting this, the indicators that were considered most relevant concerned air and water quality, resource lifetime, work safety and noise. The goals considered least relevant dealt with energy efficiency, energy equity and energy security. The indicators considered to be least relevant to Icelandic stakeholders were those dealing with income levels in the community, energy company R&D expenditure, the project EBIDTA ratio, household expenditure on energy and the percentage of renewables in total energy supply. Icelandic stakeholders may consider the goal of energy efficiency to be less important, since the level of efficiency depends on the geothermal resource in question and whether energy cascading is possible. The relative abundance of energy available to the small Icelandic population may also contribute to a lack of concern for efficiency. Energy security is likely of less concern to Iceland since the country produces most of its energy indigenously using sources such as hydropower and geothermal. Energy equity is also probably of less concern in a developed country like Iceland where the entire population has access to affordable and reliable energy.

The focus on resource renewability in Iceland could be related to recent cases of geothermal fields being exploited aggressively, such as the Hellisheiði power plant, which is predicted to become uneconomic after just 34 years of exploitation [19]. The issue has been discussed extensively Iceland, and a considerable amount of literature dealing with the issue already has already been published

[2] The UNU-GTP Delphi is not a full iteration but for the purposes of this paper the Delphi is still used in the result.

**Table 4-8**
Linkages of common indicators to sustainability goals.

| Common Indicator | Sustainability Goal: **G1** Renewability | **G2** Water Resource Usage | **G3** Environmental Mgt | **G4** Efficiency | **G5** Economic Mgt | **G6** Energy Equity | **G7** Energy Security | **G8** Community Responsibility | **G9** Research and Innovation | **G10** Knowledge Dissemination |
|---|---|---|---|---|---|---|---|---|---|---|
| Air quality in the surrounds of the geothermal power plant | | | ■ | | ░ | | | ▒ | | |
| Average Income Levels in Project-Affected Communities | | | | | ■ | | | ■ | | |
| Direct and indirect local job creation over lifetime of project | | | | | ■ | | | ▒ | | |
| Duration of Plant Power Outages per year | | | | | | ■ | ■ | | | |
| Estimated productive lifetime of geothermal resource | ■ | | | | ▒ | | ▒ | ░ | | |
| Expenditure on heat and electricity as a percentage of household income | | | | | | ■ | | ▒ | | |
| Impact on important or vulnerable geothermal features | | | ■ | | ■ | | | ▒ | | |
| Imported energy as a percentage of total (national level) | | | | | | | | | | |
| Income-to-expenditure ratio for project-affected municipalities | | | | | ■ | | | ▒ | | |
| Level of induced seismicity per year | | | | | | | | ■ | | |
| Noise levels in working, recreation and residential areas in the surrounds of the geothermal power plant. | | | ■ | | | | | ▒ | | |
| Number of accidents leading to work absence in the energy company per year | | | ■ | | | | | | | |
| Percentage of community residents that must be relocated due to energy project | | | | | ▒ | | | ■ | | |
| Percentage of energy company expenditure given to R&D per year | | | | | | | | | ■ | ░ |
| Percentage of renewables in total energy supply nationally | | | ■ | | | | ▒ | | | |
| Project internal rate of return (IRR) | | | | | ■ | | ░ | | | |
| Rate of subsidence in the geothermal field | ░ | | ■ | | | | | ░ | | |
| Resource reserve capacity ratio of the geothermal resource | ■ | | | ░ | ▒ | | ░ | | | |
| Tons of greenhouse gas emissions resulting from geothermal operations | | | ■ | | | | | | | |
| Utilization efficiency for the geothermal power plant | ░ | | | ■ | ░ | | | | | |
| Water Quality of water bodies impacted by geothermal power plant operations | | ▒ | ■ | | | | | ░ | | |

[1]. Such concerns may also have arisen regarding proposals for the aggressive simultaneous development of a large portion of the country's available geothermal resources, for example in the event of the construction of an undersea cable for electricity export.

*5.1.2. New Zealand group*

In the New Zealand group the goals with the highest relevance to the sustainability of geothermal developments were focused on environmental management, economic management and research and innovation. The most relevant indicators were considered to be those concerning air and water quality, noise, threatened species and impact on geothermal features. This is not surprising since geothermal features are important to Maori culture and geothermal tourism is important to the New Zealand economy, due to the uniqueness of its geothermal features and ecosystems. Certain geothermal areas are therefore categorized as protected and are off-limits to development [13]. The goals considered least relevant dealt with energy equity, energy efficiency and resource renewability. The indicators considered least relevant for the New Zealand Delphi concerned household

**Table 4-9**
Linkages of satellite indicators to sustainability goals.

| Sattelite Indicator | G1 Renewability | G2 Water Resource Usage | G3 Environmental Mgt | G4 Efficiency | G5 Economic Mgt | G6 Energy Equity | G7 Energy Security | G8 Community Responsibility | G9 Research and Innovation | G10 Knowledge Dissemination |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Sustainability Goal** | | | | | | | | | |
| EBIDTA ratio per project | | | | | ▓ | | | | | |
| Percentage of protected area removed/affected due to geothermal project | | | ▓ | | | | | | | |
| Number of threatened species that may be affected by the geothermal project. | | | ▓ | | | | | | | |
| Rate of literacy of existing population in project-affected areas | | | | | ▒ | ▓ | | ░ | | |
| Cost per MW of power produced compared to price per MW from other sources | | | | | | | ▓ | | | |
| Income Equity in Project-Affected Communities | | | | | ▓ | | | | | |
| Infant mortality rates in the project-affected area | | | | | | ▓ | | ░ | | |
| Life expectancy at birth in project-affected area | | | | | | ▓ | | | | |
| Percentage of mass of fluid reinjected and/or cascaded compared to total extracted fluid mass | ▓ | | | ▒ | | | | | | |

| Sattelite Indicator | G1 Renewability | G2 Water Resource Usage | G3 Environmental Mgt | G4 Efficiency | G5 Economic Mgt | G6 Energy Equity | G7 Energy Security | G8 Community Responsibility | G9 Research and Innovation | G10 Knowledge Dissemination |
|---|---|---|---|---|---|---|---|---|---|---|
| Percentage of satisfied workers in the energy company per year | | | ■ | | | | | | | |
| Ratio of average male income to female income for similar jobs for the project staff | | | | | | | | ■ | | |
| Percentage of population with access to commercial energy in project-affected area | | | | | | ▓ | | | | |
| Amount of freshwater used during geothermal development as a percentage of available freshwater in the project area | | ▓ | ▒ | | | | | | | |
| Monetary value of socially beneficial initiatives in project-affected communities as a percentage of total project expenditure | | | | | | | | ▓ | | |
| Percentage of community residents that have agreed to potential culture-changing activities relating to the energy project | | | | | | | | ▓ | | |
| Unemployment rate in project-affected communities | | | | | ▓ | | | | | |
| Percentage of population below poverty line in project-affected area | | | | | | ▓ | | ░ | | |
| Economic diversity of project-impacted areas | | | | | ■ | | | | | |

expenditure on energy, plant power outages, energy company R&D expenditure, renewables in the total energy supply and literacy rates in the project area.

Iceland and New Zealand are developed countries and similarities existed in the stakeholder priorities. However, whilst Icelanders considered resource renewability among the most relevant goals, New Zealanders did not, even though policies in New Zealand seem to suggest otherwise. The current New Zealand Energy Strategy (2011–2021) cites a target of having 90 percent of electricity generation from renewable sources by 2025 [33]. In addition, the Waikato Regional Policy Statement advocates “controlled depletion” using a precautionary approach, encourages reinjection and acknowledges that a process of stepped production should be used in order to test the effects on the resource before increasing the take volume [14]. Furthermore, energy security is of more concern to New Zealanders than to Icelanders, which is interesting, because New

Zealand is almost as self-sufficient in terms of producing energy as Iceland. New Zealand's total energy self-sufficiency was 83% in 2013 [29], whilst Iceland's was 87% [44]. Being a developed country, access to reliable, affordable energy is probably not currently a big concern for the population of New Zealand and this is reflected in the country's energy affordability indicator [29]. Resource renewability may not be currently a pressing concern since there are no examples of a dramatic depletion in any of the exploited geothermal fields to date. Nonetheless, the issue of resource renewability has been discussed in particular with regard to Wairakei power plant [34], where the extraction of geothermal heat from the Wairakei–Tauhara system has been described as "unsustainable" as it currently occurs at around 5 times the system's natural recharge rate. However, while operation at a reduced capacity only may be possible after some time, the authors predict that both the resource pressure and temperature may fully recover to their pre-exploitation state after an extended shut-down period of 400 years.

#### 5.1.3. Kenyan group

In the Kenyan group, the goals of environmental management, economic management and research and innovation were considered most relevant. The indicators considered most relevant were those concerning project IRR, air quality, noise, reinjection and utilization efficiency, which resonate with the most relevant goals. The least relevant goals for the Kenyan stakeholders were those concerning water resource usage, energy efficiency and knowledge dissemination. It is surprising that water resource usage is not considered important in such a water-scarce region [32], however, as mentioned, water resource management could come under environmental management and be combined with that goal instead. Indicators concerning induced seismicity and subsidence, poverty, unemployment and household expenditure on energy were considered least relevant. Subsidence and induced seismicity are not common problems so far in Kenyan geothermal developments, so these choices are not surprising. However, poverty, unemployment, energy access and the affordability of energy are all issues of concern to funding bodies such as the World Bank and it is normally expected that geothermal developments should result in social benefits in the communities in which they are located. Furthermore, studies of the impacts of geothermal development on poor communities have also revealed that the issues of local employment and energy access are key concerns in Kenya [25]. It has also been shown that geothermal development in Kenya could have significant positive implications for the attainment of the Millenium Development Goals (MDGs) [36], which have the aims of eliminating poverty and hunger; attaining universal primary education, gender equality, reduction in child mortality, improvements in maternal and general health as well as environmental sustainability. It is therefore unclear as to why the stakeholders did not rate these indicators as highly relevant.

#### 5.1.4. UNU-GTP group

Among the UNU fellows, the goals with the highest relevance to the sustainability of geothermal developments were focused on water resource usage, research and innovation and economic management. The most relevant indicators were those regarding project IRR, utilization efficiency, air quality, resource lifetime and worker satisfaction, which somewhat reflect the most relevant goals of economic management and water resource usage. The goals considered least relevant dealt with community responsibility, resource renewability and energy equity. Indicators for male to female income ratio, income equity, impacts on geothermal features, greenhouse gas emissions and induced seismicity were considered least relevant.

The choices of the UNU stakeholders are interesting in that they do not include environmental management as a priority goal, apart from the goal concerning water resource usage. Economic and technical aspects appear to be more important than social aspects of geothermal developments for the group. The UNU-GTP and Kenyan Delphi group, whilst both having participants from developing countries, expressed different views on the relevance of the goals. Water resource usage was highly relevant to the UNU-GTP group, but less so for the Kenyans. This is expected since many of the participants come from water scarce countries, but it is in contradiction to the results of the Kenyan Delphi. Both groups considered economic management as highly relevant goals. The Kenyans were more concerned about environmental management, community responsibility and energy equity than the UNU-GTP group. These differences may also be due to differing levels of experience with regard to developing geothermal resources. Whilst it is somewhat to be expected that energy equity would be of less concern in developed countries, it is somewhat surprising that energy equity and other social issues, were in general of less concern to the stakeholders from developing countries also. Participating stakeholders in the UNU-GTP group were from such countries as China, Djibouti, El Salvador, Ethiopia, Iran, Malawi, Mexico, Morocco, Nicaragua, Philippines and Rwanda, many of which are striving to reach Millenium Development Goal targets. However, it should be noted that the stakeholders in the UNU-GTP stakeholder group were not, like the other groups, selected from a variety of sectors. The group was made up of students attending the UNU school in Reykjavik, most of whom already work for energy companies in their home countries, in varying capacities, which could lead to some bias in the results of this particular Delphi. These results should not be taken to represent a diversity of views as they could well be more industry-focused.

### 5.2. Consensus levels

Indicators may hold universally importance regardless of the nation or culture in which they are used [27]. This was clearly the case for some of the indicators that were produced from the Delphis in this study. Some indicators were considered universally relevant by all four groups (albeit to varying degrees), whilst others were important to one or some groups only. The specific choice of statistical tests in analyzing Delphi results can vary. Although the attainment of a consensus among participants was not the main goal of the Delphis, the level of consensus for each item after each round was indicated by its standard deviation. For the majority of items, consensus increased after each Delphi round, but consensus on items varied between the groups. It should also be noted that the standard deviation may also have been affected by a decrease in the number of participants after each round. As well as this, the same participants did not necessarily participate in each round.

Consensus was high in three out of four groups for the relevance of the goal of environmental management. Interestingly, in three out of four groups, however, consensus was low on the relevance of the goal of renewability. The levels of consensus for goals differed between developed and developing country groups. There was high consensus among stakeholders in developed country for the issues of economic management and research and innovation. In developed countries, there was low consensus on the goal of efficiency. In general, for all groups there was higher consensus on indicators relating to environmental impacts but lower consensus on the indicators relating to socio-economic and community issues which is reflected in the theory that the conditions for defining sustainable development tend to be determined by values and highly context-specific [38,27]. This does not mean that these indicators should be discarded but it is still important for potential users of the assessment framework to know which issues are likely to generate conflicting views among stakeholders. Given these differences in agreement on the relevance of certain goals and indicators, it could be worth exploring these issues further with stakeholders prior to carrying out an assessment.

### 5.3. Validity and effectiveness of the development process

The validity and effectiveness of the development process used to produce the assessment framework is discussed in this section. The limitations of the stakeholder engagement processes used and of the assessment framework itself are examined and potential improvements are discussed.

#### 5.3.1. Stakeholder engagement process

Stakeholder engagement is important in developing tools for assessing sustainability since there tends to be an absence of scientific consensus on the components of sustainable development. As well as this, conditions for defining sustainable development tend to be dynamic and context-specific and depend on the values of current as well as future human societies. The diversity of available frameworks already available suggests an uncertainty or differences regarding the measurement of sustainable development in different regions or in different groups [38,27]. Ideally, indicator selection works best with grassroots and expert participation, but this must be done carefully. Any indicators that have been chosen to assess sustainability should be rigorously checked by a panel of experts [27]. The strengths and weaknesses of both the World Café and Delphi techniques have been summarized in more detail by the authors in a paper describing the methodology of the indicator development process [43].

*5.3.1.1. World Café.* The pre-engagement workshops served to provide many useful ideas regarding the modification of the indicator set, as well as putting suggestions for new indicators forward. It also provided local insights and qualitative information, which although not directly useful for indicator development, did help to highlight important issues regarding geothermal development in both the Icelandic and Kenyan contexts.

The disadvantages of using the World Café technique, as for any type of stakeholder group meeting [46], include the potential for conflict in a group setting, due to differences in opinion of stakeholders. The cost of organizing and facilitating the workshop may be prohibitive and participants may need to travel long distances to reach the location. Many of these disadvantages were observed in the Icelandic World Café workshop [43].

In Nairobi, there were only five attendees, even though many more had originally agreed to attend. The low attendance may in part be explained by the difficult traffic conditions in Nairobi. It was also possible that people did not attend because the invitation letter did not indicate that travel expenses would be covered, which is apparently customary in many such meetings in Kenya. The organizers of the workshop had also only a limited time to make personal connections in Nairobi. Having a prior relationship with the invitees may also help to increase the attendance rate. For the Icelandic workshop, many of the attendees were already known to the organizers. The knowledge of participants regarding indicators in general also varied significantly, although this was to be expected and even desirable [16]. In the Kenyan workshop, voting was not used due to the time constraint, therefore the bandwagon effect was not observed. Not all participants had knowledge of each issue but the discussion between stakeholders served to educate and inform the group.

*5.3.1.2. Delphis.* Disadvantages associated with the Delphi technique include a high time commitment; hasty decisions by participants; the risk of producing a “watered down” opinion; or the potential for low response rates [39]. Other issues of concern include the selection of participants, the organization of feedback and the meaning or measurement of agreement or consensus [23]. Furthermore, clustering at the high end of the scale may occur when category scales are used to score items, making it difficult to interpret the result [26].

Participants were allowed several weeks to complete each round of the Delphi, in order to provide ample time and avoid the need to rush responses. In terms of response rates, there is no specific minimum response rate required when carrying out a Delphi, however the literature seems to agree that a minimum expert group size of 7–10 people [2] is necessary, with a maximum size of up to 30 participants being acceptable [49]. Response rates tended to drop after the first round, indicating the unwillingness of some participants to invest time in the survey, perhaps due to their other work commitments. Score clustering did occur to some extent, suggesting in retrospect that a different score allocation system may have been more appropriate.

Every attempt was made to involve a diverse group of stakeholders, using stakeholder mapping, during the process, however, this also meant that some participants came from a background with limited scientific knowledge. Although it is desirable to combine both grassroots and other expert views during indicator development, this can also lead to difficulties in understanding [20], especially when participants are geographically dispersed and have limited time to spare. The information sessions and introductory workshops were intended to help to educate participants to some extent, but they were not attended by everyone involved. In addition, although a diverse group of stakeholders were invited to take part in the Delphis, not all of them responded. In the case of the New Zealand group, for example, no NGO representatives took part. The Delphi technique was chosen in order to allow viewpoints from minority groups, however, some of these invited members, e.g. from the Maasai community did not have the means to take part in an online survey. It may have been more appropriate to carry out the survey with these individuals in person. It should be noted that in this study, the participant “samples” were not intended to be representative of a wider population.

If we consider only the overall result of a Delphi, we may neglect the minority views that are present. Where minority views are not taken into account, the participant may be tempted to drop out of the Delphi, leading to a “false consensus” in the final result. The Delphi must therefore “explore dissension” [22]. During the Delphis, the facilitators used personal judgement when synthesizing results of each round. Although it has been argued that facilitators may have too much influence on the Delphi [20], in this case it was instrumental in making sure minority views were taken account of.

During the Delphis, low scoring items were not discarded if it seemed that a greater consensus could be reached after feedback was provided. A mean score was considered “low” if it fell below 3. In the literature, the cut-off point for low scoring indicator tends to vary, depending on the type of research, and in this study, the mean score was used mainly as a rough guideline by the facilitators since other factors were considered when deciding to discard or keep an item for the next round. Although the mean score for some items reduced between rounds in some cases, this could perhaps be attributed to new stakeholders joining the Delphi after the first or second round and rating items with lower scores. All results, however, should be interpreted with some caution, since they do not take account changes in panel members after each round. It was not possible to ensure that each round would have exactly the same participants as the last. Also, as previously mentioned, for the UNU-GTP Delphi, the group members were all studying geothermal-related topics, probably worked for a geothermal development company previously and came from developing countries. This Delphi can thus be considered to have a more industry-focused viewpoint.

With regard to the consensus among participants, we chose the standard deviation of each item as a measure, although attaining a consensus was not the primary aim of the Delphis. The Delphis were carried out as more of an exploratory exercise to elicit the knowledge of the stakeholders on the complex issues of geothermal sustainability. Hence, the qualitative data gleaned from the stakeholder comments was perhaps of greater importance than the quantitative results overall. Due to the small sample size and variability of participants during the rounds, we confined ourselves to the use of mean and standard deviation as statistical indicators. The literature commonly advocates the use of mean and standard deviation in the interpretations of Delphi results as measures of control tendency and convergence ("consensus") respectively (see [28,7,15]), although other statistical tests may also be used, such as Friedman's X2r and Kendall's W [23] or fuzzy methods [10].

Participants were obliged to give each Delphi item a score in the survey, but comments were optional. This meant that stakeholder reasons for giving indicators a particular score were not always clear. It also meant that participants may have rushed through the survey without giving much thought to their responses in some cases. Similarly, the issue of the controlled feedback was a concern, since it was difficult to ascertain how the synthesized results sent out after each round actually influenced stakeholder responses throughout the Delphi process. In order to avoid drop-outs by the participants after each round, small prizes were offered to the participants who finished first and a grand prize was offered to the person who finished the entire Delphi fastest. As mentioned, the results of the Delphi should nonetheless be interpreted with caution, as it was not possible to keep the same panel members between rounds and excluding the responses from the statistical analyses was not practically feasible for all stakeholder groups, an issue that has been noted when using the Delphi in other fields for similar ends [23].

### 5.3.2. Status and use of indicator framework

At time of writing, four Delphis and three iterations of the indicator development process have been carried out. A common set of indicators has been identified based on the results of four Delphis, along with a set of supplementary indicators. Based on the Tables 4-6 and 4-7 it can be observed that the current set of sustainability indicators adequately cover the themes put forward in the CSD framework [48]. In order to be influential, consensus must exist among policy actors that the indicators are legitimate, credible and salient [8]. This means that the indicators must not only answer questions that are relevant to the policy actor, but also provide a scientifically plausible and technically adequate assessment. Since the CSD framework is not specifically tailored to geothermal developments, we therefore also used the sustainability goals chosen by the stakeholders as a conceptual classification for the indicators (the coverage of these goals by the indicators is shown in Tables 4-8 and 4-9). To be legitimate, the indicators must be perceived to be developed through a politicaly, socially and ethically acceptable procedure. The results of the Delphi show a definite increase in the level of consensus among the participants by the end of the third round. This is evident from the change in the standard deviation for the majority of the goals and indicators between rounds. We suggest that the Delphi process used in this study lends legitimacy, credibility and saliency to goals and indicators that were produced. Having said this, a number of limitations are also associated with indicator frameworks in general.

*5.3.2.1. Limitations of assessment frameworks.* The inherent limitations of sustainability assessment frameworks should be acknowledged. These include difficulties in defining sustainable development; imperfect systemic coverage; data availability concerns; institutional concerns and difficulties in aggregating values.

In developing tools for assessing sustainable development, a difficulty lies in defining sustainable development itself, as this involves the imposition of a particular worldview [40]. It can be argued that this problem would be remedied by good communication between stakeholders on the relevance of indicators and to ensure that they are continually reviewed and updated [30], however in practice this process may be time consuming and costly if not managed appropriately. In this research, the Delphi technique was chosen to encourage structured communication and feedback between stakeholders and facilitators and to avoid confrontation in a group of people with potentially very diverse world views and backgrounds. It was found that although there was a general agreement on a set of sustainability goals by all participants, different Delphi groups chose different indicators based on their priorities, which meant that it was not possible to produce a homogenous group of indicators to measure the sustainability of geothermal development. However, it was at least possible to identify some indicators that were considered important by all groups, albeit to different degrees and thus produce a set of core and optional indicators.

The adequacy of the coverage of sustainability indicators can also be called into question as they sometimes fail to provide information on the systemic causes of the indicator values and the interactions between them [18]. The themes put forward in the CSD indicator framework [48] were used to organise the sustainability issues for geothermal energy developments that were identified in this study. However it is outside the scope of this work to assess the adequacy of coverage of the CSD thematic framework itself. The coverage of these themes by the indicators produced in this study has been shown to be adequate, although in some instances, some themes received more coverage than others. Stakeholders found it particularly difficult to select social and cultural indicators, so more research is needed in this regard. Regardless of the extent of coverage, indicators will never capture all the nuances of a system and the OECD recommends that indicators should, be reported and interpreted in the appropriate context and have non-scientific descriptions included with them [35]. It is also recommended that to make them fully understandable, indicators should also be developed alongside a fully dynamic model [27].

Unfortunately, without adequate data collection, even good indicators will not be useful. In some countries, the collection of data for certain indicators may not automatically be done by governments or other organizations and can be time consuming and expensive. A lack of quantitative information for certain indicators, may lead to important issues being neglected by decision-makers. Several indicators in this study were rejected on the basis of lack of data, although potentially mechanisms could be put in place to collect this data.

The governance context within which the assessment framework is embedded will determine the effectiveness of its use [3,4]. Institutional barriers may include the absence of integrated strategic planning, lack of experience in developing, using or monitoring indicators or lack of resources [9]. If no accountability mechanisms are in place, then the indicators will have little impact in the policy process and will lack credibility and legitimicay in the eyes of the public. As well as this, indicators are often developed without adequately considering the needs of the end users, e.g. policymakers, meaning that they fail to bridge the gap between science and policy [8]. It is not possible for the creators of indicators to control the way in which they are eventually used, i.e. the "software" that ensures sustainability concerns will be taken into account in policymaking [24] and the authors can only make recommendations regarding the institutional context in which the indicators may be used. To avoid a particular normative bias, in this study the indicators

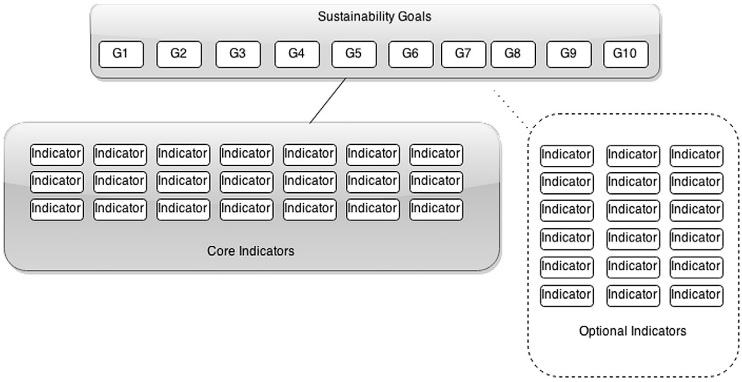


**Fig. 5-1.** Suggested sustainability assessment framework structure.

were developed with the input of varied stakeholders, which will hopefully at the very least lend them some added credibility and legitimacy as well as improve the policy-relevance of the indicators chosen. It would also be beneficial to clearly link the indicators to national frameworks that monitor sustainable energy policies as a whole. These indicators can provide a more refined means of tracking sustainability progress on the project level that may then feed into national level indicator systems (i.e., a multi-level indicator system).

It was decided not to add weights to the indicators as it was felt that too much information would be lost due to the "information iceberg" effect [30] if the indicators were to be aggregated. As well as this, the choice of weights is a politically sensitive and value-laden process, prone to arbitrariness and inconsistency [6]. The framework could form the basis, however, for the calculation of an index that uses weights, but careful consideration would need to be given to the themes that would be aggregated as well as the units used.

*5.3.2.2. Proposed structure of assessment framework.* Overarching issues that transcend nations and cultures require overarching indicators to measure them, helping to narrow the differences between worldviews [27]. We suggest that a framework (Fig. 5-1) of sustainability goals measured by core and optional indicators can be derived from the results of the Delphis presented here. Core indicators are those that have been deemed universally relevant by all of the stakeholders. Optional indicators are those that have potential relevance, depending on the circumstances. More optional indicators could be produced in the future, with further stakeholder input. Qualitative information can aid with the selection and development of optional indicators.

For the framework to become a useable tool, a set of guidelines for users will need to be produced in the form of a handbook, where the assessment process will be outlined to assessors. Qualitative information will also need to be incorporated into the assessment, alongside the indicator data and reported in an appropriate way so as to fully inform the potential audience of the unique circumstances surrounding the geothermal project in question.

Indicators of sustainability are only likely to be effective if they provide users and the public with meaningful information they can relate to. Users like policy- and decision-makers will be in a better position to set attainable policy goals if they understand environment–society interactions well, and this is all the more likely to happen if indicators are derived from a participatory process, as they will reflect the objectives and values of the public [41]. The sustainability goals and indicators were chosen or critically reviewed by the stakeholders in this study, so the list should prove useful to useful to future users, such as policy-makers or regulators in the national context. However, stakeholder input should continuously be sought to ensure that the assessment framework remains up-to-date and reflects the views and values of all impacted parties.

*5.3.2.3. Next steps – implementation of sustainability assessment framework.* We suggest that the sustainability assessment framework proposed in this paper be implemented on existing geothermal developments to further test its suitability. The framework of goals and indicators can be used to assess geothermal projects at all stages of development, however, in the earlier phases it is likely that data will not be available for all indicators. In these cases, additional socio-economic models may be required to predict the impacts of the geothermal development before the indicators can be calculated. If assessments are carried out over a number of years, time series data can be built up for the indicators. The creation of successful indicators, more than anything else, depends on how they are integrated into governance and policy processes [45]. Further research into the way in which the sustainability indicators in this assessment framework can be used to inform the process of policy- or decision-making is required. However we suggest that at a minimum, the indicators and their development process can be very useful in facilitating social learning and in lending political credibility to the assessment and monitoring of current and future geothermal developments. And, whilst the assignment of weights to indicators is a politically sensitive process, the indicator framework can serve as a starting point for decision-makers faced with the task of creating strategies to guide geothermal developments along a sustainable path.

## 6. Conclusion

This paper describes the development of a customized sustainability assessment framework for geothermal energy development through case studies in Iceland, New Zealand and Kenya. The research resulted in the choice of a set of ten stakeholder-validated sustainability goals and 21 core and 18 optional indicators which form a flexible assessment tool that has potential to be used or developed further in a variety of ways. By documenting the experiences of the stakeholder-driven indicator development process in three different countries, this paper not only contributes to academic knowledge on the methods of development of indicators of energy sustainability in general, but also regarding their development across national and cultures, which is increasingly acknowledged as a necessity in this field. It provides evidence of the need to consider and incorporate a diversity of opinion when measuring sustainability progress and therefore the need for more advanced and inclusive forms of local stakeholder engagement methods in all types of development projects. The results of the stakeholder engagement process showed a significant diversity of opinion regarding the relevance of goals and indicators between stakeholder groups. For instance, with regard to goals of sustainable geothermal developments, environmental management was a common concern among the Icelandic, New Zealand and Kenyan participants, whereas water usage was considered the most important environment-related issue for the UNU-GTP fellows. The Kenyan, New Zealand and the UNU-GTP groups rated economic management and profitability, along with research and innovation, highly, whereas the Icelandic group placed highest emphasis on resource renewability and also rated knowledge dissemination highly.

The methods illustrated and tested in this paper are of practical value to policy and decision-makers in the context of developing indicators using a participatory process. The action of involving stakeholders in the indicator development process can facilitate the provision of more plausible and relevant information between scientists and policy-makers or the general public. As well as this, given that it has been qualified and evaluated by a diverse range of international stakeholders, the framework can be said to have increased political credibility in the eyes of the public, since it merges different societal and political norms. Whilst the framework produced in this research is generally intended to serve in retrospective assessment of the performance of geothermal projects in attaining sustainability goals, it may also serve as a basis for designing qualitative tools for prospective assessments of such projects. In view of the likely expansion of geothermal capacity in coming years, we foresee an urgent need to ensure the sustainable development of geothermal resources worldwide and recommend that such tools be used by decision and policy-makers and that additional research be carried out to develop them further.

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**Appendix A**

*Final list of geothermal sustainability goals produced using results of all Delphis*

*GOAL 1 – Renewability:* In order to ensure that a geothermal resource remains replenishable, sustainable production should be the goal in all geothermal projects. For each geothermal area and each mode of production there exists a certain maximum level of production, E0, so that with production below E0 it is possible to sustain steady energy production from the system for at least 100–300 years. If the level of production exceeds E0 it is not possible to sustain steady production from the system for so long. Geothermal production that is less than or equal to E0 is defined as sustainable production but production exceeding E0 is not sustainable.

*GOAL 2 – Water Resource Usage:* Water usage of a power plant must not reduce supply of cold fresh water to communities nearby.

*GOAL 3 – Environmental Management:* A geothermal resource should be managed in such a way as to avoid, remedy or mitigate adverse environmental effects.

*GOAL 4 – Efficiency:* Geothermal utilization shall be managed in such a way as to maximize the utilization of exergy available where practical at sustainable production levels. The desired maximum efficiency for electricity generation should be based on the theoretical maximum efficiency for converting heat to electrical energy (Carnot efficiency).

*GOAL 5 – Economic Management & Profitability:* Energy use from geothermal power and heat plants must be competitive, cost effective and financially viable. The financial risk of the project shall be minimized. The project should carry positive net national and community economic benefits.

*GOAL 6 – Energy Equity:* The energy supplied by the geothermal resource is readily available, accessible and affordable to the public.

*GOAL 7 – Energy Security & Reliability:* The operation of geothermal power and heat plants shall be reliable and prioritize the security of supply.

*GOAL 8 – Community Responsibility:* The power companies should be responsible toward the community and the effect of the utilization of the geothermal resource shall be as positive for the community as possible and yield net positive social impact.

*GOAL 9 – Research and Innovation:* Power companies shall encourage research that improves the knowledge of the geothermal resource as well as technical developments that improve efficiency, increase profitability and reduce environmental effects.

*GOAL 10 – Dissemination of Knowledge:* Information and experience gained through geothermal utilization shall be accessible and transparent to the public and the academic community alike while respecting confidential intellectual property rights.

**Appendix B**

Highest scoring goals – Icelandic Delphi

| Goal | Score |
|---|---|
| GOAL 1 – Renewability | 4.55 |
| GOAL 3 – Environmental Management | 4.45 |
| GOAL 10 – Dissemination of knowledge | 4.27 |

Highest scoring goals – New Zealand Delphi

| Goal | Score |
|---|---|
| GOAL 3 – Environmental Management | 5 |
| GOAL 5 – Economic Management & Profitability | 4.8 |
| GOAL 9 – Research and Innovation | 4.8 |

Highest scoring goals – Kenyan Delphi

| Goal | Score |
|---|---|
| Goal 3- Environmental Management | 5 |
| Goal 5 – Economic Management & Profitability | 5 |
| Goal 9 – Research and Innovation | 5 |

Highest scoring goals – UNU-GTP Delphi

| Goal | Score |
|---|---|
| GOAL 2: Water Usage | 4.89 |
| GOAL 9 – Research and Innovation | 4.89 |
| GOAL 5 – Economic Management & Profitability | 4.78 |

Lowest scoring goals – Icelandic Delphi

| Goal | Score |
|---|---|
| GOAL 4 – Efficiency | 3.64 |
| GOAL 6 – Energy Equity | 3.64 |
| GOAL 7 – Energy Security | 4 |

Lowest scoring goals – New Zealand Delphi

| Goal | Score |
|---|---|
| GOAL 6 – Energy Equity | 4 |
| GOAL 4 – Efficiency | 4.1 |
| GOAL 1 – Renewability | 4.2 |

Lowest scoring goals – Kenyan Delphi

| Goal | Score |
|---|---|
| Goal 2 – Water Resource Usage | 4.29 |
| Goal 4 – Efficiency | 4.57 |
| Goal 10 – Knowledge Dissemination | 4.57 |

Lowest scoring goals – UNU-GTP Delphi

| Goal | Score |
|---|---|
| GOAL 8 – Community Responsibility | 4.22 |
| GOAL 1 – Renewability | 4.33 |
| GOAL 6 – Energy Equity | 4.33 |

## Appendix C

Icelandic Delphi – indicator scores after each Delphi round and reasons for elimination

| Indicator | Mean R1 | Mean R2 | Mean R3 | Reason for elimination |
|---|---|---|---|---|
| Air quality in the surrounds of the geothermal power plant | 4.28 | 4.36 | 4.78 | |
| Area of land used due to geothermal energy project (including infrastructure) | 3.04 | n/a | n/a | No clear reference value available |
| Average Income Levels in Project-Affected Communities | 2.32 | 2.72 | 3.33 | |
| Direct and indirect local job creation over lifetime of project | 3.09 | 2.93 | 3.44 | |
| Duration of Plant Power Outages per year | 3.07 | 3.36 | 3.89 | |
| EBIDA ratio per project | n/a | 3.04 | 3.33 | |
| Economic diversity of project-impacted areas | 3.16 | n/a | n/a | No clear reference value available, relevance to sustainable development unclear |
| Energy diversity index for project-affected regions | 2.76 | n/a | n/a | Not considered a relevant measure of geothermal sustainability |
| Estimated productive lifetime of geothermal resource | 4.48 | 4.68 | 4.56 | |
| Expenditure on heat and electricity as a percentage of household income | 3.09 | 3.25 | 3.33 | |
| Housing value in the area compared to national average | 2.1 | n/a | n/a | Not considered a relevant measure of geothermal sustainability |
| Impact on important or vulnerable geothermal features | 3.47 | 4.20 | 4.00 | |
| Imported energy as a percentage of total (national level) | 3.13 | 3.43 | 3.56 | |
| Income Equity in Project-Affected Communities | 2.48 | n/a | n/a | Not considered a relevant measure of geothermal sustainability |
| | 3.22 | 3.43 | 3.56 | |

| | | | | |
|---|---|---|---|---|
| Income-to-expenditure ratio for project-affected municipalities | | | | |
| Initial phase capacity as a percentage of estimated total capacity | 2.35 | 3.0 | n/a | No clear reference value available |
| Level of induced seismicity per year | 3.22 | 3.61 | 3.67 | |
| Make-up holes as a function of time | 2.79 | n/a | n/a | Indicator not easily understandable |
| Noise levels in working, recreation and residential areas in the surrounds of the geothermal power plant. | 3.66 | 3.71 | 4.22 | |
| Number of accidents leading to work absence in the energy company per year | 2.93 | 3.65 | 4.22 | |
| Odor experience from $H_2S$ gas in residential or recreational areas near the power plant | 3.65 | n/a | n/a | Already covered by air quality indicator (double counting) |
| Percentage of community residents that must be relocated due to energy project | 3.73 | 3.75 | 3.89 | |
| Percentage of energy company expenditure given to R&D per year | 3.04 | 3.79 | 3.33 | |
| Percentage of females with university education in local energy company | 2.4 | n/a | n/a | Not considered a relevant measure of geothermal sustainability |
| Percentage of population with access to commercial energy in project-affected area | 2.98 | n/a | n/a | Not considered a relevant measure of geothermal sustainability (in Iceland) |
| Percentage of protected area removed/ affected due to geothermal project | 4.27 | 4.04 | 4.11 | |
| | 3.66 | 4.22 | 3.33 | |
| Percentage of renewables in total energy supply nationally | | | | |
| Percentage of satisfied workers in the energy company per year | 2.4 | n/a | n/a | Not considered a relevant measure of geothermal sustainability |
| Project internal rate of return (IRR) | 3.61 | 3.68 | 3.67 | |
| Rate of subsidence in the geothermal field | 3.26 | 3.97 | 4.11 | |
| Ratio of average male income to female income for the project-affected area. | 2.25 | 3.65 | 3.89 | |
| Ratio of rate of change in housing prices to rate of change in income levels (Housing affordability) | 1.9 | n/a | n/a | Indicator not easily understandable |
| Ratio of reinjection to production | n/a | 4.00 | n/a | No clear reference value available |
| Resource reserve capacity ratio of the geothermal resource | 4.04 | 4.22 | 4.22 | |
| Tons of acidifying air pollutants ($H_2S$, $SO_2$) emitted as a result of geothermal operations | 4.35 | n/a | n/a | |
| Tons of greenhouse gas emissions resulting from geothermal operations | 3.76 | 4.04 | 4.11 | Already covered by air quality indicator (double counting) |
| Total cases lost in supreme court by energy company per year | 1.57 | n/a | n/a | No clear reference value available |
| Unemployment rate in project affected areas | 2.43 | n/a | n/a | Already covered by the employment indicator (double counting) |
| Utilization efficiency for the geothermal power plant | 4.04 | 4.25 | 4.22 | |
| Water Quality of water bodies impacted by geothermal power plant operations | 4.13 | 4.54 | 4.67 | |

New Zealand Delphi – indicator scores after each Delphi round and reasons for elimination

| Indicator | **Mean Round 1** | **Mean Round 2** | **Mean Round 3** | **Reason for Elimination** |
|---|---|---|---|---|
| (Potential) loss of earnings in impacted communities resulting from changes in land use as a result of the geothermal development | n/a | 4.25 | n/a | Double counting – already covered by the income/purchasing power indicator |
| Air quality in the surrounds of the geothermal power plant | 3.5 | 4.5 | 4.5 | |
| Area of land used due to geothermal energy project (including infrastructure) | 1.86 | n/a | n/a | No clear reference value available |
| Average income (purchasing power of income) | 2.34 | 3.63 | 4 | |
| Cost of food to families who originally would have sourced significant amounts of their food from the nearby areas/rivers and who now have to buy food | n/a | 3.75 | n/a | Double counting – already covered by the income/purchasing power indicator |
| Direct and indirect local job creation over lifetime of project | 2.34 | 4.25 | 4.1 | |
| Duration of Plant Power Outages per year | 1.84 | 4 | 3.6 | |
| Economic diversity of project-impacted areas | 2.67 | n/a | n/a | No clear reference value available, relevance to sustainable development unclear |
| Energy diversity index for project-affected regions | 1.75 | n/a | n/a | Not considered a clear or relevant measure of geothermal sustainability |
| Estimated productive lifetime of geothermal resource | 4.59 | 4.5 | 3.9 | |
| Expenditure on heat and electricity as a percentage of household income | 2.17 | 3.25 | 3.5 | |
| Impact on important or vulnerable geothermal features | 4.13 | 5 | 4.8 | |
| Imported energy as a percentage of total (national level) | 3 | 3.63 | 3.9 | |
| Income Equity in Project-Affected Communities | 1.25 | n/a | n/a | Not considered a clear or relevant measure of geothermal sustainability |
| Income-to-expenditure ratio for project-affected municipalities | 2.17 | 3.75 | 4.3 | |
| Infant mortality rates in the project-affected area | 1.42 | 2.88 | n/a | Not considered a clear or relevant measure of geothermal sustainability |
| Level of induced seismicity per year | 3.25 | 3.75 | 4 | |
| Life expectancy at birth in project-affected area | 1.42 | 2.88 | n/a | Not considered a clear or relevant measure of geothermal sustainability |
| Noise levels in working, recreation and residential areas in the surrounds of the geothermal power plant. | 3.94 | 4.13 | 4.4 | |
| Number of accidents leading to work absence in the energy company per year | 2 | 3.88 | 4.4 | |
| Number of threatened species that may be affected by the geothermal project. | n/a | 4.5 | 4.5 | |
| | 3.57 | n/a | n/a | |

| | | | | |
|---|---|---|---|---|
| Odor experience from $H_2S$ gas in residential or recreational areas near the power plant | | | | Double counting – already covered by the air quality indicator |
| Percentage of community residents that must be relocated due to energy project | 4.25 | 4.25 | 3.9 | |
| Percentage of energy company expenditure given to R&D per year | 2.75 | 3.75 | 3.8 | |
| Percentage of population below poverty line in project-affected area | 1.5 | n/a | n/a | Not considered a clear or relevant measure of geothermal sustainability |
| Percentage of population with access to commercial energy in project-affected area | 2.42 | 4.25 | 4 | |
| Percentage of renewables in total energy supply nationally | 2.5 | 4.38 | 3.8 | |
| Percentage of satisfied workers in the energy company per year | 1.5 | n/a | n/a | Not considered a clear or relevant measure of geothermal sustainability |
| Percentage of unlicensed teachers in the project-affected area | 0.42 | 2.88 | n/a | Not considered a clear or relevant measure of geothermal sustainability |
| Project internal rate of return (IRR) | 3 | 3.75 | 3.9 | |
| Rate of literacy in project-affected areas | 1.2 | 3.38 | 3.8 | |
| Rate of literacy of existing population in project-affected areas | 1.2 | 3.38 | 3.8 | |
| Rate of subsidence in the geothermal field | 3.65 | 4.13 | 4.3 | |
| Ratio of average male income to female income for the project-affected area. | 0.25 | n/a | n/a | Not considered a clear or relevant measure of geothermal sustainability (in New Zealand) |
| Ratio of rate of change in housing prices to rate of change in income levels (Housing affordability) | 1.17 | n/a | n/a | Not considered a clear or relevant measure of geothermal sustainability |
| Resource reserve capacity ratio of the geothermal resource | 3 | 3.88 | 4 | |
| Tons of acidifying air pollutants ($H_2S$, $SO_2$) emitted as a result of geothermal operations | 3.32 | n/a | n/a | Double counting – covered by air quality indicator |
| Tons of greenhouse gas emissions resulting from geothermal operations | 3.63 | 4.25 | 4.1 | |
| Total cases lost in supreme court by energy company per year | 1.42 | n/a | n/a | No clear reference value available |
| Unemployment rate in project affected areas | 1.42 | n/a | n/a | Better counted by job creation indicator |
| Utilization efficiency for the geothermal power plant | 3.67 | 3.88 | 4.1 | |
| Value of land for nearby communities | n/a | 3 | n/a | Double counting – already covered by the income/ purchasing power indicator |
| Water Quality of water bodies impacted by geothermal power plant operations | 4.19 | 4.88 | 4.9 | |

Kenyan Delphi – indicator scores after each Delphi round and reasons for elimination

| Indicator | Mean Round 1 | Mean Round 2 | Mean Round 3 | Reasons for Elimination |
|---|---|---|---|---|
| Air quality in the surrounds of the | 4.86 | 5.00 | 4.86 | No clear reference value available |

| | | | | |
|---|---|---|---|---|
| geothermal power plant | | | | |
| Amount of freshwater used during geothermal development (exploration, construction or operation activities) as a percentage of available freshwater in the project area | 4.29 | 4.40 | 4.43 | |
| Area of land used due to geothermal energy project (including infrastructure) | 3.57 | n/a | n/a | |
| Average Income Levels in Project-Affected Communities | 4.14 | 4.30 | 4.43 | |
| Direct and indirect local job creation over lifetime of project | 4.71 | 4.20 | 4.43 | |
| Duration of Plant Power Outages per year | 4.00 | 4.40 | 4.43 | |
| Economic diversity of project-impacted areas | 4.14 | 4.40 | 4.14 | |
| Energy diversity index for project-affected regions | 3.86 | n/a | n/a | Not considered a clear or relevant measure of geothermal sustainability |
| Estimated productive lifetime of geothermal resource | 4.57 | 4.50 | 4.57 | |
| Expenditure on heat and electricity as a percentage of household disposable income | 4.14 | 4.00 | 3.71 | |
| Impact on important or vulnerable geothermal features | 4.57 | 4.10 | 4.43 | |
| Imported energy as a percentage of total (national level) | 4.00 | 4.20 | 4.00 | |
| Income Equity in Project-Affected Communities | 3.86 | 4.00 | 4.00 | |
| Income-to-expenditure ratio for project-affected municipalities | 4.14 | 4.10 | 4.00 | |
| Infant mortality rates in the project-affected area | 3.86 | 3.90 | 4.00 | |
| Level of induced seismicity per year | 3.00 | 4.00 | 3.71 | |
| Life expectancy at birth in project-affected area | 3.29 | 3.70 | n/a | Not considered a clear or relevant measure of geothermal sustainability |
| Monetary value of socially beneficial initiatives in project-affected communities as a percentage of total project expenditure | 4.14 | 4.40 | 4.43 | |
| Noise levels in working, recreation and residential areas around the geothermal power plant. | 4.71 | 4.60 | 4.86 | |
| Number of accidents leading to work absence in the energy company per year | 3.71 | 3.90 | 4.29 | |
| Number of threatened species that may be affected by the geothermal project | 4.29 | 4.40 | 4.00 | |
| Percentage of community residents that have agreed to potential culture-changing activities relating to the energy project | 3.43 | 4.10 | 4.00 | |
| Percentage of community residents that must be | 4.71 | 4.70 | 4.43 | |

| | | | | |
|---|---|---|---|---|
| relocated due to energy project | | | | |
| Percentage of energy company expenditure given to R&D per year | 3.86 | 3.90 | 4.43 | |
| Percentage of mass of fluid reinjected and/ or cascaded compared to total extracted fluid mass | n/a | 4.40 | 4.71 | |
| Percentage of population below poverty line in project-affected area | 3.71 | 3.90 | 3.57 | |
| Percentage of population with access to commercial energy in project-affected area | 3.71 | 3.90 | 4.29 | |
| Percentage of renewables in total energy supply nationally | 4.29 | 4.50 | 4.57 | |
| Percentage of satisfied workers in the energy company per year | 3.57 | 4.20 | 4.29 | |
| Percentage of unlicensed teachers in the project-affected area | 3.29 | n/a | n/a | Not considered a clear or relevant measure of geothermal sustainability (in Kenya) |
| Project internal rate of return (IRR) | 4.86 | 4.30 | 5.00 | |
| Rate of literacy in project-affected areas | 3.71 | 3.90 | 4.00 | |
| Rate of subsidence in the geothermal field | 3.86 | 4.10 | 3.86 | |
| Ratio of average male income to female income for the project-affected area. | 3 | n/a | n/a | Not considered a clear or relevant measure of geothermal sustainability |
| Ratio of rate of change in housing prices to rate of change in income levels (Housing affordability) | 3.14 | n/a | n/a | Not considered a clear or relevant measure of geothermal sustainability |
| | 4.29 | 4.30 | 4.14 | |
| Resource reserve capacity ratio of the geothermal resource | | | | |
| Tons of acidifying air pollutants ($H_2S$, $SO_2$) emitted as a result of geothermal operations | 4.57 | n/a | n/a | Double counting – covered by air quality indicator |
| Tons of greenhouse gas emissions resulting from geothermal operations | 4.57 | 4.40 | 4.43 | |
| Total area of land that has been compacted due to geothermal development activities | 3.43 | 3.60 | n/a | No clear reference value available |
| Total cases lost in supreme court by energy company per year | 3.14 | n/a | n/a | No clear reference value available |
| Unemployment rate in project-affected communities | 3.86 | 4.30 | 3.86 | |
| Utilization efficiency for the geothermal power plant | 4.71 | 4.30 | 4.57 | |
| Water Quality of water bodies impacted by geothermal power plant operations | 4.86 | 4.60 | 4.43 | |

UNU-GTP Delphi – indicator scores after each Delphi round and reasons for elimination

| **Indicator** | **Mean Round 1** | **Mean Round 2** | **Mean Round 3** | **Reasons for Elimination** |
|---|---|---|---|---|
| Air quality in the surrounds of the geothermal power plant | 4.28 | 4.55 | 4.63 | |
| Area of land used due to geothermal energy project (including infrastructure) | 3.28 | n/a | n/a | No clear reference value available |
| Average Income Levels in Project-Affected Communities | 4.06 | 4 | 3.88 | |

| | | | | |
|---|---|---|---|---|
| Cost (price) per MW of power produced compared to price per MW from other sources | n/a | 4.09 | 4.25 | |
| Direct and indirect local job creation over lifetime of project | 4.44 | 4.55 | 4 | |
| Duration of Plant Power Outages per year | 3.72 | 4.36 | 4.13 | |
| Economic diversity of project-impacted areas | 4.17 | 3.82 | n/a | Economic diversity of project-impacted areas |
| Energy diversity index for project-affected regions | 4 | n/a | n/a | Not considered a clear or relevant measure of geothermal sustainability |
| Estimated productive lifetime of geothermal resource | 4.67 | 4.55 | 4.5 | |
| Expenditure on heat and electricity as a percentage of household income | 3.78 | 3.91 | 4.13 | |
| Impact on important or vulnerable geothermal features | 4.22 | 4.27 | 3.75 | |
| Imported energy as a percentage of total (national level) | 4.11 | 4.09 | 4 | |
| Income Equity in Project-Affected Communities | 3.56 | 3.91 | 3.75 | |
| Income Equity in Project-Affected Communities | 3.56 | 3.91 | n/a | Not considered a clear or relevant measure of geothermal sustainability |
| Income-to-expenditure ratio for project-affected municipalities | 3.94 | 3.91 | 3.88 | |
| Infant mortality rates in the project-affected area | 3 | 3.82 | 3.88 | |
| | 3.72 | 4.36 | 3.75 | |
| Level of induced seismicity per year | | | | |
| Life expectancy at birth in project-affected area | 3.33 | 3.91 | 3.75 | |
| Noise levels in working, recreation and residential areas in the surrounds of the geothermal power plant. | 4.56 | 4.09 | 3.88 | |
| Number of accidents leading to work absence in the energy company per year | 3.28 | 4 | 4.38 | |
| Odor experience from $H_2S$ gas in residential or recreational areas near the power plant | 4.56 | n/a | n/a | Double counting – covered by air quality indicator |
| Percentage of community residents that must be relocated due to energy project | 3.5 | 3.82 | 3.88 | |
| Percentage of energy company expenditure given to R&D per year | 3.94 | 3.82 | 4 | |
| Percentage of mass of fluid reinjected and/or cascaded compared to total extracted fluid mass | n/a | 4.36 | 4 | |
| Percentage of population below poverty line in project-affected area | 3.83 | n/a | n/a | Not considered a clear or relevant measure of geothermal sustainability |
| Percentage of population with access to commercial energy in project-affected area | 3.83 | 4.09 | 4.25 | |
| Percentage of renewables in total energy supply nationally | 4.44 | 4.18 | 4.25 | |
| Percentage of satisfied workers in the | 4.06 | 3.82 | 4.5 | |

| | | | | |
|---|---|---|---|---|
| energy company per year | | | | |
| Percentage of unlicensed teachers in the project-affected area | 2.44 | n/a | n/a | Not considered a clear or relevant measure of geothermal sustainability |
| Project internal rate of return (IRR) | 4.5 | 4.45 | 4.88 | |
| Rate of literacy of existing population in project-affected areas | 3.72 | 4.09 | 3.88 | |
| Rate of subsidence in the geothermal field | 4.22 | 4.27 | 3.88 | |
| Ratio of average male income to female income for similar jobs for the project staff | 2.94 | 3.27 | 3.13 | |
| Ratio of rate of change in housing prices to rate of change in income levels (Housing affordability) | 3.06 | n/a | n/a | Not considered a clear or relevant measure of geothermal sustainability |
| Resource reserve capacity ratio of the geothermal resource | 4.33 | 4.36 | 4 | |
| Tons of acidifying air pollutants ($H_2S$, $SO_2$) emitted as a result of geothermal operations | 4.17 | n/a | n/a | Double counting – covered by air quality indicator |
| Tons of greenhouse gas emissions resulting from geothermal operations | 4.17 | 4.27 | 3.5 | |
| Total cases lost in supreme court by energy company per year | 3 | n/a | n/a | No clear reference value available |
| Unemployment rate in project-affected communities | 3.89 | 4.09 | n/a | Better counted by job creation indicator |
| Utilization efficiency for the geothermal power plant | 4.67 | 4.73 | 4.88 | |
| Water Quality of water bodies impacted by geothermal power plant operations | 4.56 | 4.82 | 4.38 | |

Sample comments for high scoring indicator from Icelandic Delphi: Air Quality

| Delphi Round | Sample comment |
|---|---|
| Round 2 | Important measure and regulated but I think that the odor threshold can be too stringent. |
| Round 1 | But the WHO reference values are not very strict |
| Round 1 | This indicator should replace also the one on odor. That is air quality should also be measured in residential and recreational areas – and that should be the indicator. There is some repetition though – as the indicator before this one measures total emissions, whereas concentrations are more important |

Sample comments for low scoring indicators from Icelandic Delphi: Percentage of renewables in total energy supply nationally

| Delphi Round | Sample comment |
|---|---|
| Round 2 | I do not see the direct relevance for each project but a good indicator on a national level |
| Round 1 | Again – wonder about the relevance. As this is indicator system is for a renewable energy source – is this relevant? |
| Round 2 | One of the goal of geothermal utilization is to lower the use of non-renewables, so important indicator to monitor. |

Sample comments for high scoring indicators from New Zealand Delphi: Water Quality

| Delphi Round | Sample comment |
|---|---|
| Round 1 | Geothermal development should have no impact on water quality. There should be no discharges to water bodies unless to water of similar, contaminated, quality. In this case, the net impact should be no more than minor. |
| Round 1 | I would suggest that there should be no change to waterbodies near geothermal powerstations if the development and design of the station cooling and reinjection has been done right. |
| Round 1 | Water quality is very important to Maori communities and the 'reference values' listed above are part of that. There is also an overlying understanding of water that Maori also value – mauri, or the life-supporting capacity of the water, which includes those reference values as well as meta-physical attributes. Interestingly as an example water with elevated levels of naturally occurring geothermal 'contaminants' – e.g. arsenic, chloride may not have a negative impact on the mauri if people have been living in and around the waters for generations. |

| | |
|---|---|
| Round 2 | All effects of geothermal use need to be accounted for, including the externalities of affecting surface water bodies. This is so that policy decisions will adequately weigh up all the impacts, including by doing cost benefit analyses, and put in place strategies/contracts to avoid remedy and mitigate these effects. To measure these would be USEFUL in measuring sustainable development and it is possible to create indicators that are MEASURABLE and EASY TO INTERPRET. |

Sample comments for low scoring indicators from New Zealand Delphi: Rate of literacy of existing population in project-affected areas

| Delphi Round | Sample comment |
|---|---|
| Round 1 | You can import literate people to run the plant, which will artificially improve literacy in the area. Should rewrite to specify local people. |
| Round 1 | Outside the scope |
| Round 2 | I agree with these indicators. Geothermal development should have a net positive impact on the health and wellbeing of poor, rural communities where they are located. |
| Round 2 | What random idea is this? unless you are tying development with a whole lot of developing-country millennium goals requirements that the developer must fund? In which case use any/all of the millennium goals in this category. and if you do, my particular preference, and one that has huge tie-ins with all the others is female literacy. |
| Round 2 | Could be one positive outcome but not the only way of achieving literacy |

Sample comments for high scoring indicators from Kenyan Delphi: Project internal rate of return (IRR)

| Delphi Round | Sample comment |
|---|---|
| Round 1 | Unattractive IRR will cause the project to be unable to attract investors or financers. |
| Round 1 | The project internal rate of return is essential to determine the affordability and sustainability of the project. |
| Round 3 | Important for economic feasibility and sustainability |

Sample comments for low scoring indicators from Kenyan Delphi: Level of induced seismicity per year

| Delphi Round | Sample comment |
|---|---|
| Round 1 | Not yet evident in Kenya but experience from other geothermal-active regions/countries strongly suggests it will be appropriate to put systems in place to measure and monitor seismic activity at geothermal sites |
| Round 2 | Institute geohazard monitoring program. |

Sample comments for high scoring indicators from UNU-GTP Delphi: Utilization efficiency for the geothermal power plant

| Delphi Round | Sample comment |
|---|---|
| Round 1 | The plant should be efficient and reliable |
| Round 2 | The best technology available should be always used to ensure efficiency of a power plant. The higher efficiency the better use of the resource, and thus a more sustainable project. |
| Round 2 | This will indicate how good the resource is being utilized and if need is there to cascade utilization. |

Sample comments for low scoring indicators from UNU-GTP Delphi: Ratio of average male income to female income for the project-affected area

| Delphi Round | Sample comment |
|---|---|
| Round 1 | Country Cultural aspect should be evaluated before, maybe |
| Round 1 | There are areas where women are not financially independent because of traditional reasons. Education may help this situation, but it will be a complicated matter. |
| Round 1 | The geothermal industry is currently more male dominated |
| Round 2 | Very important factor to consider when opening new job opportunities. Gender equity should be always considered when hiring and defining salaries for every position in a project. Same job responsibilities and capacities should be equally paid. |
| Round 2 | The over arching objective is progress in the project. Unless if there are some gender ties to the project, this may not be of relevance. |
| Round 2 | This will be quite closely linked with capacity building and local culture. Usually, the higher paying jobs are the technical jobs and in some areas, women just do not take on these jobs. Geophysical exploration, for example, is just an inherently male-dominated field not only because of the strenuous physical requirements of the position, but also many women eventually drop out of it because they want to have children or take care of their children. Using averages may be forcing companies to employ the wrong person with the right gender just to fulfill such requirements. It would be better to make the comparison on a technical/administrative. For example, average salary for senior engineers should be 1:1. |

## Appendix D

Icelandic Delphi Indicators with metrics

| Indicator | Metric (where applicable) |
|---|---|

| | |
|---|---|
| Air quality in the surrounds of the geothermal power plant | Metric: concentrations (μg/ $m^3$) of potentially toxic gases (hydrogen sulfide, mercury, sulfur dioxide, carbon dioxide, etc.)<br>Reference value: World Health Organisation reference values – Whichever is the most stringent of national regulation or WHO guideline values. For $H_2S$, odor threshold (7 μg/$m^3$)should not be exceeded. Should take account of natural background concentrations if very high. |
| Area of land used due to geothermal energy project (including infrastructure) | |
| Average Income Levels in Project-Affected Communities | Metric: dollars per annum<br>Reference Value: income level before the project begins |
| Direct and indirect local job creation over lifetime of project | Metric: no. full-time employees per year<br>Reference Value: predicted number of jobs before the project begins |
| Duration of Plant Power Outages per year | Metric: Use hours of unplanned interrupted service<br>Reference Value: zero |
| EBIDA ratio per project | Metric: ratio<br>Reference Value: EBITA recommended for geothermal industry |
| Economic diversity of project-impacted areas | |
| Energy diversity index for project-affected regions | |
| Estimated productive lifetime of geothermal resource | Metric: years<br>Reference Value: at least 100-300 years |
| Expenditure on heat and electricity as a percentage of household income | Metric: percentage<br>Reference Value: Remain below 10% |
| Housing value in the area compared to national average | |
| Impact on important or vulnerable geothermal features | Metric: value of predefined impact parameters<br>Reference value: condition of important or vulnerable geothermal features before exploitation of the geothermal field.<br>NOTE: Important features should be defined before development by relevant stakeholders, based on uniqueness, cultural and economic importance. All features should be scaled with a vulnerability metric and the most important or vulnerable be monitored, using pre-defined criteria, such as temperature and activity. It is not considered enough to measure number or diversity of features. |
| Imported energy as a percentage of total (national level) | Metric: Percentage<br>Reference Value: 0% is desirable |
| Income Equity in Project-Affected Communities | |
| Income-to-expenditure ratio for project-affected municipalities | Metric: ratio<br>Reference Value: A ratio greater than or equal to one is desirable. |
| Initial phase capacity as a percentage of estimated total capacity | |
| Level of induced seismicity per year | Metric: Peak ground velocity levels (PGV) during the year<br>Reference value: US department of energy "traffic light" system based on detectability of ground motion levels |
| Make-up holes as a function of time | |
| Noise levels in working, recreation and residential areas in the surrounds of the geothermal power plant. | Metric: dB<br>Reference value: Whichever is more stringent, World Health Organisation or national acceptable noise levels for working, recreational and residential areas. |
| Number of accidents leading to work absence in the energy company per year | Metric: count<br>Reference Value: zero |
| Odor experience from $H_2S$ gas in residential or recreational areas near the power plant | |
| Percentage of community residents that must be relocated due to energy project | Metric: percentage<br>Reference Value: zero |
| Percentage of energy company expenditure given to R&D per year | Metric: %<br>Reference Value: TBD |
| Percentage of females with university education in local energy company | |

| | |
|---|---|
| Percentage of population with access to commercial energy in project-affected area | |
| Percentage of protected area removed/affected due to geothermal project | Metric: Percentage<br>Reference value: size of protected area before energy project |
| Percentage of renewables in total energy supply nationally | Metric: percentage<br>Reference Value: 100% |
| Percentage of satisfied workers in the energy company per year | |
| Project internal rate of return (IRR) | Metric: percentage<br>Reference Value: IRR exceeds the cost of capital. |
| Rate of subsidence in the geothermal field | Metric: Millimeters (mm) per year<br>Reference values: predicted subsidence levels before development |
| Ratio of average male income to female income for the project-affected area. | Metric: ratio<br>Reference Value: 1:1 |
| Ratio of rate of change in housing prices to rate of change in income levels (Housing affordability) | |
| Ratio of reinjection to production | |
| Resource reserve capacity ratio of the geothermal resource | Metric: ratio<br>Reference Value: predicted ratio for which non-declining production can be maintained |
| Tons of acidifying air pollutants ($H_2S$, $SO_2$) emitted as a result of geothermal operations | |
| Tons of greenhouse gas emissions resulting from geothermal operations | Metric: Tons of $CO_2$ equivalents per kilowatt hour per annum<br>Reference Value: zero emissions |
| Total cases lost in supreme court by energy company per year | |
| Unemployment rate in project affected areas | |
| Utilization efficiency for the geothermal power plant | Metric: Percentage<br>Reference Value: best known example |
| Water Quality of water bodies impacted by geothermal power plant operations | Metric: status of water bodies impacted by geothermal power plant operations, based on national water directive ratings<br>Reference Value: Biological, hydromorphological and physio-chemical status of the water body before geothermal exploitation |

New Zealand Delphi Indicators with metrics

| Indicator | Metric (where applicable) |
|---|---|
| (Potential) loss of earnings in impacted communities resulting from changes in land use as a result of the geothermal development | |
| Air quality in the surrounds of the geothermal power plant | Metric: concentrations (μg/m$^3$) of potentially toxic gases (hydrogen sulfide, mercury, sulfur dioxide, carbon dioxide, etc.)<br>Reference value: World Health Organisation reference values - Whichever is the most stringent of national regulation or WHO guideline values. For $H_2S$, odor threshold (7 μg/m$^3$)should not be exceeded. Should take account of natural background concentrations if very high. |
| Area of land used due to geothermal energy project (including infrastructure) | |
| Average income (purchasing power of income) | Metric: dollars per annum<br>Reference Value: purchasing power of income level before the project begins *Note: Impacts on income levels should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Cost of food to families who originally would have sourced significant amounts of their food from the nearby areas/rivers and who now have to buy food | |
| Direct and indirect local job creation over lifetime of project | Metric: no. full-time employees per year<br>Reference Value: number of jobs before the project begins *Note: Impacts on job creation should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Duration of Plant Power Outages per year | Metric: Use hours of unplanned interrupted service<br>Reference Value: zero |
| Economic diversity of project-impacted areas | |

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| Energy diversity index for project-affected regions | |
| Estimated productive lifetime of geothermal resource | Metric: years<br>Reference Value: at least 100-300 years |
| Expenditure on heat and electricity as a percentage of household income | Metric: percentage<br>Reference Value: Remain below 10%<br>(Note: this is a measure of energy affordability, with the reference value signifying the energy poverty threshold for a household) |
| Impact on important or vulnerable geothermal features | Metric: value of predefined impact parameters<br>Reference value: condition of important or vulnerable geothermal features before exploitation of the geothermal field.<br>NOTE: Important features should be defined before development by relevant stakeholders, based on uniqueness, cultural and economic importance. All features should be scaled with a vulnerability metric and the most important or vulnerable be monitored, using pre-defined criteria, such as temperature and activity. It is not considered enough to measure number or diversity of features. |
| Imported energy as a percentage of total (national level) | Metric: Percentage<br>Reference Value: 0% is desirable |
| Income Equity in Project-Affected Communities | |
| Income-to-expenditure ratio for project-affected municipalities | Metric: ratio<br>Reference Value: ratio before the project begins compared to afterwards<br>*Note: Geothermal projects may result in income flows to local governments through taxes or royalties.<br>Impacts on income-to-expenditure ratio should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project. |
| Infant mortality rates in the project-affected area | |
| Level of induced seismicity per year | Metric: Peak ground velocity levels (PGV) during the year<br>Reference value: US department of energy "traffic light" system based on detectability of ground motion levels, takes into account background levels of seismicity |
| Life expectancy at birth in project-affected area | |
| Noise levels in working, recreation and residential areas in the surrounds of the geothermal power plant. | Metric: dB<br>Reference value: Whichever is more stringent, World Health Organisation or national acceptable noise levels for working, recreational and residential areas. |
| Number of accidents leading to work absence in the energy company per year | Metric: count<br>Reference Value: zero |
| Number of threatened species that may be affected by the geothermal project. | Metric: Count<br>Reference Value: zero |
| Odor experience from $H_2S$ gas in residential or recreational areas near the power plant | |
| Percentage of community residents that must be relocated due to energy project | Metric: percentage<br>Reference Value: zero |
| Percentage of energy company expenditure given to R&D per year | Metric: % Reference Value: TBD |
| Percentage of population below poverty line in project-affected area | |
| Percentage of population with access to commercial energy in project-affected area | Metric: percentage<br>Reference value: Percentage of population in project-affected areas with access to commercial energy before energy project.<br>*Note: Impacts on energy access should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Percentage of renewables in total energy supply nationally | Metric: percentage<br>Reference Value: percentage before the project begins<br>*Note: Impacts on renewable energy percentage should be calculated with all other things |

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| | being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Percentage of satisfied workers in the energy company per year | |
| Percentage of unlicensed teachers in the project-affected area | |
| Project internal rate of return (IRR) | Metric: percentage<br>Reference Value: IRR exceeds the cost of capital. |
| Rate of literacy in project-affected areas | Metric: percentage<br>Reference Value: literacy rates before the project began compared to afterwards<br>*Note: Impacts on literacy should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Rate of literacy of existing population in project-affected areas | |
| Rate of subsidence in the geothermal field | Metric: Millimeters (mm) per year<br>Reference values: predicted subsidence levels before development |
| Ratio of average male income to female income for the project-affected area. | |
| Ratio of rate of change in housing prices to rate of change in income levels (Housing affordability) | |
| Resource reserve capacity ratio of the geothermal resource | Metric: ratio<br>Reference Value: predicted ratio for which non-declining production can be maintained<br>Note: The reserve capacity for a geothermal resource is what remains of probable reserves once we take away proven reserves. The proven reserves in a geothermal field are taken to be the installed capacity and available capacity from existing wells, exploratory and production wells, which are not being utilized. The probable reserve can be estimated using the volumetric method or using areal production values and resistivity measurements. |
| Tons of acidifying air pollutants ($H_2S$, $SO_2$) emitted as a result of geothermal operations | |
| Tons of greenhouse gas emissions resulting from geothermal operations | Metric: Tons of $CO_2$ equivalents per kilowatt hour per annum<br>Reference Value: zero emissions |
| Total cases lost in supreme court by energy company per year | |
| Unemployment rate in project affected areas | |
| Utilization efficiency for the geothermal power plant | Metric: Percentage<br>Reference Value: best known example<br>Note: The utilization efficiency should be calculated taking into account optimal reinjection and is only relevant if comparing equivalent field and plant factors. |
| Value of land for nearby communities | |
| Water Quality of water bodies impacted by geothermal power plant operations | Metric: status of water bodies impacted by geothermal power plant operations, based on national water directive ratings<br>Reference Value: Biological, hydromorphological and physio-chemical status of the water body before geothermal exploitation |

Kenyan Delphi Indicators with metrics

| Indicator | Metric (where applicable) |
|---|---|
| Air quality in the surrounds of the geothermal power plant | Metric: concentrations ($\mu g/m^3$) of potentially toxic gases (hydrogen sulfide, mercury, sulfur dioxide, carbon dioxide, etc.)<br>Reference value: World Health Organisation reference values - Whichever is the most stringent of national regulation or WHO guideline values. For $H_2S$, odor threshold (7 $\mu g/m^3$) should not be exceeded. Should take account of natural background concentrations if very high. |
| Amount of freshwater used during geothermal development (exploration, construction or operation activities) as a percentage of available freshwater in the project area | Metric: percentage<br>Reference value: The permitted amount of freshwater extraction that will not lead to water shortages in |

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| | the area - i.e. use of freshwater for geothermal development does not conflict with other existing freshwater needs |
| Area of land used due to geothermal energy project (including infrastructure) | |
| Average Income Levels in Project-Affected Communities | Metric: dollars per annum<br><br>Reference Value: income level before the project begins<br>*Note: Impacts on income levels should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Direct and indirect local job creation over lifetime of project | Metric: no. full-time employees per year<br><br>Reference Value: number of jobs before the project begins<br>Impacts on job creation should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Duration of Plant Power Outages per year | Metric: Use hours of unplanned interrupted service<br>Reference Value: zero |
| Economic diversity of project-impacted areas | Metric: Adjusted Shannon-Wiener Index (%)<br>Reference Value: Complete economic diversity (100%) |
| Energy diversity index for project-affected regions | |
| Estimated productive lifetime of geothermal resource | Metric: years<br><br>Reference Value: at least 100–300 years |
| Expenditure on heat and electricity as a percentage of household disposable income | Metric: percentage<br><br>Reference Value: Remain below 10%<br>(Note: this is a measure of energy affordability, with the reference value signifying the energy poverty threshold for a household) |
| Impact on important or vulnerable geothermal features | Metric: value of predefined impact parameters<br><br>Reference value: condition of important or vulnerable geothermal features before exploitation of the geothermal field.<br>NOTE: Important features should be defined before development by relevant stakeholders, based on uniqueness, cultural and economic importance. All features should be scaled with a vulnerability metric and the most important or vulnerable be monitored, using pre-defined criteria, such as temperature and activity. It is not considered enough to measure number or diversity of features. |
| Imported energy as a percentage of total (national level) | Metric: Percentage<br><br>Reference Value: 0% is desirable |
| Income Equity in Project-Affected Communities | Metric: Gini coefficient<br><br>Reference Value: Income equity before the project compared to afterwards<br>Note: income equity should be measured considering all other things equal, that is to say that the impact of the energy project on this indicator should be clearly traceable |
| Income-to-expenditure ratio for project-affected municipalities | Metric: ratio<br><br>Reference Value: ratio before the project begins compared to afterwards<br>*Note: Impacts on income-to-expenditure ratio should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Infant mortality rates in the project-affected area | Metric: percentage<br><br>Reference Value: Infant mortality rates before the project began compared to afterwards<br>*Note: Impacts on infant mortality should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Level of induced seismicity per year | Metric: Peak ground velocity levels (PGV) during the year<br>Reference value: US department of energy "traffic light" system based on detectability of ground motion levels |
| Life expectancy at birth in project-affected area | |
| Monetary value of socially beneficial initiatives in project-affected communities as a percentage of total project expenditure | Metric: percentage<br><br>Reference Value: TBD |

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| | *Note: socially beneficial initiatives are funded by the geothermal development and should have been approved by the local community. They may include such facilities as schools, clinics, etc. |
| Noise levels in working, recreation and residential areas around the geothermal power plant. | Metric: dB<br>Reference value: Whichever is more stringent, World Health Organisation or national acceptable noise levels for working, recreational and residential areas. |
| Number of accidents leading to work absence in the energy company per year | Metric: count<br>Reference Value: zero |
| Number of threatened species that may be affected by the geothermal project | Species on the IUCN red list, or if not on the red list, or on any national lists of threatened species<br>Metric: Count Target/<br>Reference Value: zero |
| Percentage of community residents that have agreed to potential culture-changing activities relating to the energy project | Metric: percentage (e.g. from survey responses)<br>Reference Value: TBD<br>Note: culture-changing activities may include resettlement, influx of migrant workers from outside, changes in livelihoods or social structures as a result of new economic activities or land use changes, new infrastructure, access to electricity, etc. |
| Percentage of community residents that must be relocated due to energy project | Metric: percentage<br>Reference Value: zero |
| Percentage of energy company expenditure given to R&D per year | Metric: percentage<br>Reference Value: TBD |
| Percentage of mass of fluid reinjected and/or cascaded compared to total extracted fluid mass | Metric: Percentage<br>Reference Value: 100% is ideal (no waste fluid is released to the environment) |
| Percentage of population below poverty line in project-affected area | Metric: percentage<br>Reference Value: The percentage of population below the poverty line in surrounding regions. |
| Percentage of population with access to commercial energy in project-affected area | Metric: percentage<br>Reference value: Percentage of population in project-affected areas with access to commercial energy before energy project.<br>*Note: Impacts on energy access should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Percentage of renewables in total energy supply nationally | Metric: percentage<br>Reference Value: percentage before the project begins<br>*Note: Impacts on renewable energy percentage should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Percentage of satisfied workers in the energy company per year | Metric: percentage<br>Reference Value: 100% |
| Percentage of unlicensed teachers in the project-affected area | |
| Project internal rate of return (IRR) | Metric: percentage<br>Reference Value: IRR exceeds the cost of capital. |
| Rate of literacy in project-affected areas | Metric: percentage<br>Reference Value: literacy rates before the project began compared to afterwards<br>*Note: Impacts on literacy should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Rate of subsidence in the geothermal field | Metric: Millimeters (mm) per year<br>Reference values: predicted subsidence levels before development |
| Ratio of average male income to female income for the project-affected area. | |
| Ratio of rate of change in housing prices to rate of change in income levels (Housing affordability) | |
| Resource reserve capacity ratio of the geothermal resource | Metric: ratio<br>Reference Value: predicted ratio for which non-declining production can be maintained |

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| | Note: The reserve capacity for a geothermal resource is what remains of probable reserves once we take away proven reserves. The proven reserves in a geothermal field are taken to be the installed capacity and available capacity from existing wells, exploratory and production wells, which are not being utilized. The probable reserve can be estimated using the volumetric method or using areal production values and resistivity measurements. |
| Tons of acidifying air pollutants ($H_2S$, $SO_2$) emitted as a result of geothermal operations | |
| Tons of greenhouse gas emissions resulting from geothermal operations | Metric: Tons of $CO_2$ equivalents per kilowatt hour per annum<br>Reference Value: zero emissions |
| Total area of land that has been compacted due to geothermal development activities | |
| Total cases lost in supreme court by energy company per year | |
| Unemployment rate in project-affected communities | Metric: percentage |
| | Reference Value: unemployment rates before the project begins<br>*Note: Impacts on unemployment rates should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Utilization efficiency for the geothermal power plant | Metric: Percentage<br><br>Reference Value: best known example Note: The utilization efficiency should be calculated taking into account optimal reinjection and is only relevant if comparing equivalent field and plant factors. |
| Water Quality of water bodies impacted by geothermal power plant operations | Metric: status of water bodies impacted by geothermal power plant operations, based on national water directive ratings Reference Value: Biological, hydromorphological and physio-chemical status of the water body before geothermal exploitation |

UNU-GTP Delphi Indicators with metrics

| Indicator | Metric (where applicable) |
|---|---|
| Air quality in the surrounds of the geothermal power plant | Metric: concentrations (μg/$m^3$) of potentially toxic gases (hydrogen sulfide, mercury, sulfur dioxide, carbon dioxide, etc.)<br>Reference value: World Health Organisation reference values - Whichever is the most stringent of national regulation or WHO guideline values. For $H_2S$, odor threshold (7 μg/$m^3$)should not be exceeded. Should take account of natural background concentrations if very high. |
| Area of land used due to geothermal energy project (including infrastructure) | |
| Average Income Levels in Project-Affected Communities | Metric: dollars per annum |
| | Reference Value: income level before the project begins<br>*Note: Impacts on income levels should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Cost (price) per MW of power produced compared to price per MW from other sources | Cost should include social and environmental costs<br>Metric: Ratio<br>Reference Value: TBD |
| Direct and indirect local job creation over lifetime of project | Metric: no. full-time employees per year<br>Reference Value: number of jobs before the project begins<br>Impacts on job creation should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Duration of Plant Power Outages per year | Metric: Use hours of unplanned interrupted service<br>Reference Value: zero |
| Economic diversity of project-impacted areas | |
| Energy diversity index for project-affected regions | |
| Estimated productive lifetime of geothermal resource | Metric: years<br><br>Reference Value: at least 100–300 years |

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| Expenditure on heat and electricity as a percentage of household income | Metric: percentage<br>Reference Value: Remain below 10%<br>(Note: this is a measure of energy affordability, with the reference value signifying the energy poverty threshold for a household) |
| Impact on important or vulnerable geothermal features | Metric: value of predefined impact parameters<br>Reference value: condition of important or vulnerable geothermal features before exploitation of the geothermal field.<br>NOTE: Important features should be defined before development by relevant stakeholders, based on uniqueness, cultural and economic importance. All features should be scaled with a vulnerability metric and the most important or vulnerable be monitored, using pre-defined criteria, such as temperature and activity. It is not considered enough to measure number or diversity of features. |
| Imported energy as a percentage of total (national level) | Metric: Percentage<br>Reference Value: 0% is desirable |
| Income Equity in Project-Affected Communities | |
| Income Equity in Project-Affected Communities | Metric: Gini coefficient<br>Reference Value: Income equity before the project compared to afterwards<br>Note: income equity should be measured considering all other things equal, that is to say that the impact of the energy project on this indicator should be clearly traceable |
| Income-to-expenditure ratio for project-affected municipalities | Metric: ratio<br>Reference Value: ratio before the project begins compared to afterwards<br>*Note: Impacts on income-to-expenditure ratio should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Infant mortality rates in the project-affected area | Metric: percentage<br>Reference Value: Infant mortality rates before the project began compared to afterwards<br>*Note: Impacts on infant mortality should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Level of induced seismicity per year | Metric: Peak ground velocity levels (PGV) during the year<br>Reference value: US department of energy "traffic light" system based on detectability of ground motion levels |
| Life expectancy at birth in project-affected area | Metric: years<br>Reference Value: Average life expectancy before project compared to afterwards<br>Impacts on life expectancy should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Noise levels in working, recreation and residential areas in the surrounds of the geothermal power plant. | Metric: dB<br>Reference value: Whichever is more stringent, World Health Organisation or national acceptable noise levels for working, recreational and residential areas. |
| Number of accidents leading to work absence in the energy company per year | Metric: count<br>Reference Value: zero |
| Odor experience from $H_2S$ gas in residential or recreational areas near the power plant | |
| Percentage of community residents that must be relocated due to energy project | Metric: percentage<br>Reference Value: zero |
| Percentage of energy company expenditure given to R&D per year | Metric: percentage<br>Reference Value: TBD |
| Percentage of mass of fluid reinjected and/or cascaded compared to total extracted fluid mass | Metric: Percentage<br>Reference Value: 100% is ideal (no waste fluid is released to the environment) |
| Percentage of population below poverty line in project-affected area | |
| Percentage of population with access to commercial energy in project-affected area | Metric: percentage |

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| | Reference value: Percentage of population in project-affected areas with access to commercial energy before energy project.<br>*Note: Impacts on energy access should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Percentage of renewables in total energy supply nationally | Metric: percentage<br>Reference Value: percentage before the project begins<br>*Note: Impacts on renewable energy percentage should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Percentage of satisfied workers in the energy company per year | Metric: percentage<br>Reference Value: 100% |
| Percentage of unlicensed teachers in the project-affected area | |
| Project internal rate of return (IRR) | Metric: percentage<br>Reference Value: IRR exceeds the cost of capital. |
| Rate of literacy of existing population in project-affected areas | Metric: percentage<br>Reference Value: literacy rates before the project began compared to afterwards<br>*Note: Impacts on literacy should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Rate of subsidence in the geothermal field | Metric: Millimeters (mm) per year<br>Reference values: predicted subsidence levels before development |
| Ratio of average male income to female income for similar jobs for the project staff | Metric: ratio<br>Reference Value: 1:1 |
| Ratio of rate of change in housing prices to rate of change in income levels (Housing affordability) | |
| Resource reserve capacity ratio of the geothermal resource | Metric: ratio<br>Reference Value: predicted ratio for which non-declining production can be maintained |
| Tons of acidifying air pollutants ($H_2S$, $SO_2$) emitted as a result of geothermal operations | |
| Tons of greenhouse gas emissions resulting from geothermal operations | Metric: Tons of $CO_2$ equivalents per kilowatt hour per annum<br>Reference Value: zero emissions |
| Total cases lost in supreme court by energy company per year | |
| Unemployment rate in project-affected communities | |
| Utilization efficiency for the geothermal power plant | Metric: Percentage<br>Reference Value: best known example |
| Water Quality of water bodies impacted by geothermal power plant operations | Metric: status of water bodies impacted by geothermal power plant operations, based on national water directive ratings<br>Reference Value: Biological, hydromorphological and physio-chemical status of the water body before geothermal exploitation |

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# 5 Book Chapter: Assessing the Sustainability of Geothermal Utilization


## Abstract

With increasing global energy consumption and a growing interest in low carbon energy sources, geothermal energy is set to play an increasingly important part in the new sustainable energy paradigm. While much has been written about sustainable geothermal utilization, the renewability and sustained yield of energy resources are generally agreed to be necessary, but not sufficient, requirements for sustainable energy development. A broader viewpoint must be adopted to account for the wider social, economic and environmental implications of geothermal energy developments. Accordingly, in this chapter, we introduce a multi-dimensional sustainability assessment framework for geothermal energy projects.


## 5.1 Introduction

Sustainable development (SD) was defined by the Brundtland commission as "*development that meets the needs of the present without affecting the ability of future generations to meet their own needs*" (WCED, 1987). Energy is central to all three dimensions of sustainable development, sometimes as a necessary prerequisite for sustainable development (e.g. social and economic), but sometimes the culprit for movement away from sustainable development (e.g. environmental dimension). Consequently, the development of sustainable energy systems relying on clean, low-carbon, and sustainable energy resources has "*emerged as one of the priority issues in the move towards global sustainability*" (Davidsdottir, 2012).

Geothermal energy developments have been found to have both positive and negative impacts across all sustainability themes (United Nations, 2007) in regions where they are located, including impacts on poverty, health, education, natural hazards, air quality, land, biodiversity and economic development (Shortall et al., 2014a). For instance, negative environmental impacts may include air and water pollution (Heath, 2002; Kristmannsdóttir & Ármannsson, 2003), unforeseen impacts in protected areas (Hunt, 2001), or depletion of freshwater supplies for use in drilling or cooling (Mwangi, 2010). However, since it is generally believed to be renewable and to have relatively low carbon emissions (Intergovernmental Panel on Climate Change, 2012), geothermal energy is an attractive option, particularly when its low levelized cost (Matek & Gawell, 2014), high capacity factor, reliability (Shibaki & Beck, 2003) and flexibility (Matek & Schmidt, 2013) are taken into account. Furthermore, positive socio-economic impacts, particularly in the Global South, may include poverty reduction, higher living standards through increased access to energy, water supplies, sanitation and education as well as increased employment and economic development (Ogola, Davidsdottir & Fridleifsson, 2011). In addition geothermal energy can assist in mitigating and adapting to climate change (Ogola, Davidsdottir & Fridleifsson, 2012). As a result geothermal resources play an important role in sustainable energy development and sustainable geothermal utilization has received ever-increasing attention over the last 1 – 2 decades. The discussion however, has suffered from a lack of a clear definition of what it involves and from a lack of relevant policies and guidelines. The term *sustainable* has in addition become quite fashionable and different authors have used it at will. The terms *renewable* and *sustainable* are, furthermore, often confused.

A considerable amount of literature dealing with the issue has been published with Wright (1999) and Stefánsson (2000) publishing early discussions, Rybach and Mongillo (2006) presenting a good review and Axelsson (2010) discussing relevant definitions and examples. The reader is in particular referred to a recent special issue of the international journal *Geothermics* (Mongillo and Axelsson, 2010), compiled under the auspices of the Geothermal Implementing Agreement of the International Energy Agency (IEA-GIA).

In this chapter we first examine sustainable geothermal utilization focusing on sustainable yield, but then broaden our scope to multi-dimensional sustainability assessment in the context of sustainable geothermal development.

# 5.2 Sustainable Geothermal Utilization

## 5.2.1 Nature and production capacity of geothermal resources

Geothermal resources are distributed throughout the Earth's crust with the greatest energy concentration associated with hydrothermal systems in volcanic regions at crustal plate boundaries. Yet exploitable geothermal resources may be found in most countries, either as warm ground-water in sedimentary formations or in deep circulation systems in crystalline rocks. Shallow thermal energy suitable for ground-source heat-pump utilization is available world-wide and attempts are underway at developing enhanced geothermal systems (EGS) in places where limited permeability precludes natural hydrothermal activity. Saemundsson et al. (2009) discuss the classification and geological setting of geothermal systems in considerable detail.

The theoretical potential of the Earth's geothermal resources is enormous when compared to its use today and to the future energy needs of mankind. Stefánsson (2005) estimated the technically feasible electrical generation potential of identified high-temperature geothermal resources (> 200°C) to be 240 $GW_e$ (1 GW = $10^9$ W), which is only a small fraction of yet unidentified resources. He also indicated the most likely direct use potential of lower temperature resources (< 150°C) to be 140 EJ/yr (1 EJ = $10^{18}$ J). Geothermal energy utilization is still miniscule compared with the Earth's potential. 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 (Intergovernmental Panel on Climate Change, 2012). Bertani (2010) estimated the worldwide installed geothermal electricity generation capacity to have been about 10.7 $GW_e$ in 2010 and Lund et al. (2010) estimated the direct geothermal utilization in 2009 to have amounted to 438 PJ/yr (1 PJ = $10^{15}$ J).

The long-term response of a geothermal system to production (mainly pressure-decline, but also cooling) and hence their production capacity is mainly controlled by (1) their size and energy content, (2) permeability structure, (3) boundary conditions (i.e. significance of natural and production induced recharge), and (4) reinjection management. In the case of natural systems the production capacity is predominantly determined by pressure decline due to production. If the decline is too great, geothermal wells decline in output or even cease to produce. The pressure decline is determined by the rate of production, on one hand, and the nature and characteristics of the geothermal system listed above, on the other hand. The production capacity of all systems is also determined by the energy content of the system in question. This is particularly relevant for EGS-systems and sedimentary systems.

Geothermal resources are generally classified as renewable as they are maintained by a continuous energy current. In addition, geothermal resources simply don't fit well with non-renewable energy sources like coal and oil. Classifying geothermal resources as renewable has been disputed, however, on the grounds that geothermal energy utilization actually involves heat-mining. We claim that this dispute simply arises from a need to force a complex natural phenomenon into an inadequate classification scheme as classifying geothermal resources as renewable is an oversimplification. They are of a double nature; a combination of an energy current (through heat convection and conduction) and stored energy. The renewability of these two aspects is quite different as the energy current is steady (fully renewable) while the stored energy is renewed relatively slowly. The double nature of geothermal resources is discussed by Axelsson (2011) as well as the diverse renewability of different types of geothermal systems.

### 5.2.2 Sustainable geothermal production – Definition and time-scale

Two main issues are of principal significance when sustainable geothermal production is being discussed and evaluated. These are (1) the question whether geothermal resources can be used in some kind of sustainable manner, and (2) the issue of defining an appropriate time-scale. Long utilization histories clearly indicate that geothermal systems can be utilized for several decades without significant decline in output due to the fact that they often appear to attain a sort of semi-equilibrium during long-term energy-extraction or the physical changes in geothermal systems are so slow that their output is not affected for decades. Modelling studies have extended the periods to 1 or 2 centuries.

The second issue is the time-scale. It is clear that the short time-scale of 25-30 years usually used for assessing the economic feasibility of geothermal projects is too short to reflect the essence of sustainability, even though economic considerations are an essential part therein. It is furthermore self-evident that a time-scale with a geological connotation, such as of the order of millions of years, is much too long. This is because at such a time scale the potential of a geothermal system would only equal the natural flow through the system. Therefore an Icelandic working group proposed a time-scale of the order of 100 – 300 years as appropriate (Axelsson et al., 2001). Figure 5-1 is intended to capture the essence of this definition of sustainable production. If production is below a certain level ($E_0$) it can be maintained while production above the limit can't be maintained and has to be reduced before the period chosen has ended.

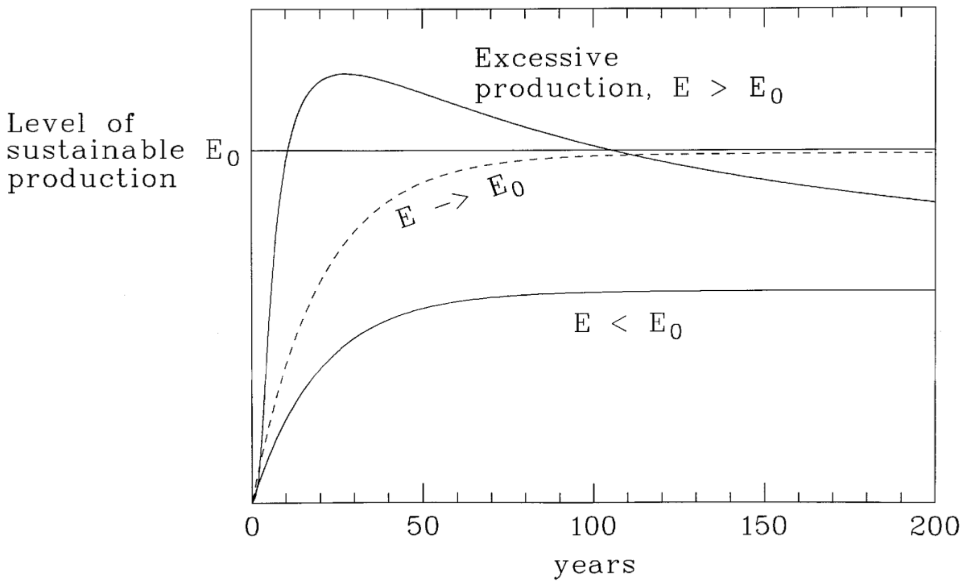



*Figure 5-1: A schematic graph showing the essence of the definition of sustainable production presented by Axelsson et al. (2010). Production below the sustainable limit $E_0$ can be maintained for the whole period being assessed, while greater production cannot be maintained.*

Sustainable geothermal utilization not only involves maintaining production from each individual geothermal system. This is because sustainable development should incorporate all aspects of human needs and activity. It is also important to keep in mind that sustainable development does, in addition, not only involve preserving the environment, as sometimes assumed. In fact, sustainable utilization involves an integrated economic, social and environmental development. Therefore geothermal production can e.g. to some extent be excessive (greater than the sustainable level) for a certain period if outweighed by improved social and/or economic conditions.

It is difficult to establish the sustainable production level, $\boldsymbol{E_0}$, for a given geothermal system. This is because the production capacity of geothermal systems is usually very poorly known during exploration and the initial utilization step. Even when considerable production experience has been acquired, estimating the sustainable production level accurately can be challenging.

In spite of this downside one should bear in mind that the sustainable production level of a particular geothermal resource can be expected to increase over time with increasing knowledge on the resource. In addition it can be expected to increase additionally through technological advances, e.g. in exploration methods, drilling technology and utilization efficiency.

When appraising the more general sustainable geothermal utilization an evaluation should not necessarily focus on a single geothermal system. Either the combined overall production from several systems controlled by a single power company can be considered or several systems in a certain geographical region. Therefore, individual geothermal systems can e.g. be used in a cyclic manner, through which one system is rested while another is produced at a rate considerably greater than $E_0$, and vice versa. This idea is based on an expected reclamation (recovery) of most geothermal systems when utilization is stopped, on a time-scale comparable to that of the utilization (Axelsson, 2010). The recovery expectation is both based on experience and results of numerical modelling.

### 5.2.3 Long Utilization Case Histories And Modelling

#### Long utilization case histories

A number of geothermal systems worldwide have been utilized for several decades (3 – 5 or more). These provide the most important information on the response of geothermal systems to long-term production, and on the nature of the systems, if a comprehensive monitoring program has been in operation in the field. Such information provides the basis of understanding the issue of sustainable geothermal utilization, as well as the basis of sustainability modelling. Information on some of these can be found in the special sustainability issue of *Geothermics* (Mongillo and Axelsson, 2010) while Axelsson (2010) lists 16 geothermal systems with long histories as examples.

Many of the case histories referred to above have shown it is possible to produce geothermal energy in such a manner that a previously unexploited geothermal system reaches a new equilibrium, and this new state may be maintained for a long time. Pressure decline during production in geothermal systems can cause the recharge to the system to increase approximately in proportion to the rate at which mass is extracted. The new equilibrium is achieved when the increased recharge balances the discharge.

One of the best examples of long-term utilization is the low-temperature Laugarnes geothermal system in Reykjavík, Iceland, where semi-equilibrium has been maintained the last 4-5 decades, indicating that the recharge to the system is now about tenfold what it was before production started (Figure 5-2).

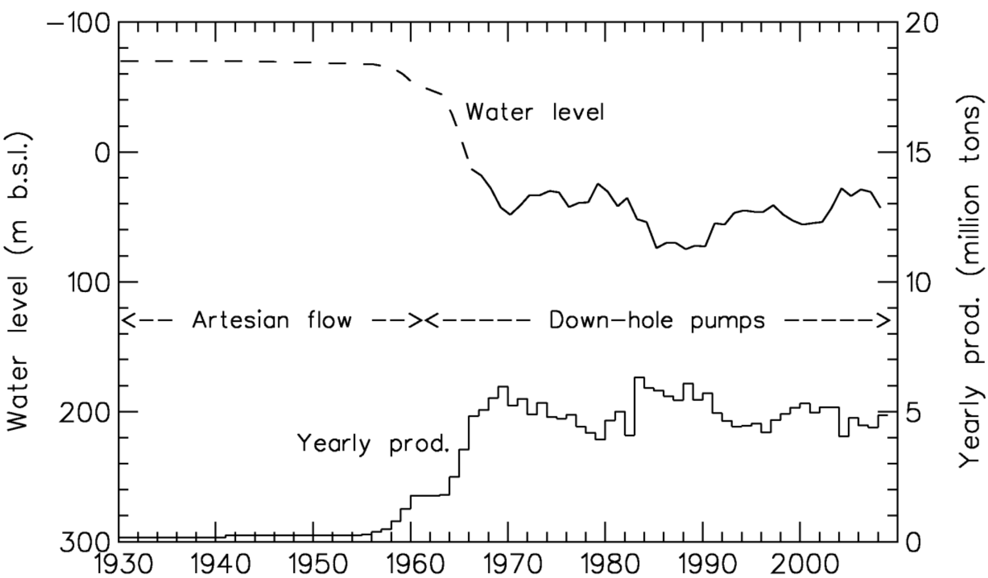


*Figure 5-2: Production and water-level history of the Laugarnes low-temperature geothermal system in SW-Iceland up to 2010 (Axelsson et al., 2010).*

In other cases geothermal production has been excessive and it has not been possible to maintain it in the long-term. The utilization of the Geysers geothermal system in California is a well-known example of excessive production. For a few years, the installed electric generation potential corresponded to more than 2000 $MW_e$, which has since been reduced by more than half because of pressure decline in the system due to insufficient fluid recharge (Goyal & Conant, 2010).

### Sustainability modelling

Modelling studies, which are performed on the basis of available data on the structure and production response of geothermal systems, are the most powerful tools to estimate the sustainable potential ($\boldsymbol{E_0}$) of each system (Axelsson, 2010). It is possible to use either complex numerical models, or simpler analytical models, for such modelling studies. The former models can be much more accurate and they can both simulate the main features in the structure and nature of geothermal systems and their response to production. Yet many simpler models can be very powerful for simulating pressure changes, the main response controlling factor.

The basis of reliable modelling studies is accurate and extensive data, including data on the geological structure of a system, its physical state and not least its response to production. The last mentioned information is most important when the sustainable potential of a geothermal system is being assessed and if the assessment is to be reliable the response data must extend over a few years at least, or even a few decades, as the model predictions must extend far into the future.

The sustainable potential of geothermal systems, that have still not been harnessed, can only be assessed very roughly. This is because in such situations the response data mentioned above is not available. It is, however, possible to base a rough assessment on available ideas on the size of a geothermal system and temperature conditions as well as knowledge on comparable systems. This is often done by using the so-called volumetric assessment method (Sarmiento & Björnsson, 2007).

Axelsson (2010) reviews the results of modelling studies for four geothermal systems in Iceland, Kenya and China, which were performed to assess their sustainable production potential, or to provide answers to questions related to this issue. He concludes that for one of these, Nesjavellir in SW-Iceland, the present rate of utilization is not sustainable for 100 to 300 years, because of pressure decline. The model calculations indicate, however, that the effects of the present production should be mostly reversible so that the system can be allowed to recover for a given period, before utilization at a comparable rate, or a more sustainable rate is continued. In the case of another one of the examples, the Hamar system in N-Iceland, which has been used since 1969 for space-heating, the modelling calculations show that its sustainable capacity is actually slightly more than the present utilization.

Model calculations for a third example, the Beijing Urban sedimentary system, demonstrate that its sustainable capacity is of the order of 100 L $s^{-1}$ average yearly production. Through a revision of the mode of utilization, which would involve reinjection of a large proportion of the water extracted, the sustainable potential could be as much as 200 L $s^{-1}$ average yearly production, or more than a 100% increase from the present use.

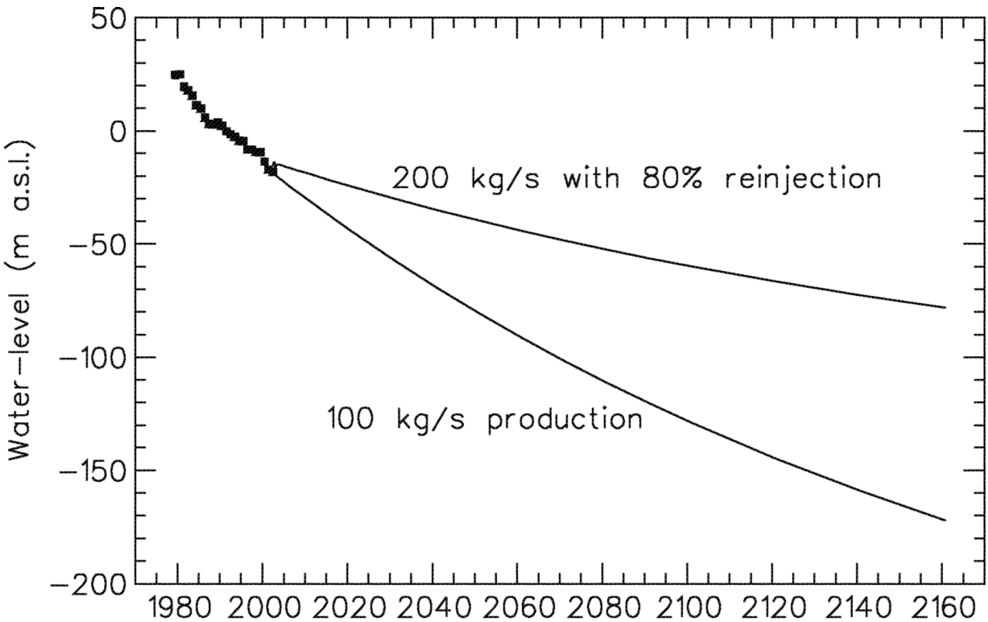
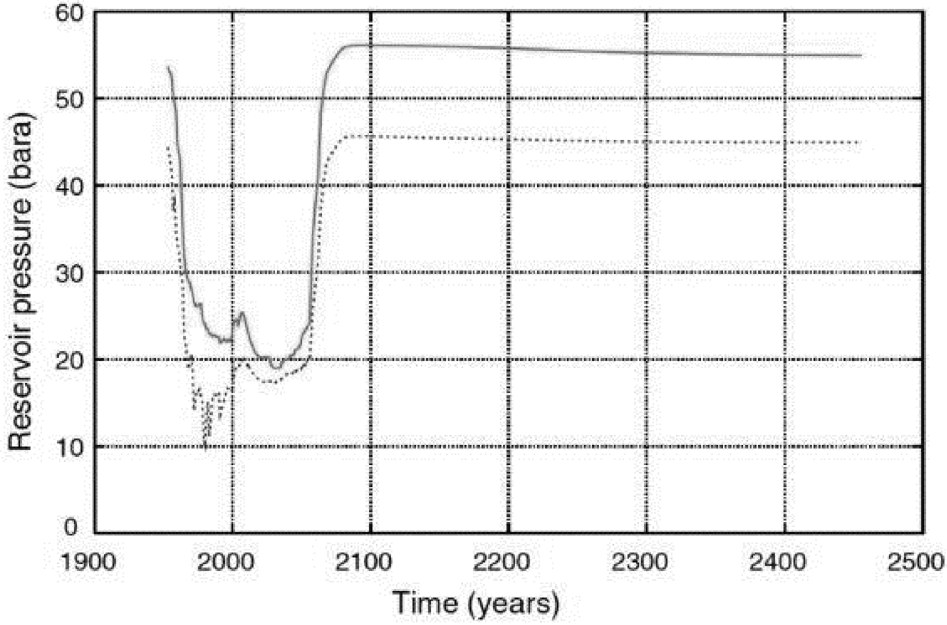



*Figure 5-3: Predicted water-level changes in the Urban geothermal field in Beijing for a 200-year production history (figure shows annual average values). Figure from Axelsson (2010).*

Another modelling study of interest is a study conducted for the Wairakei geothermal system in New Zealand. The sustainability modelling study for Wairakei focussed on predicting the systems response for another 50 years or so as well as predicting the recovery of the system if energy production will be stopped after about 100 years of utilization (O'Sullivan et al., 2010). An example of the results of the study is shown in Figure 5-4, which shows on one hand the pressure response of the system and on the other its temperature evolution. The pressure recovers very rapidly, as can be seen, while temperature conditions evolve much more slowly.



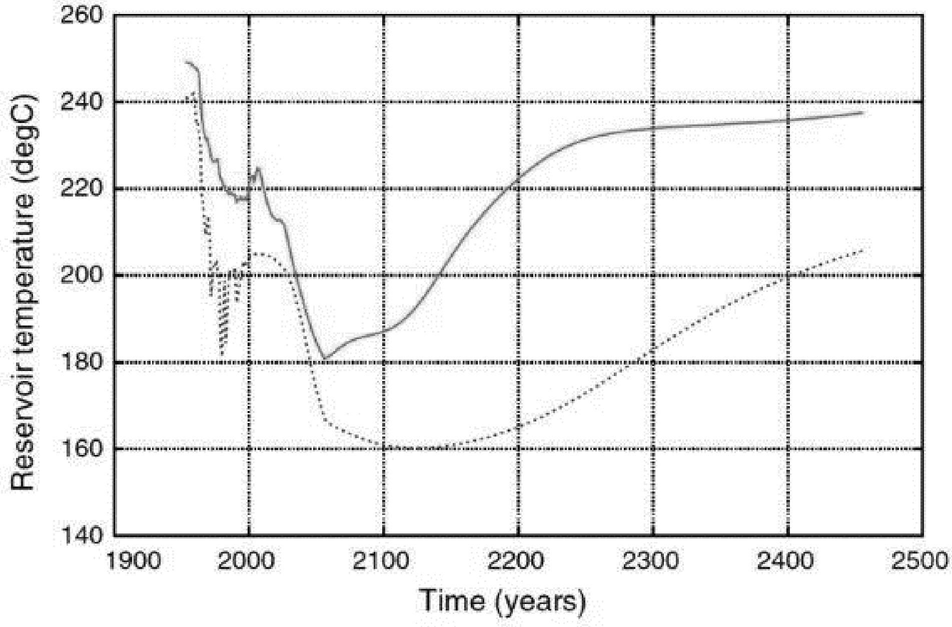




*Figure 5-4: Predicted pressure and temperature recovery in the Wairakei geothermal system in New Zealand following 100 years of production. Figure from O'Sullivan et al. (2010).*

## 5.3 Broader Sustainability Assessment Of Energy Developments

### 5.3.1 Sustainable energy development

Sustainable energy development (SED) is defined by the International Atomic Energy Agency (IAEA) as "*the provision of adequate energy services at affordable cost in a secure and environmentally benign manner, in conformity with social and economic development needs*". Its challenges involve reducing negative health and environmental impacts, whilst simultaneously increasing energy access, affordability, security and the efficiency of energy use (Modi et al., 2006; Alanne & Saari, 2006). Renewability and sustained yield of energy resources are generally agreed to be necessary, but not sufficient, requirements for sustainable energy development (UNDP, 2002). The sustainability perspective requires a broader assessment. As a result environmental, social and economic impacts associated with geothermal energy developments must be monitored (IAEA, 2005).

### 5.3.2 Sustainability Assessment and Energy Development

Sustainability assessments provide the means of showing whether development projects are contributing to sustainability or not, and consist of sustainability criteria, goals and indicators. Goals and indicators should not be rigid, but should take account of the local context as well as changes in opinions over time (Lim and Yang, 2009). To this end, broad stakeholder engagement is an essential part of the indicator development process (Fraser et al., 2006).

Several broad based indicator frameworks exist to measure sustainable development in the context of energy developments such as the Energy indicators for sustainable development (IAEA, 2005), and the Energy Sustainability Index developed by the World Energy Council (WEC, 2011). In addition a few renewable energy associations have developed sustainability assessment frameworks for energy developments. Although not based on indicators as such, the International Hydropower Association (IHA) published an assessment tool for hydropower projects in 2006 (IHA, 2006). The World Wind Energy Association (WWEA) has developed Sustainability and Due Diligence Guidelines (WWEA, 2005), for the assessment of new wind projects, similar to those developed by the IHA in their Sustainability Assessment Protocol. The WWF Sustainability Standards for Bioenergy (WWF, 2006) do not provide any indicators but highlight sustainability issues in bioenergy and offer recommendations for its sustainable use. UN-Energy has also published a report with a similar focus (UN-Energy, 2007).

## 5.4 Sustainability Assessment Framework For Geothermal Power

### 5.4.1 Framework development

In this section, we present a sustainability assessment framework consisting of a set of sustainability goals and indicators that allow monitoring of geothermal projects during their entire life cycle and at different scales. The goals and indicators in this framework were developed using an iterative process for thematic indicator development (Davidsdottir et al., 2007) in Iceland, New Zealand and Kenya (Shortall et al., 2015b).

Guiding principles known as the Bellagio STAMP (International Institute of Sustainable Development, 2012) were incorporated into the entire development process. The Bellagio STAMP principles are intended to serve as guidelines for the entire sustainability assessment process including the choice and design of indicators, their interpretation and communication of results.

A literature review of the impacts of geothermal energy projects on sustainable development (Shortall et al., 2015a) was carried out in order to determine the boundaries of the system that the assessment framework was intended for. Following the literature review, an initial, small group of stakeholders in Iceland was gathered for a pre-engagement "World Café" (Brown & Isaacs, 2005) workshop to critically review a set of possible sustainability goals and indicators creating a preliminary set of sustainability goals and indicators. This set of goals and indicators provided a starting point for which further stakeholder input was sought later in the process (Shortall et al., 2015b).

### 5.4.2 Stakeholder Engagement

Following the Bellagio STAMP (International Institute for Sustainable Development, 2012), a diverse group of stakeholders was selected to contribute to the development process. Stakeholders are generally defined as persons or groups who are directly, or indirectly, affected by a development project, as well as those who may have interests in a project and/or the ability to influence its outcome, either positively or negatively (International Finance Corporation, 2007).

For a geothermal project, stakeholders may include locally affected communities or individuals and their formal and informal representatives, the geothermal industry, national or local government authorities, politicians, religious leaders, civil society organizations and groups with special interests, the academic community, or other businesses, such as suppliers or those that may use the geothermal power. A stakeholder mapping exercise was conducted in each country to identify the relevant stakeholders (Shortall et al., 2015c).

Stakeholder engagement methods such as a pre-engagement "World Café" (Brown & Isaacs, 2005) workshop or information session and a Delphi survey (Linstone & Turoff, 2002), were used at various points in each iteration of the development process, from setting sustainability goals to choosing sustainability indicators (see Figure 5-5).

### 5.4.3 Iterative development process

An iterative approach (Davidsdottir et al., 2007) to indicator development was applied. Three iterations where conducted in three countries; Iceland, Kenya and New Zealand. This enabled refining goals as well as indicators after each of the country specific iterations and minimized country or stakeholder biases, which could arise if stakeholders in only one country were consulted. The method consists of the following steps, which may be repeated as necessary, in an iterative fashion (Figure 5-5).

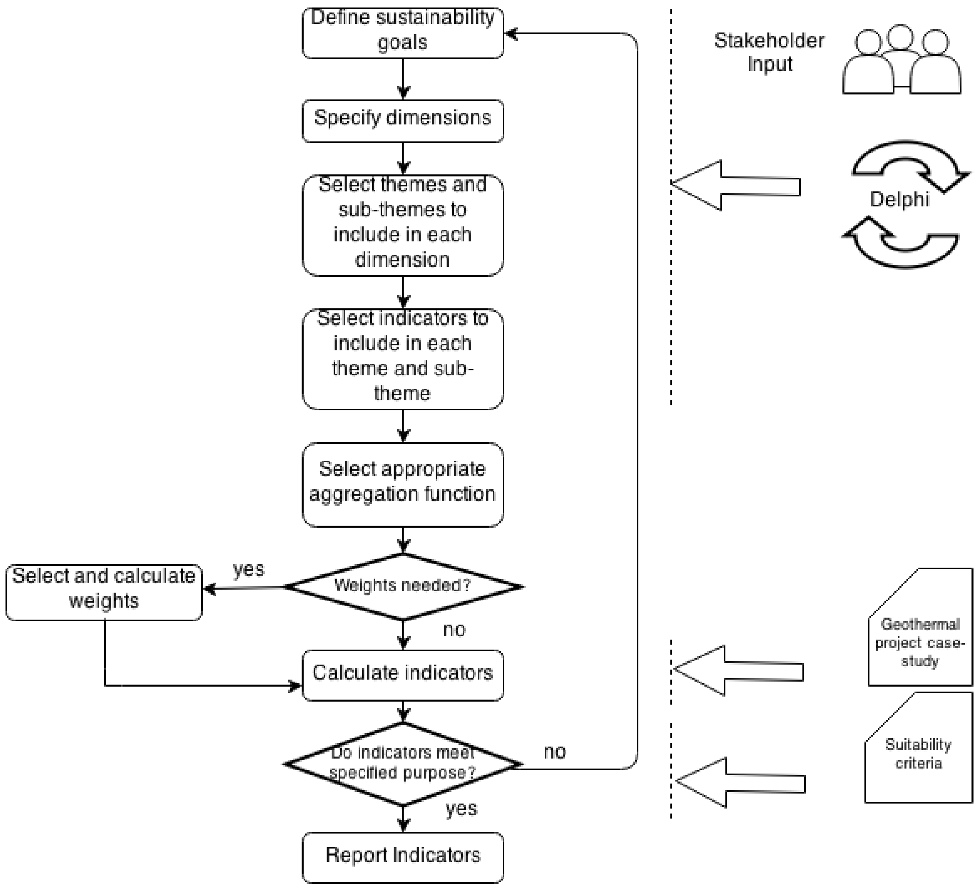



*Figure 5-5: Iterative method of indicator development modified from Davidsdottir et al. (2007).*

During the first four steps, the facilitators used personal expert judgment and stakeholder input from a World Café and a Delphi survey, to determine sustainability goals and the most suitable indicators in each country. As stated before the World Café workshop technique was used as a starting point, or pre-engagement method, in order to convey information and to gather stakeholder input on potential sustainability goals and indicators. Following the World Café a Delphi survey was conducted. The Delphi technique is an established survey method for seeking unbiased opinions and consensus on a complex issue, and involves sequential questionnaires answered anonymously by a group of experts (Linstone & Turoff, 2011).

The Delphi process consisted of three rounds in each iteration (country). Participants were asked to rate a list of goals and indicators introduced at the pre-engagement workshop using scoring from 1-5. Feedback from participants was incorporated into the next round by the facilitators and goals and indicators that received low scores were removed from the survey. When round 3 closed, the facilitators incorporated the feedback and consensus had been reached on a final set of goals and indicators (Shortall et al., 2015c). The results of the Delphi surveys thereby revealed the priority the stakeholders in different countries placed individual goals and indicators, as well as the level of consensus between them.

### 5.4.4 Final set of sustainability goals and sustainability indicators

Once goals and indicators were chosen they were evaluated for their suitability to their purpose against suitability criteria (Shortall et al., 2015b). The results yielded a final list of ten sustainability goals (Table 5-1) and a set of 21 common (“core”) (Table 5-2) and 18 supplementary (“optional”) sustainability indicators (Table 5-3) (Shortall et al., 2015c). The core indicators were rated important by stakeholder in all three countries whereas the satellite indicators were rated important in one or two countries.

*Table 5-1: Sustainability Goals (Shortall et al. 2015c)*

| |
|---|
| GOAL 1 - Renewability<br>In order to ensure that a geothermal resource remains replenishable, sustainable production should be the goal in all geothermal projects. |
| GOAL 2 - Water Resource Usage<br>Water usage of a power plant must not reduce supply of cold fresh water to communities nearby. |
| GOAL 3- Environmental Management<br>A geothermal resource should be managed so as to avoid, remedy or mitigate adverse environmental effects. |
| GOAL 4 – Efficiency<br>Geothermal utilization shall be managed so as to maximize the utilization of exergy available where practical at sustainable production levels. The desired maximum efficiency for electricity generation should be based on the theoretical maximum efficiency for converting heat to electrical energy (Carnot efficiency). |
| GOAL 5 - Economic Management & Profitability<br>Energy use from geothermal power and heat plants must be competitive, cost effective and financially viable. The financial risk of the project shall be minimized. The project should carry positive net national and community economic benefits. |
| GOAL 6 - Energy Equity<br>The energy supplied by the geothermal resource is readily available, accessible and affordable to the public. |
| GOAL 7 - Energy Security & Reliability<br>The operation of geothermal power and heat plants shall be reliable and prioritize the security of supply. |
| GOAL 8 - Community Responsibility<br>The power companies should be responsible toward the community and the effect of the utilization of the geothermal resource shall be as positive for the community as possible and yield net positive social impact. |
| GOAL 9 - Research and Innovation<br>Power companies shall encourage research that improves the knowledge of the geothermal resource as well as technical developments that improve efficiency, increase profitability and reduce environmental effects. |
| GOAL 10 - Dissemination of Knowledge<br>Information and experience gained through geothermal utilization shall be accessible and transparent to the public and academic community alike while respecting confidential intellectual property rights. |

*Table 5-2: Core sustainability indicators (Shortall et al 2015c)*

| Indicator | Metric |
|---|---|
| Air quality in the surrounds of the geothermal power plant | Metric: concentrations (μg $m^{-3}$) of potentially toxic gases (hydrogen sulphide, mercury, sulphur dioxide, carbon dioxide, etc.)<br><br>Reference value: World Health Organisation reference values - Whichever is the most stringent of national regulation or WHO guideline values. For H2S, odour threshold (7 μg $m^{-3}$)should not be exceeded. Should take account of natural background concentrations if very high. |
| Tons of greenhouse gas emissions resulting from geothermal operations | Metric: Tons of $CO_2$ equivalents per kilowatt hour per annum<br><br>Reference Value: zero emissions |
| Water quality of water bodies impacted by geothermal power plant operations | Metric: status of water bodies impacted by geothermal power plant operations, based on national water directive ratings<br><br>Reference Value: Biological, hydromorphological and physio-chemical status of the water body before geothermal exploitation |
| Noise levels in working, recreation and residential areas in the surrounds of the geothermal power plant | Metric: dB<br><br>Reference value: Whichever is more stringent, World Health Organisation or national acceptable noise levels for working, recreational and residential areas. |
| Impact on important or vulnerable geothermal features | Metric: value of predefined impact parameters<br><br>Reference value: condition of important or vulnerable geothermal features before exploitation of the geothermal field.<br><br>NOTE: Important features should be defined before development by relevant stakeholders, based on uniqueness, cultural and economic importance. All features should be scaled with a vulnerability metric and the most important or vulnerable be monitored, using pre-defined criteria, such as temperature and activity. It is not considered enough to measure number or diversity of features. |
| Rate of subsidence in the geothermal field | Metric: Millimeters (mm) per year<br><br>Reference values: predicted subsidence levels before development |

*(Continued)*

*Table 5-2 Core sustainability indicators (Continued)*

| | |
|---|---|
| Number of accidents leading to work absence in the energy company per year | Metric: count<br><br>Reference Value: zero |
| Duration of Plant Power Outages per year | Metric: Use hours of unplanned interrupted service<br><br>Reference Value: zero |
| Level of induced seismicity per year | Metric: Peak ground velocity levels (PGV) during the year<br><br>Reference value: US department of energy "traffic light" system based on detectability of ground motion levels |
| Estimated productive lifetime of geothermal resource | Metric: years<br><br>Reference Value: at least 100-300 years |
| Resource reserve capacity ratio of the geothermal resource | Metric: ratio<br><br>Reference Value: predicted ratio for which non-declining production can be maintained |
| Utilization efficiency for the geothermal power plant | Metric: Percentage<br><br>Reference Value: best known example |
| Project internal rate of return (IRR) | Metric: percentage<br><br>Reference Value: IRR exceeds the cost of capital. |
| Average Income Levels in Project-Affected Communities | Metric: dollars per annum<br><br>Reference Value: income level before the project begins |
| Direct and indirect local job creation over lifetime of project | Metric: number of full-time employees per year<br><br>Reference Value: predicted number of jobs before the project begins |
| Expenditure on heat and electricity as a percentage of household income | Metric: percentage<br><br>Reference Value: Remain below 10% |
| Imported energy as a percentage of total (national level) | Metric: Percentage<br><br>Reference Value: 0% is desirable |
| Income-to-expenditure ratio for project-affected municipalities | Metric: ratio<br><br>Reference Value: A ratio greater than or equal to one is desirable. |

*(Continued)*

*Table 5-2 Core sustainability indicators (Continued)*

| | |
|---|---|
| Percentage of community residents that must be relocated due to energy project | Metric: percentage<br><br>Reference Value: zero |
| Percentage of energy company expenditure given to R&D per year | Metric: %<br><br>Reference Value: TBD |
| Percentage of renewables in total energy supply nationally | Metric: percentage<br><br>Reference Value: 100% |

*Table 5-3: Optional sustainability indicators*

| **Indicator** | **Metric** |
|---|---|
| EBIDTA ratio per project | Metric: ratio<br><br>Reference Value: EBIDTA recommended for geothermal industry |
| Percentage of protected area removed/affected due to geothermal project | Metric: Percentage<br><br>Reference value: size of protected area before energy project |
| Number of threatened species that may be affected by the geothermal project. | Metric: Count<br>Reference Value: zero |
| Rate of literacy of existing population in project-affected areas | Metric: percentage<br><br>Reference Value: literacy rates before the project began compared to afterwards<br>*Note: Impacts on literacy should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy projects |
| Cost per MW of power produced compared to price per MW from other sources | Note: Cost should include social and environmental costs<br>Metric: Ratio<br><br>Reference Value: TBD |
| Income Equity in Project-Affected Communities | Gini coefficient<br>Reference Value: Income equity before the project compared to afterwards<br><br>Note: income equity should be measured considering all other things equal, that is to say that the impact of the energy project on this indicator should be clearly traceable |

*(Continued)*

*Table 5-3 Optional sustainability indicators (Continued)*

| | |
|---|---|
| Infant mortality rates in the project-affected area | Metric: percentage<br><br>Reference Value: Infant mortality rates before the project began compared to afterwards<br><br>*Note: Impacts on infant mortality should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Life expectancy at birth in project-affected area | Metric: years<br><br>Reference Value: Average life expectancy before project compared to afterwards<br>Impacts on life expectancy should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Percentage of mass of fluid reinjected and/or cascaded compared to total extracted fluid mass | Metric: Percentage<br><br>Reference Value: 100% is ideal (no waste fluid is released to the environment) |
| Percentage of satisfied workers in the energy company per year | Metric: percentage<br><br>Reference Value: 100% |
| Ratio of average male income to female income for similar jobs for the project staff | Metric: ratio<br><br>Reference Value: 1:1 |
| Percentage of population with access to commercial energy in project-affected area | Metric: percentage<br><br>Reference value: Percentage of population in project-affected areas with access to commercial energy before energy project.<br>*Note: Impacts on energy access should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Amount of freshwater used during geothermal development (exploration, construction or operation activities) as a percentage of available freshwater in the project area | Metric: percentage<br><br>Reference value: The permitted amount of freshwater extraction that will not lead to water shortages in the area - i.e. use of freshwater for geothermal development does not conflict with other existing freshwater needs |

*(Continued)*

*Table 5-3 Optional sustainability indicators (Continued)*

| | |
|---|---|
| Monetary value of socially beneficial initiatives in project-affected communities as a percentage of total project expenditure | Metric: percentage<br><br>Reference Value: TBD *Note: socially beneficial initiatives are funded by the geothermal development and should have been approved by the local community. They may include such facilities as schools, clinics, etc. |
| Percentage of community residents that have agreed to potential culture-changing activities relating to the energy project | Metric: percentage (e.g. from survey responses)<br><br>Reference Value: TBD<br><br>Note: culture-changing activities may include resettlement, influx of migrant workers from outside, changes in livelihoods or social structures as a result of new economic activities or land use changes, new infrastructure, access to electricity, etc. |
| Unemployment rate in project-affected communities | Metric: percentage<br><br>Reference Value: unemployment rates before the project begins<br>*Note: Impacts on unemployment rates should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Percentage of population below poverty line in project-affected area | Metric: percentage<br><br>Reference Value: The percentage of population below the poverty line in surrounding regions. |
| Economic diversity of project-impacted areas | Metric: Adjusted Shannon-Wiener Index (%)<br><br>Reference Value: Complete economic diversity (100%) |

Based on these results we suggest a prototype assessment framework structure (Figure 5-6) of sustainability goals measured by core and optional indicators derived from the results. Core indicators are those that have been deemed universally relevant by all stakeholders in all countries. Optional indicators are those that have potential relevance, depending on the circumstances such as state of economic development (Shortall et al., 2015c). More optional indicators could be produced in the future, with further stakeholder input.

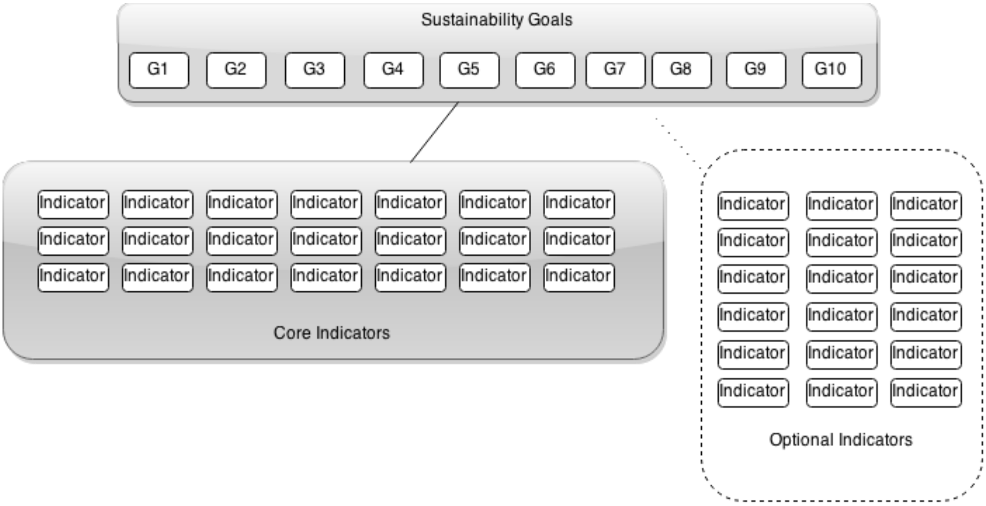



*Figure 5-6: Suggested sustainability assessment framework structure.*

## 5.5 Conclusion

This chapter has illustrated how the utilization of geothermal resources can be assessed both with regard to sustainable yield as well as in the context of broader sustainability assessments of which sustainable yield and renewability are necessary but not sufficient elements. The sustainability goals and indicators presented in this chapter enable comprehensive sustainability assessment of geothermal utilization.

It is clear that geothermal resources can significantly contribute to the movement towards economic and social goals of sustainable development as well as minimize environmental impact, if the sustainability goals presented in this chapter are adhered to. The indicators are then used to evaluate expected or actual fulfilment of the goals.

Careful use of geothermal resources can contribute to sustainable energy development in all sustainability dimensions and as a result the development of geothermal energy is intimately related to the movement towards global sustainability.

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# 6 Summary and Discussion

## 6.1 Summary

This research set out to create a tool for decision-makers for assessing the sustainabilty of geothermal energy projects. Geothermal energy usage is set to increase substantially in the future and whilst it is generally regarded as an environmentally benign and renewable energy source, certain issues need to be addressed to ensure that it is used in a sustainable manner. The literature was reviewed to identify sustainability issues and themes relating to geothermal utilization, as well as to review currently available sustainability assessment tools for energy developments (Paper I). Some cases exist where geothermal resources have been managed in a less than sustainable manner and the unique nature of geothermal resources means that currently available assessment tools are not adequate for assessing the sustainability of geothermal energy developments. This research builds on international sustainability indicator frameworks for energy resource assessment and uses the input of a diverse group of stakeholders from countries with geothermal resources at their disposal to create a customized assessment tool.

Three iterations of the indicator development process were carried out in Iceland, New Zealand and Kenya, as well as an additional Delphi process involving the UNU-GTP fellows in Reykjavik (Papers II and III). A framework consisting of sustainability goals and indicators was produced as a result of this process. The results also revealed differences in priorities of stakeholders from different economic backgrounds and cultures, highlighting the role social values have in shaping the definition of sustainable development. The insights from the stakeholder groups were key in creating an assessment framework that takes account of differences in cultures and priorities.

Based on the results of all of the Delphis, a suggested framework structure (Figure 6-1) of ten sustainability goals (Appendix A) measured by 21 core and 18 optional indicators (Appendix B) was derived. Each Delphi resulted in the choice of a set of sustainability goals and indicators by the stakeholders. It was found that the groups considered some of the indicators universally relevant (common or core indicators), leaving a subset of indicators that were only considered relevant by some groups. It was decided that the indicators in this subset should be used as optional or “satellite” indicators, to be chosen at the discretion of the end-user. These indicators have potential relevance, depending on the circumstances. More optional indicators could be produced in the future, with further stakeholder input.

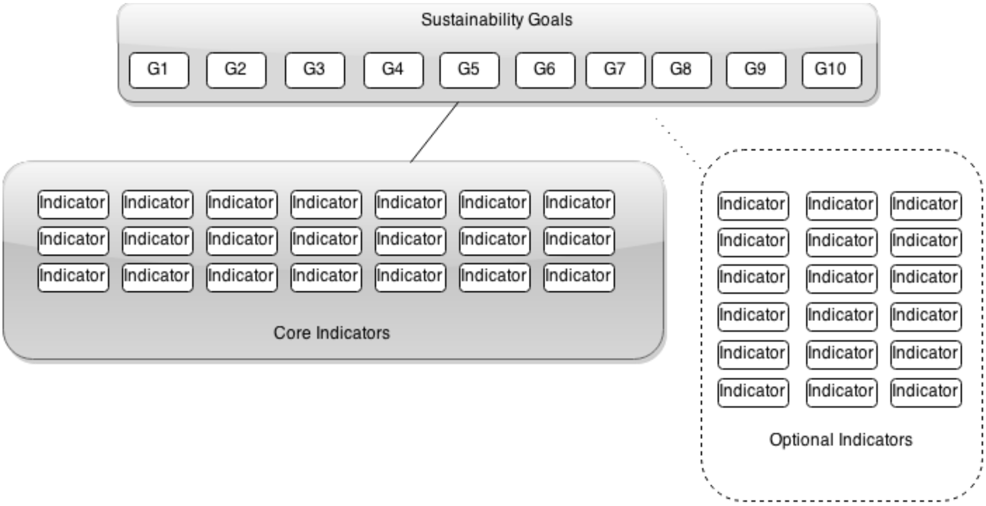


*Figure 6-1: Suggested sustainability assessment framework structure*

# 6.2 Discussion of Results

In this section the results will be discussed in terms of

- Stakeholder priorities: What do the results tell us about the stakeholder priorities for each group (Iceland, New Zealand, Kenya and the UNU-GTP group)?
- Coverage of the assessment framework: Do the indicators cover all of the relevant issues for geothermal sustainability?

## 6.2.1 Stakeholder Priorities and Consensus

The perceived relevance of each sustainability goal and indicator was reflected in the mean scores awarded by the stakeholders for each item during the Delphi processes. Although the attainment of a consensus among participants was not the main goal of the Delphis, the level of consensus for each item after each round was indicated by its standard deviation.

Items were kept or eliminated after each round, their suitability being determined by a combination of the mean score, stakeholder comments and facilitator judgement. A list of criteria (OECD, 1993; United Nations, 2007) were used to determine suitability. For the majority of items, consensus increased after each Delphi round, but consensus on items varied between the groups. The standard deviation may also have been affected by a decrease in the number of participants after each round. As well as this, the same participants did not necessarily participate in each round. The limitations of the Delphi technique are discussed in greater detail in Papers II and III. Bearing this in mind, in general for all groups there was higher consensus on indicators relating to environmental impacts but lower consensus on the indicators relating to socio-economic and community issues which resounds with the theory that the conditions for defining sustainable development tend to be determined by values and highly context-specific (Pinter, Hardi & Bartelmus, 2005; Meadows, 1998). The findings for each group are summarized in Table 6-1.

*Table 6-1: Summary of main findings on relevance of goals and indicators for each of the stakeholder groups*

| Group | Most relevant goals | Most relevant indicator topics | Possible reasons for choice | Least relevant goals | Least relevant indicator topics | Possible reasons for choice |
|---|---|---|---|---|---|---|
| Iceland | Resource renewability<br>Environmental management<br>Dissemination of knowledge | Air and water quality<br>Resource lifetime, Work safety<br>Noise | Recent cases of aggressive exploitation | Energy efficiency<br>Energy equity<br>Energy security | Community income levels<br>Energy company R&D expenditure<br>Project EBIDTA ratio<br>Household expenditure on energy<br>Percentage of renewables in total energy supply | Efficiency levels depend on resource and project design<br>Abundance of energy in Iceland<br>Majority of energy produced indigenously<br>Whole population has access to energy |
| New Zealand | Environmental management Economic management Research and innovation. | Air and water quality<br>Noise<br>Threatened species<br>Impact on geothermal features | Geothermal features important to Maori culture<br>Geothermal tourism economically important | Energy equity<br>Energy efficiency<br>Resource renewability | Household expenditure on energy<br>Plant power outages<br>Energy company R&D expenditure<br>Renewables in the total energy supply<br>Literacy rates in the project area. | Whole population has access to electricity<br><br>Rapid resource depletion not a concern |
| Kenya | Environmental management<br>Economic management<br>Research and innovation | Project IRR<br>Air quality<br>Noise<br>Reinjection Utilization efficiency | Some geothermal projects are located in or near national parks<br><br>Projects are funded by international institutions requiring careful economic and financial management | Water resource usage<br>Energy efficiency<br>Knowledge dissemination | Induced seismicity<br>Subsidence Poverty<br>Unemployment<br>Household expenditure on energy | Water resources part of environmental management<br>Subsidence and induced seismicity not common problems in Kenya |
| UNU-GTP | Water resource usage<br>Research and innovation Economic management | Project IRR,<br>Utilization efficiency<br>Air quality<br>Resource lifetime<br>Worker satisfaction | Group may have industry-biased focus<br><br>Many participants from water-scarce regions | Community responsibility<br>Resource renewability<br>Energy equity | Male to female income ratio<br>Income equity<br>Impacts on geothermal features Greenhouse gas emissions Induced seismicity | Group may have industry-biased focus |

### 6.2.2 Coverage of the assessment framework

Following a literature review of possible sustainability impacts, the characteristics of sustainable energy development were identified in this research (Paper I). The literature review found that a sustainable energy 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. Result in sustained yield, efficiently produced and used.
5. Be equitable and thus readily accessible, available and affordable, as well as secure.

These characteristics were then linked to a set of ten sustainability goals more specifically relating to sustainable geothermal energy development with the help of stakeholder input. The impacts reviewd in the literature were also classified into sustainability themes and sub-themes (Table 1-2). The well-known CSD sustainability themes were chosen as a guideline for this purpose. In order to determine if the assessment framework produced in this research adequately covered the relevant sustainability issues relating to geothermal energy development, its coverage was compared with that of similar well-known indicator frameworks identified in the literature (Paper I). Tables 6-2 and 6-3 show an analysis of coverage of the CSD themes to the indicators produced in this study by describing the linkages between indicators and sustainability themes. As well as this, the "internal" coverage of the framework (Tables 6-5 and 6-6) was considered in the context of the sustainability goals that were chosen by the stakeholders (Paper III). Since other frameworks may be designed for national level assessment, the scales of assessment will differ. The structural arrangement of each framework may also differ, however their main thematic foci or scope of coverage can be still compared. It is not the purpose of this research, however, to analyze or critically compare the adequacy of different kinds of sustainability assessment tools.

#### Coverage Compared to Other Sustainability Assessment Frameworks

A review of available assessment frameworks was carried out (Paper I) to determine the best structure for the framework that would be developed in this research. The frameworks reviewed included national level indicator frameworks, such as the CSD thematic framework, energy specific frameworks (the WEC index and IAEA's EISDs), and frameworks for the assessment of particular energy types (e.g. IHA-SAP) (Shortall, Davidsdottir & Axelsson, 2015a). None of these frameworks in themselves were found to be suitable for assessing geothermal projects, although they provided valuable insights and guidance for the most suitable structure of an assessment framework. This section provides a discussion of the coverage of the framework produced in this research compared to other currently available energy-related frameworks.

*Table 6-2: Linkages of common indicators to CSD sustainability themes*

| Common Indicator | Sustainability Theme: Poverty | Health | Education | Natural Hazards | Demographics | Atmosphere | Land | Freshwater | Biodiversity | Economic Development | Consumption and Production |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Air quality in the surrounds of the geothermal power plant | | | | | | | | | | | |
| Average Income Levels in Project-Affected Communities | | | | | | | | | | | |
| Direct and indirect local job creation over lifetime of project | | | | | | | | | | | |
| Duration of Plant Power Outages per year | | | | | | | | | | | |
| Estimated productive lifetime of geothermal resource | | | | | | | | | | | |
| Expenditure on heat and electricity as a percentage of household income | | | | | | | | | | | |
| Impact on important or vulnerable geothermal features | | | | | | | | | | | |
| Imported energy as a percentage of total (national level) | | | | | | | | | | | |
| Income-to-expenditure ratio for project-affected municipalities | | | | | | | | | | | |
| Level of induced seismicity per year | | | | | | | | | | | |

*(Continued)*

*Table 6-2 Linkages of common indicators to CSD sustainability themes (Continued)*

| **Common Indicator** | **Poverty** | **Health** | **Education** | **Natural Hazards** | **Demographics** | **Atmosphere** | **Land** | **Freshwater** | **Biodiversity** | **Economic Development** | **Consumption and Production** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Noise levels in working, recreation and residential areas in the surrounds of the geothermal power plant | | | | | | | | | | | |
| Number of accidents leading to work absence in the energy company per year | | | | | | | | | | | |
| Percentage of community residents that must be relocated due to energy project | | | | | | | | | | | |
| Percentage of energy company expenditure given to R&D per year | | | | | | | | | | | |
| Percentage of renewables in total energy supply nationally | | | | | | | | | | | |
| Project internal rate of return (IRR) | | | | | | | | | | | |
| Rate of subsidence in the geothermal field | | | | | | | | | | | |
| Resource reserve capacity ratio of the geothermal resource | | | | | | | | | | | |
| Tons of greenhouse gas emissions resulting from geothermal operations | | | | | | | | | | | |
| Utilization efficiency for the geothermal power plant | | | | | | | | | | | |
| Water Quality of water bodies impacted by geothermal power plant operations | | | | | | | | | | | |

*Table 6-3: Linkages of satellite indicators to CSD sustainability themes*

| Satellite Indicator | Sustainability Theme: Poverty | Health | Education | Natural Hazards | Demographics | Atmosphere | Land | Freshwater | Biodiversity | Economic Development | Consumption and Production Patterns |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EBIDTA ratio per project | | | | | | | | | | | |
| Percentage of protected area removed/affected due to geothermal project | | | | | | | | | | | |
| Number of threatened species that may be affected by the geothermal project. | | | | | | | | | | | |
| Rate of literacy of existing population in project-affected areas | | | | | | | | | | | |
| Cost per MW of power produced compared to price per MW from other sources | | | | | | | | | | | |
| Income Equity in Project-Affected Communities | | | | | | | | | | | |
| Infant mortality rates in the project-affected area | | | | | | | | | | | |
| Life expectancy at birth in project-affected area | | | | | | | | | | | |
| Percentage of mass of fluid reinjected / cascaded compared to total extracted fluid mass | | | | | | | | | | | |

*(Continued)*

*Table 6-3: Linkages of satellite indicators to CSD sustainability themes (Continued)*

| **Satellite Indicator** | **Poverty** | **Health** | **Education** | **Natural Hazards** | **Demographics** | **Atmosphere** | **Land** | **Freshwater** | **Biodiversity** | **Economic Development** | **Consumption and Production** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Percentage of satisfied workers in the energy company per year | | | | | | | | | | | |
| Ratio of average male income to female income for similar jobs for the project staff | | | | | | | | | | | |
| Percentage of population with access to commercial energy in project-affected area | | | | | | | | | | | |
| Amount of freshwater used during geothermal development as a percentage of available freshwater in the project area | | | | | | | | | | | |
| Monetary value of socially beneficial initiatives in project-affected communities as a percentage of total project expenditure | | | | | | | | | | | |
| Percentage of community residents that have agreed to potential culture-changing activities relating to the energy project | | | | | | | | | | | |
| Unemployment rate in project-affected communities | | | | | | | | | | | |
| Percentage of population below poverty line in project-affected area | | | | | | | | | | | |
| Economic diversity of project-impacted areas | | | | | | | | | | | |

**The CSD thematic framework** provides guidelines for developing national sustainability indicators, including energy indicators (United Nations, 2007) This framework consists of indicators under a number themes that are intended for use at the national or regional level for measuring sustainability progress retrospectively for a number of sectors and is not specifically focussed on energy development. It is therefore not suitable as a geothermal assessment tool, but the themes of the CSD conceptual framework are useful for categorizing geothermal sustainability issues that should be assessed. In this research, therefore, the CSD thematic framework was taken further by applying additional stakeholder engagement methods to develop indicators for geothermal developments in this research. Themes that were not considered relevant to geothermal energy development and were consequently not used such as the themes of oceans or global economic partnership. The coverage of the CSD themes is shown in the Tables 6-2 and 6-3. The darker the cell shading, the higher the estimated degree of connectedness of the indicator to the CSD theme. Note that an indicator may apply to more than one theme, as for example with "*Percentage of community residents that must be relocated due to energy project*", which has primary links to the demographics theme, has black shading. Medium-grey shading indicates a clear but possibly secondary link. Light grey shading indicates a possible but weaker link. The community relocation indicator could also be used to indirectly estimate possible increases in poverty for displaced communities, due to loss of livelihood or disenfranchisement and, therefore, the poverty theme is shaded medium-grey. It should be noted that the choice of these linkages has been based on the literature review of Paper I and knowledge gained throughout this research work.

**The International Atomic Energy Agency (IAEA) energy indicators for sustainable development (EISDs)** (International Atomic Energy Agency (IAEA), 2005) were also reviewed. These indicators were created to provide policy-makers with information about a nation's energy sustainability. The themes covered by the indicators are shown in Table 6-4.

The EISD framework is intended to provide an overall picture of the social, environmental and health impacts of energy use to help in making decisions relating to choices of energy sources, fuels and energy policies and plans. Since these indicators are intended for use at a national level and cover many different types of energy usage, they are unsuited to assessing individual geothermal projects. For example, the economic indicators provide only very general information on the usage of energy or energy prices, which are difficult to link to direct impacts of energy projects. As well as this, other shortcomings with the EISD framework can be identified. The social dimension, consisting of only four indicators in total, covers the themes of energy accessibility, affordability, disparities and health and safety (accidents). Cultural issues are not included, nor are various other social issues that may arise during energy developments, such as resettlement or livelihood displacment. Whether or not the scope of the EISD indicators is deliberately limited in this regard is not clear. [6] The shortcomings of the EISD framework in this regard are further discussed in Section 6.2.2.

In this research, after carrying out a literature review of possible impacts (Paper I) and defining sustainability goals, it was decided that the system boundaries of an assessment

[6] It is mentioned in the EISD report that these indicators were created to compliment the CSD general sustainability indicators.

should encompass the direct, indirect and induced effects of geothermal development (Section 6.2.1). In comparison with the EISD framework, the CSD thematic framework allowed inclusion of a wider range of issue–areas dealing with the broader social implications of energy development such as its impacts on living standards, general health, education or cultural impacts, for instance. The issues of incomes, noise and odour nuisance could be included here, as could the issue of potential damage to important geothermal features. It also allowed inclusion of the concern of natural hazards, such as seismicity, landslides or hydrothermal eruptions, which may be associated with geothermal energy projects and indeed other energy projects such as hydropower or oil and gas fracking.

The environmental dimension of the EISDs (10 indicators) covers climate change (GHGs), air quality, water quality, land/forests, and waste management (solid and nuclear waste). However it neglects, for instance, the issues of freshwater usage, biodiversity, threatened species and impacts on rare ecosystems, all of which are concerns in any energy development, let alone just geothermal developements. These issues are covered in the geothermal assessment framework, however (see Appendix A, B, C).

The EISD economic dimension, whilst covering the issues of energy efficiency and security, neglects the broader economic impacts of energy development such as long term employment creation or economic stimulation. The rationale for the inclusion of the EISD theme of energy diversification may also be questioned, in that it may be understood to imply that higher energy diversity automatically results in sustainable development, regardless of the energy types in the mix. In general, the EISD economic dimension tends to steer clear of making an attempt to measure the economic costs and benefits that might arise from energy development. In contrast, the framework produced in this research implicitly calls for an assessment of economic costs and benefits on some level, since it requires assessment of for instance, impacts on geothermal features and ecosystems which are important for tourism, the extent of community initiatives or the purchasing power of local communities.

The EISD indicators are also too general to allow assessment of developer company issues such as their financial performance, gender diversity, community responsibility, or their investment in R&D activities. These issues were highlighted during the development of sustainability goals for geothermal development and were considered essential to cover.

**The Energy Sustainability Index**, developed by the World Energy Council (WEC), ranks country energy policies in terms of energy sustainability based on the three dimensions of energy security, social equity, and environmental sustainability. The index uses two types of indicator, energy performance indicators and contextual indicators which cover broader issues such as living standards and the economic and political conditions. Each category is also assigned a particular weight (World Energy Council, 2014). In total there are 22 indicators used to calculate a composite index to allow rankings. The themes and indicators are shown in Table 6-4.

The WEC framework attempts to measure the aggregate outcome of energy policies, rather than simply the impacts of energy developments themeslves. The index's values are calculated through the collection of existing high-level indicator data available from organisations like the IEA or World Bank, which does not capture the direct impacts of energy projects. It assesses issues on a much broader scale than would be appropriate if assessing individual energy projects. Issues such as macroeconomic or political stability, regulatory quality or effectiveness of government are outside the scope of such assessments. Such issues were not considered important by the stakeholders in this research. It may not be appropriate, therefore, to compare the coverage of the indicators in the WEC framework with the framework produced in this research and an in-depth analysis of the WEC framework is beyond the scope of this research. However, after a basic examination of the main dimensions or thematic areas, the most marked differences in coverage are those of cultural issues, which are not included in the social equity or social strength categories, and of land or biodiversity impacts, which are not included in the environmental impact mitigation category. The social equity category only includes indicators for energy equity, but not broader social equity indicators such as income equity, gender equity and so on. With regard to the energy security dimension, it is unclear how measuring diversity of energy production would help to measure energy sustainability, especially when there are no indicators measuring the share of renewables in the energy supply.

**The Gold Standard Foundation (GSF) toolkit** provides a sustainability assessment framework for new renewable energy or end-use efficiency improvement project accreditation. The toolkit includes several qualitative self-assessment tools as well as a "sustainability matrix" of indicators for detailed prospective impacts assessments (The Gold Standard Foundation, 2014). Gold Standard project applicants must preemptively self-assess their project activities using a set of 12 sustainability indicator categories, in order to identify the need for compliance or mitigation measures. The themes covered by the indicators are shown in Table 7-4.

In collaboration with stakeholders, indicators are assigned scores of "negative", "neutral" or "positive" by comparing potential impact levels to a base-line situation. The indicators have equal weights. To qualify for registration, projects must contribute positively to at least two out of three categories and be neutral in the third category. The scoring of the indicators must be easily reproducible and supported by convincing arguments. A set of questions is provided for guidance during the scoring of the indicators, e.g. during a stakeholder consultation. Applicants must choose indicators and parameters from the list to report as part of a sustainability monitoring plan, based on the outcomes of the initial scoring exercise.

Compared to the framework produced in this research, the Gold Standard indicators are comprehensive in their thematic coverage of energy sustainability in general, especially in that they consider developing country issues such as technological transfer. However, they do not cover geothermal-specific issues like induced seismicity, subsidence, other hazards or impacts on geothermal features. Job creation is covered but the number of long-term jobs is not considered. Cultural issues are not addressed in the themes or indicators. Technological transfer is considered as a desirable outcome of energy development, but the potential negative impacts on societies and culture are not mentioned in this regard either.

For energy sustainability assessment tools (EISDs, WEC, GSF) found in the international literature, such as those discussed here, it appears that the definition of system boundaries or scope of the assessment is rather arbitrary. Coverage of social and economic issues is particularly inconsistent between the frameworks, and they do not provide indicators for specific energy types. The phenomena of social indicators being less established than environmental or economic indicators has been pointed out by various authors (Assefa &

Frostell, 2007; Carrera & Mack, 2010) and during the development of sustainability indicators for specific energy types including nuclear (Stamford & Azapagic, 2011). This issue is discussed in further detail in Section 6.2.4.

**The International Hydropower Association** sustainability asessement tool for hydropower projects (IHA-SAP) (International Hydropower Association, 2006), although not based on indicators as such, assesses various strategic and managerial aspects of proposed or operational hydropower projects (International Hydropower Association, 2008). The IHA-SAP framework relies on qualitative evidence-based assessment by auditors, so it is only possible to compare it to the framework produced in this research on the basis of thematic coverage. The themes covered are shown in Table 6-4.

The scope of coverage of the IHA-SAP naturally differs from other indicator-based frameworks that are designed to measure the impacts of energy projects, since the themes are focussed on strategic and managerial performance only, however the assessment categories comprehensively cover developer-related issues.

**The Global Bioenergy Partnership (GBEP)** released sustainability indicators for the assessment of bioenergy in 2011, designed for use on the regional or national level. The assessment framework consists of 24 indicators. These indicators were developed to provide policy and decision-makers with a set of analytical tools for informing the development of national bioenergy policies and monitoring their impacts. The themes covered by the indicators are shown in Table 6-4.

Evidently, many of the themes of the GBEP framework relate specifically to bioenergy, such as land use, an issue that was deemed irrelevant to geothermal development. This framework also monitors mainly nationally relevant issues, such as net energy balance, capacity and flexibility or energy diversity. Again, it can be argued that cultural impacts are not covered by this framework, apart from perhaps the aspect of women and children collecting biomass. The issues of energy poverty or equity are not explicitly examined.

Another sustainability assessment framework has been developed for nuclear power and alternative electricity options (Stamford & Azapagic, 2011) which includes comprehensive coverage of general energy development impacts and nuclear-specific impacts divided into techno-economic, environmental and social categories as shown in Table 6-4.

Since it is geared at comparing between energy options, the focus of this assessment framework naturally differs from our framework, which assesses the impacts of an individual energy projects. The techno-economic issues considered reflect this focus. However, in terms of general thematic coverage, some notable differences between the issues covered by this framework and our framework exist. For instance, social impacts of energy development covered relate mainly to employment and health and not other potential impacts on poverty, education or living standards, which would be more pronounced in countries of the Global South. Cultural impacts are not mentioned. Energy diversity is included in the energy security category, whereas our stakeholders omitted this issue, since it was not considered to necessarily indicate sustainability. Neither the issues of freshwater quantity or thermal pollution (common concerns in both geothermal and nuclear power development) are included in the environmental section.

*Table 6-4: Comparison of available sustainability assessment frameworks for energy*

| Assessment Framework | Scale / Scope | Purpose | Themes covered |
|---|---|---|---|
| IAEA EISDs | National level assessment of energy sustainability | Inform national policy making | **Social:** Equity (accessibility, affordability, disparities); health (safety)<br>**Economic:** Use and production patterns (overall use, overall productivity, supply efficiency, production, end use, diversification, prices); security (imports, strategic fuel stocks)<br>**Environmental:** Atmosphere (climate change, air quality); water (water quality); land (soil quality, forest, solid waste generation and management) |
| WEC Energy Sustainability Index | National level assessment of energy policy sustainability | Allow ranking by country | **Energy Security:** Consumption growth; ratio of energy production to consumption**;** wholesale margin on gasoline; diversity of electricity production**;** exporters - dependence on and diversity of energy exports**;** importers – oil reserve stocks<br>**Social Equity:** Affordability of retail gasoline; affordability of electricity relative to access<br>**Environmental Impact Mitigation:** Energy intensity; emissions intensity; effects on air and water; efficiency of electricity production<br>**Political Strength:** Political stability; regulatory quality; effectiveness of government<br>**Societal Strength:** Control of corruption; rule of law; quality of education; quality of health<br>**Economic Strength:** Macro-economic stability; cost of living expenditure; availability of credit to the private sector |
| IHA-SAP | Project level qualitative sustainability assessment | Creation of a sustainability profile used to identify gaps and drive continuous improvement | **Technical:** Siting and design; hydrological resource; reservoir planning filling and management; insfrastructure safety; asset reliability and efficiency.<br>**Environmental:** Downstream flows; erosion and sedimentation; water quality; biodiversity and invasive species; waste, noise and air quality.<br>**Social:** Project-affected communities and livelihoods; resettlement; indigenous peoples; cultural health; public health.<br>**Economic and Financial:** Economic viability; financial viability; project benefits; procurement<br>**Integrative:** Demonstrated need and strategic fit; communications and consultation; governance; integrated project management; environmental and social issues management. |

*(Continued)*

*Table 6-4: Comparison of available sustainability assessment frameworks for energy (Continued)*

| | | | |
|---|---|---|---|
| Gold Standard Foundation Indicators | Project level sustainability assessment | Renewable energy project accreditation | **Environment:** Air quality, water quality and quantity, soil condition; other pollutants; biodiversity<br>**Social Development:** Quality of employment, livelihood of the poor, access to affordable & clean energy services, human and Institutional Capacity<br>**Economic and Technological Development:** Quantitative employment and income generation, access to investment, technology transfer and technological self- reliance. |
| GBEP indicators | Regional and national level energy policy sustainability assessment | Inform the development of national bioenergy policies and monitor their impacts | **Environmental:** Life cycle GHG emissions; soil quality, harvest level of wood resources; emissions of pollutants; water use and efficiency; water quality; biodiversity; land use.<br>**Social:** Allocation and tenure of land for new bioenergy production; price and supply of a national food basket; change in income; jobs in the bioenergy sector; changes in unpaid time spend by women and children collecting biomass; bioenergy used to expand access to modern energy services; change in mortality and burden of disease attributable to indoor smoke, incidence of injuries, illness, fatalities.<br>**Economic:** Productivity and efficiency; net energy balance; gross value added; change in consumption of fossil fuels and traditional biomass; training and requalification of the workforce; energy diversity; infrastructure and logistics for distribution of bioenergy; capacity and flexibility of use of bioenergy. |
| Nuclear energy assessment framework | Project level comparative sustainability assessment | Comparison between energy project options | **Techno-economic:** Operability, technological lock-in, immediacy, levelized cost of generation, cost variability, financial incentives<br>**Environmental:** Material recyclability, water eco-toxicity, global warming, ozone layer depletion, acidification, eutrophication, phytochemical smog, land use and quality,<br>**Social:** Provision of employment, human health impacts, large accident risk, local community impacts, human rights and corruption, energy security, nuclear proliferation, intergenerational equity. |

### Coverage of Framework Goals by Indicators

In Table 6-5 and 6-6, the common and satellite indicators developed in this work are analyzed in terms of how they are linked to the individual sustainability goals (Appendix A) that were chosen by the stakeholder groups. Here we can see the extent of the coverage of each goal by the indicators. The shading of the cells provides an approximate guide to the linkage of each indicator to each goal. The darker the cell shading, the higher the estimated degree of connectedness of the indicator to the goal. Note that an indicator may apply to more than one goal, as for example with "*Air quality in the surrounds of the geothermal power plant*" which has primary links to Environmental Management has black shading. Medium-grey shading indicates a clear but possibly secondary link. Light grey shading indicates a possible but weaker link. The air quality indicator is also useful for measuring how much responsibility the developer company takes for mitigating air pollution and, therefore, the Community Responsibility goal is shaded medium-grey. Moreover, as air pollution can result in indirect costs, e.g. from remedying induced ecological or health impacts or from litigation suits, the indicator provides information on the quality of economic management of a project. Consequently, the goal of Economic Management is also shaded in lighter grey. It should be noted that the choice of these linkages has been based on the literature review of Paper I and knowledge gained throughout this research work.

*Table 6-5: Linkages of common indicators to sustainability goals defined in this study*

| Common Indicator | **Sustainability Goal** **G1** Renewability | **G2** Water Resource Usage | **G3** Environmental Mgt | **G4** Efficiency | **G5** Economic Mgt | **G6** Energy Equity | **G7** Energy Security | **G8** Community Responsibility | **G9** Research and Innovation | **G10** Knowledge Dissemination |
|---|---|---|---|---|---|---|---|---|---|---|
| Air quality in the surrounds of the geothermal power plant | | | | | | | | | | |
| Average Income Levels in Project-Affected Communities | | | | | | | | | | |
| Direct and indirect local job creation over lifetime of project | | | | | | | | | | |
| Duration of Plant Power Outages per year | | | | | | | | | | |
| Estimated productive lifetime of geothermal resource | | | | | | | | | | |
| Expenditure on heat and electricity as a percentage of household income | | | | | | | | | | |
| Impact on important or vulnerable geothermal features | | | | | | | | | | |
| Imported energy as a percentage of total (national level) | | | | | | | | | | |
| Income-to-expenditure ratio for project-affected municipalities | | | | | | | | | | |
| Level of induced seismicity per year | | | | | | | | | | |

*(Continued)*

*Table 6-5: Linkages of common indicators to sustainability goals defined in this study (Continued)*

| **Common Indicator** | **G1** Renewability | **G2** Water Resource Usage | **G3** Environmental Mgt | **G4** Efficiency | **G5** Economic Mgt | **G6** Energy Equity | **G7** Energy Security | **G8** Community Responsibility | **G9** Research and Innovation | **G10** Knowledge Dissemination |
|---|---|---|---|---|---|---|---|---|---|---|
| Noise levels in working, recreation and residential areas in the surrounds of the geothermal power plant. | | | | | | | | | | |
| Number of accidents leading to work absence in the energy company per year | | | | | | | | | | |
| Percentage of community residents that must be relocated due to energy project | | | | | | | | | | |
| Percentage of energy company expenditure given to R&D per year | | | | | | | | | | |
| Percentage of renewables in total energy supply nationally | | | | | | | | | | |
| Project internal rate of return (IRR) | | | | | | | | | | |
| Rate of subsidence in the geothermal field | | | | | | | | | | |
| Resource reserve capacity ratio of the geothermal resource | | | | | | | | | | |
| Tons of greenhouse gas emissions resulting from geothermal operations | | | | | | | | | | |
| Utilization efficiency for the geothermal power plant | | | | | | | | | | |
| Water quality of water bodies impacted by geothermal power plant operations | | | | | | | | | | |

*Table 6-6: Linkages of satellite indicators to sustainability goals defined in this study*

| Satellite Indicator | **G1** Renewability | **G2** Water Resource Usage | **G3** Environmental Mgt | **G4** Efficiency | **G5** Economic Mgt | **G6** Energy Equity | **G7** Energy Security | **G8** Community Responsibility | **G9** Research and Innovation | **G10** Knowledge Dissemination |
|---|---|---|---|---|---|---|---|---|---|---|
| EBIDTA ratio per project | | | | | | | | | | |
| Percentage of protected area removed/affected due to geothermal project | | | | | | | | | | |
| Number of threatened species that may be affected by the geothermal project. | | | | | | | | | | |
| Rate of literacy of existing population in project-affected areas | | | | | | | | | | |
| Cost per MW of power produced compared to price per MW from other sources | | | | | | | | | | |
| Income Equity in Project-Affected Communities | | | | | | | | | | |
| Infant mortality rates in the project-affected area | | | | | | | | | | |
| Life expectancy at birth in project-affected area | | | | | | | | | | |
| Percentage of mass of fluid reinjected and/or cascaded compared to total extracted fluid mass | | | | | | | | | | |

*(Continued)*

*Table 6-6: Linkages of satellite indicators to sustainability goals defined in this study (Continued)*

| **Satellite Indicator** | **G1** Renewability | **G2** Water Resource Usage | **G3** Environmental Mgt | **G4** Efficiency | **G5** Economic Mgt | **G6** Energy Equity | **G7** Energy Security | **G8** Community Responsibility | **G9** Research and Innovation | **G10** Knowledge Dissemination |
|---|---|---|---|---|---|---|---|---|---|---|
| Percentage of satisfied workers in the energy company per year | | | | | | | | | | |
| Ratio of average male income to female income for similar jobs for the project staff | | | | | | | | | | |
| Percentage of population with access to commercial energy in project-affected area | | | | | | | | | | |
| Amount of freshwater used during geothermal development as a percentage of available freshwater in the project area | | | | | | | | | | |
| Monetary value of socially beneficial initiatives in project-affected communities as a percentage of total project expenditure | | | | | | | | | | |
| Percentage of community residents that have agreed to potential culture-changing activities relating to the energy project | | | | | | | | | | |
| Unemployment rate in project-affected communities | | | | | | | | | | |
| Percentage of population below poverty line in project-affected area | | | | | | | | | | |
| Economic diversity of project-impacted areas | | | | | | | | | | |

Both Table 6-5 and Table 6-6 show that although some goals appear to receive more coverage than others through the chosen indicators, all of the goals have at least one corresponding indicator, either common or optional. The fact that certain goals that have greater representation through the indicators, such as environmental management, economic management and community responsibility, may signal that these issues are of particular importance to the stakeholders, or alternatively that it was easier to chose the indicators for these goals.  In order to ascertain which was the case it would be necessarily to divide or break down these goals into a number of more specific sub-goals for greater clarity, for instance, the goal of community responsibility could be broken up into categories of direct or induced impacts.  For some goals, it may be the case that it was rather difficult for the stakeholders to find indicators to measure a given goal. For instance, the goal of research and innovation, although rated as highly relevant by most groups, receives sparse coverage by indicators. Without clear examples of policy targets for some goals, the task of assigning reference values became more difficult.  For other goals with little coverage, such as water resource usage, it may simply make more sense to combine two goals, e.g. the goal of water resource usage could be included in the goal relating to environmental management as a sub-goal. For this reason, we advise against assigning weights to any of the goals, as one would perhaps do for themes in other assessment frameworks, because it is clear that the goals were chosen by stakeholders without reflecting on their relative importance or weight.

The goal of efficiency did not receive many indicator suggestions, nor was it rated as highly relevant by most groups, which is interesting, since efficiency is often cited as a key tenet of sustainable energy development (UNDP, 2002). This suggests that using efficiency as an indicator of sustainable energy development without placing it in context may not be appropriate for this framework. Increasing the efficiency of geothermal energy sources may in fact be at odds with other criteria for sustainability, such as sustained yield, e.g. where fluid is cascaded and not reinjected. It may therefore be necessary to examine the efficiency of power production strictly within a systemic context.

With regard to the satellite or optional indicators (Table 6-6), the goals of research and innovation and knowledge dissemination do not receive any coverage by the chosen indicators, again showing the unwillingness of the stakeholders to come up with metrics for these goals. Efficiency is still sparsely covered. Environmental management, economic management, energy equity  and community responsibility are again the best covered goals by the optional indicators, with energy equity receiving more attention in the optional indicators than in the common ones. The goal of energy equity was considered among the least relevant in nearly all of the groups, which is perhaps unexpected, given that many participants come from countries in which energy equity is a concern, such as Kenya, where it has already been pointed out that only around 23% of the population have access to electricity (Government of Kenya, 2011).

### 6.2.3 The Importance of Social and Cultural Sustainability

> *"There is an increasing recognition that the "three pillars" of sustainable development need to be complemented by a dimension that is variously described as institutional, cultural or ethical, and that would include governance, efficiency, motivation, values and other less tangible factors that may be important determinants of sustainable human prosperity"* (Dahl, 2012)

Sustainability assessments of energy technologies often fail to account for social impacts and the long-term repercussions of energy systems development. While economic and ecological sustainability assessments of energy systems are common, little social research has been carried out on the topic (Carrera & Mack, 2010). Whilst such aspects may be difficult to define, it does not mean that they are less important, or should not be measured.

During this research, the views and values of each stakeholder group were markedly different, as evidenced by the different levels of relevance assigned to either sustainability goals or indicators by the participants. Clearly social norms and cultural values played a part in the choices of each group. This suggests that whist some issues will be universally important to decision-makers, it is not correct to assume that a small group of people can come up with a one-size-fits-all assessment framework and that care must be taken to incorporate culturally-specific sub-themes and indicators into assessment tools.

Culture is an important aspect of sustainable development. Whilst the social dimension is commonly found in the discourse on sustainable development, although arguably to a lesser extent than the other dimensions (Murphy, 2012) the cultural aspect has been less clearly defined (European Commission, 2006), but is receiving increasing attention in the international policy literature. Culture has been acknowledged to be instrumental in promoting economic progress and simply to be necessary for human well-being. According to the European Commission and Council, cultural diversity contributes to Europe's goals for, sustainable and inclusive economic growth (European Commission, 2006). However, it remains difficult to define or measure either social or cultural sustainability (Axelsson et al., 2013).

Issues such as housing, education, employment, equity and gender have been traditionally considered in the social dimension and to a certain extent cultural heritage. Currently there is a growing focus on social integration and cohesion, social capital, wellbeing, happiness and quality of life (Murphy, 2012). Cultural practices, expressions, knowledge, skills, traditions, identity, values, spirituality and esthetics are also considered important. Emerging areas that are garnering attention include qualitative concepts such as creativity, critical knowledge, sense of place, empathy, trust, risk, respect, and recognition (Axelsson et al., 2013; Towse, 2003). In relation to any type of energy development, cultural sustainability should be a concern, since energy projects may have significant impacts on biodiversity and culture.

Regarding geothermal energy projects, lands used for grazing or hunting may be altered by development (Becker & Vanclay, 2003), or animal breeding and habitats may be disturbed, in turn having an effect on peoples dependent on these animals for livelihood. Geothermal development may damage features holding cultural, historical or spiritual significance such as hot springs, etc. (Stewart, 2009). Communities may need to be resettled if developers need 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 in Olkaria to Kedong (All Africa, 2012). Previous social assessments of the impacts on local communities show that the possibility of a new geothermal development may provoke a diverse range of opinions within a community (Mariita, 2002). Hikuroa (2010) suggests that in order to measure economic, environmental, social and cultural well-being, assessments of geothermal development must incorporate the values, principles and practices of indigenous peoples. Each geothermal project needs a culturally appropriate assessment of the potential impacts, both quantiative and qualitative.

In the CSD thematic framework (United Nations, 2007), which was used as a guideline for the creation of the assessment framework in this research, no specific indicators on cultural sustainability are included. The themes currently include poverty, health, education, natural hazards, demographics, atmosphere, land, oceans and seas, freshwater, biodiversity, economic development, global economic partnership and consumption and production patterns (United Nations, 2007). The IAEA Energy Indicators for Sustainable Development (EISDs), which were also used in some part to guide this research (Shortall, Davidsdottir & Axelsson, 2015b), contain only four social indicators out of a total of 30. The social indicators deal with the issues of energy access, energy poverty, household energy usage and accidents. However, as is very clear from the literature and from this research, the social and cultural implications of energy development span much further than these four indicators. The IAEA recommend that their indicator set only be used as a guideline and encourages nations to incorporate their own unique perspectives when measuring their own policy progress using indicators (International Atomic Energy Agency (IAEA), 2005). Trials of these indicators were undertaken in several countries and the findings showed that modifications in many cases were required in order to take account of differing social and cultural conditions (International Atomic Energy Agency, 2007).

Since cultural values differ significantly between groups and regions, it is understandably difficult to suggest commonly agreed-upon indicators relating to social or cultural sustainability at the international level. Furthermore, if indicators are developed within a particular institutional context, it is likely that the values of people with the most influence will prevail (Bossel, 1999; Meadows, 1998). In order for the end-users of indicators to ensure that appropriate social and cultural indicators are incorporated into assessments, the input of the relevant stakeholders from that region should be sought and efforts made to ensure data collection for the relevant indicators takes place, if it is not already done.

In developing the sustainability assessment framework in this research, the stakeholders suggested very few non-traditional indicators to measure social or cultural sustainability. The social indicators chosen dealt with the traditional social issues such as education, health and employment and some indicators such as those relating to geothermal features could be said to relate to cultural heritage. In the New Zealand Delphi panel, Maori representatives rated the suitability of the goals indicators in relation to Maori world views[7], but in the Kenyan Delphi, no Maasai representatives took part. One reason being

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[7] Indicators relating to the Maori world view exists in relation to geothermal development (Hikuroa, Integrating Indigenous Values into Geothermal Development, 2010), but these were developed specifically for use within another type of assessment framework designed to identify biases in world views (Hikuroa et al., 2011) and could not be incorporated into this research.

that the Maasai community we met in Olkaria would not have had easy access to electricity or computers. Some examples of the comments of the New Zealand panelists are listed in Box 6-1.

Goal 8 – Community Responsiblity
*Care is necessary in terms of how community is defined to ensure that the appropriate relationships are acknowledged in terms of Te Tiriti O Waitangi. If there is no net benefit for the local community then the project must be redesigned to achieve this*

Goal 9 – Research and Innovation
*Research is important. The obvious gap in current research is the paucity of studies of Indigenous rights in geothermal development and the improved responsibility of geothermal project management when Indigenous decision makers are appropriately empowered in the process. Geothermal development projects in Aotearoa NZ where Iwi and Hapu have been in decision making roles have produced inovative outcomes without sacrificing wider community accountability not otherwise possible.*

*Box 6-1 – Example comments relating to Maori world view from New Zealand panelists*

The concept of measuring intangible values was perhaps not well-known to the majority of participants in all of the Delphis. During the first pre-engagement workshop in Iceland, for instance, several social indicators were rejected based on the perception that they would be difficult to measure or because stakeholders did not understand them or find them relevant. This workshop was used as a pilot for the rest of the stakeholder engagement process and these kinds of indicators were subsequently ommitted from the Delphis, since it was felt that they did not fulfil the criteria of being easily understandable or measurable. The rejected indicators included:

- Degree of public participation during environmental impact assessment in relation to legal requirements
- Value of fines or number of sanctions for regulatory non-compliance of developer company
- Corruption perceptions index
- Total cases in supreme court involving developer company per year
- Democracy levels
- Percentage of voter turnout

Apart from the Kenyan Delphi, few cultural indicators were accepted or suggested by the stakeholders during the Delphis. The indicator “ Percentage of community residents that have agreed to potential culture-changing activities relating to the energy project”, was suggested and approved by the Kenyan group, for instance.

As previously mentioned, indicators to measure the social impacts of energy developments have been evaluated in Europe (Carrera & Mack, 2010). The majority of these indicators need to be assessed qualitatively using surveys and include the themes of energy security, political stability, social risks, and quality of life. The indicators dealt with such issues as the potential for social conflicts relating to energy systems, the reliance of participative decision-making processes during energy planning, citizen acceptance rates of power plants, risk and fairness perceptions in local communities, subjective satisfaction rates.

## 6.3 Limitations

In this section, the limitations and weaknesses of this study are discussed with regard to

1. Research methods used
2. Sustainability assessment frameworks themselves

### 6.3.1 Limitations of methods used

In discussing the limitations of the methods used in this study, the following topics are addressed:

- Difficulties in choosing suitable indicators
- Difficulties relating to stakeholder engagement techniques

#### Difficulties in choosing suitable indicators

It has been argued that the design and contents of a Delphi study reflect the culture, bias and knowledge of its formulators and participants. Specific choices will always be made by a group of individuals, shaping the exercise and influencing its results (Linstone & Turoff, 2002). The difficulty of appraising context-specific impacts has emerged in other studies involving the Delphi technique (Ribeiro & Quintanilla, 2015). In this study, different indicators were considered important in each location. Only indicators that were relvant to the participant's world view remained after the Delphi process. For example, the stakeholders in countries of the Global North were more likely to regard indicators on life expectancy, infant mortality or literacy as irrelevant, whereas in a developing country like Kenya, these issues are considered relevant with regard to geothermal developments. Whilst indicators that are potentially universally relevant could still be identified, there is clearly a need for location-specific stakeholder engagement in more places to ensure adequate representation of other world-views.

Particular difficulties were encountered in the choosing of social and cultural indicators. This problem is commonly encountered in other studies involving indicator development for energy projects and is discussed in sections 6.2.1 and 6.2.4. Indicators chosen were mainly the "classic" social indicators on education, housing, education, employment, equity or gender. Stakeholders also tended to reject otherwise suitable indicators if they felt that data might not be available for them. There was also some disagreement among the participants about the scope of the assessment, i.e. if indicators should measure the more indirect socio-economic impacts of geothermal development such as spin-off economic stimulation, poverty reduction, income equity or even national level issues such as renewable energy shares and so on, rather than the easily observable direct impacts. It would be possible to assuage such concerns with improved communication techniques and the provision of detailed methodology sheets for each indicator, clearly showing the empirical links between geothermal projects and the items being measured. A further, more informed discussion could then take place, with a focus on ethical, social and cultural aspects of goethermal development.

### Difficulties relating to stakeholder engagement techniques

The main difficulties associated with the World Café Method and Delphi Technique and examples of their occurence in this research are covered in detail in Paper III. Table 6-7 provides a summary of common difficulties that were faced in this study.

*Table 6-7: Summary of difficulties encountered with stakeholder engagement methods in this research*

| Engagement Method | Common Difficulty | Examples Observed in Study |
|---|---|---|
| World Café Method | Cost | Multiple workshops not possible due to costs |
| | Long distances | New Zealand: participants widely dispersed; Kenya: traffic issues |
| | Time constraints | More time needed to cover large numbers of indicators |
| | Bandwagon effect | Iceland: convergence of voting |
| | Varied knowledge | Lack of knowledge of linkage of socio-cultural impacts to energy development |
| Delphi Technique | High time commitment | Several weeks required for each Delphi |
| | Hasty decision-making | Heavy workload may have lead to rushing the survey |
| | Low response rates | Dropping response rates after each round |
| | Score clustering | Occurred in each Delphi group |
| | Selection of participants | Participants lacked knowledge of the fields of others<br>Some invited participants did not take part<br>Other methods e.g. interview may be more appropriate for e.g. minorities or indigenous peoples |
| | Organization of feedback | Faciliators have influence during comment synthesis |

## 6.3.2 Limitation of assessment frameworks in general

The limitations of asssessment frameworks are addressed in detail in Paper III, however Table 6-8 offers a summary of the main limitations, examples encountered during this study and possible mitigation measures that can be taken to counteract each limitation.

*Table 6-8: Summary of main limitations with examples and mitigation measures*

| Limitation | Observed Example | Solution / Mitigation Measure |
|---|---|---|
| Difficulties in defining sustainable development | Different stakeholder groups displayed different priorities for sustainability goals / indicators | Used Delphi to gain broad range of world views<br>Design of indicator framework using core and optional indicators<br>Further research on local opinions of sustainable development |
| Imperfect systemic coverage | Disagreement of stakeholders on scope of assessment | Use of CSD themes for broad coverage<br>Diversity of stakeholders<br>Report qualitative information also<br>Develop dynamic model later |
| Data availability concerns | Lack of data for certain indicators | Encourage data collection<br>Find substitute indicators |
| Institutional concerns | Indicators developed without hard targets<br>Indicators developed out of context<br>Absence of stategic planning<br>Lack of experience using indicators | Ensure varied input for more political credibility and legitimacy<br>Make recommendations for correct use of indicators e.g. better coordination of monitoring efforts |
| Difficulties in aggregating values | Different priorities of each stakeholder group made weighting impossible | Avoid creation of composite indicator, use individual indicators only<br><br>Allow assignment of weights by individual groups later, with careful consideration |

# 6.4 Recommendations

## 6.4.1 Recommendations for use of the framework

Although the results of this research have been presented to relevant stakeholders who have shown great interest in the outcomes of this research, the final indicator sets will benefit from further discussions based on different perceptions of different groups. We recommend the use of this research by policy and decision-makers in countries with geothermal resources to help implement management policies and strategies that will contribute to the mitigation of negative multidimensional impacts of geothermal development and to consequently promote the well-being of the local population.

We recommend that the goals and indicators that make up the assessment framework be used either:

1. As a tool that can be used alongside EIA or SEA to avoid homogenous assessment of geothermal energy projects prior to their development;

2. As a framework to structure information that should be reported to authorities during the operation of geothermal projects and analyze progress over time;
3. As the basis for a qualitative assessment tool or composite index that could be used to compare between projects.

We stress that stakeholder input should continuously be sought to ensure that the assessment framework remains up-to-date and reflects current research as well as the views and values of all impacted parties. Further effort is needed to develop social and cultural indicators in particular, since the linkages between energy development and socio-cultural impacts are less understood than environmental or economic impacts. To achieve this, it will be necessary to incorporate views (outside of a Delphi survey) of the wider general public (non-experts) into energy development but since this requires significant funding, it should perhaps be the financed by the developer companies or government bodies. Local level impacts should be monitored with a view to providing information into a national indicator system, where national level indicators are based on local level information, thus providing a picture of local to national environmental, economic and social sustainability and human well-being.

### 6.4.2 Recommendations to Policy- and Decision-Makers

Based on our research, we make the following recommendations to policy makers:

- Stakeholder engagement should be regarded as an integral part of the policy process in particular when it comes to the design of appropriate indicators;
- Ethical concerns, and social and cultural indicators should be given particular attention since the links between energy development and these aspects appear to be the least understood
- Indicators should be used to build bridges between institutions and the public, promote group learning and improve the flow of relevant and understandable information;
- In Iceland we recommend the use of sustainability reporting to monitor energy policy progress.

## 6.5 Contribution to Scientific Knowledge

This research has both practical and academic impacts. The development of an assessment tool is the most tangible contribution, however other less visible but nonetheless important impacts can be identified.

#### Practical Impact

A review the impacts of geothermal energy developments shows that there are numerous cases in which geothermal energy projects have not been managed sustainably and that the possible impacts of geothermal development are varied and unique. As well as this, a review of available assessment frameworks shows that currently available assessment tools do not cater to the specific needs of geothermal energy. This provided the impetus for the design of a tool that would allow policy and decision-makers to monitor the performance of geothermal projects in achieving sustainability goals and targets

In practical terms, this research involved a detailed, systematic analysis of the multidimensional impacts of geothermal development, providing a comprehensive reference for policy and decision-makers to help them manage these impacts (Paper I). It also provides insigths into the appropriateness of currently available assessment frameworks (Paper I). The research also delivers a methodological framework to policy and decision-makers for carrying out sustainability assessment, that has the potential to be adjusted for use either before development or during the operation of a geothermal project (Paper II & III). The framework incorporates stakeholder input throughout the process of indicator development and has the potential therefore to produce more policy-relevant and politically credible indicators as well as lead to the formulation of better-adjusted policies. If used, the assessment framework can bring about a change in the way geothermal resources are managed, and the way stakeholders are included in the process of managment as well as in the process of indicator development generally. With further use, greater consideration of social-cultural impacts would take place and local or project level indicators could be used to build data for national level indicators so that they truly represent sustainability progress.

Regardless of whether the indicators are used instrumentally, the less tangible conceptual impact of group learning and exchange of ideas between the stakeholders consulted as a result of the process of developing the framework is also important. Feedback from stakeholders involved in Delphi studies have cited the experience as useful for informing decision-making on policy, e.g. for biofuels (Ribeiro & Quintanilla, 2015) as well as building interest, facilitating learning or knowledge pooling on various topics. Although difficult to measure, this "side-effect" is extremely important for the exchange of ideas between different sectors and for future work in this field.

### Academic Impact

Based on the review of the impacts of geothermal energy developments, we have identified the characteristics of sustainable geothermal energy developments, forming the basis for the development of the sustainability assessment framework and providing a useful guideline for policy and decision-makers. This research also contributes to existing knowledge by identifying and drawing attention to the advantages and shortcomings of currently available assessment tools. This research builds on previously developed assessment frameworks and methods, adding an element of comprehensive stakeholder engagement. This has resulted in the development of a method for choosing stakeholder-approved sustainability goals and indicators and a new assessment framework tailored to the needs of assessing geothermal projects in particular.

By documenting the experiences in three different countries of the stakeholder-driven indicator development process, this paper not only contributes to academic knowledge on the methods of development of indicators of energy sustainability in general, but also regarding their development across national and cultures, which is increasingly acknowledged as a necessity in this field. It provides evidence of the need to consider and incorporate a diversity of opinion when measuring sustainability progress and therefore the need for more advanced and inclusive forms of local stakeholder engagement methods in all types of development projects. It highlights the importance of using local data in national level reporting.

Since very often indicators are developed in isolation from end users of the information, the act of engaging key stakeholders in the indicator and model development process for geothermal energy development, allows the gap between science and policy to be bridged and result in better decision- and policy-making. With this research we attempt to give meaning and relevance to the framework produced by including a wide range of stakeholders in the development process. We hope that users such as policy- and decision-makers will be in a better position to set attainable policy goals with indicators that are derived from a participatory process. When stakeholders from different countries agree on targets and policies, the indicators are deemed to be particularly useful (Molle & Mollinga, 2003) and may serve as a basis for an internationally recognised assessment framework. The critical evaluation of this assessment tool by an international stakeholder group should lend additional political legitimacy to the final result.

This study also lays the foundation for modelling the implications of increased geothermal usage in different countries, which will be useful for policy formulation and the design of risk governance mechanisms for increased goethermal usage, new geothermal technologies and issues such as climate change.

## 6.6 Further research

Since the usage of geothermal energy is likely to increase in the future, governments will need to assess the implications of introducing such new technologies into the energy system. Geothermal energy can be produced in numerous ways and technological advances will bring with them new sustainability concerns. Whilst this study is focussed on the impacts of electricity generation from geothermal resources, the resulting framework also has potential to be applied to other types of geothermal use, or indeed, other types of energy.

This framework could be used to structure information that should be reported to authorities during the operation of geothermal projects, so that they can analyse progress over time, or as the basis for a qualitative assessment tool or composite index that could be used to compare between projects. In order to ensure that all project phases can be assessed, further work should be done to advance the framework produced in this research so that it can be used as a prospective assessment tool (e.g. alongside EIA or SEA).

A long term vision for the framework would be to incorporate it with decision-making tools for energy options assessment at the national or regional level, potentially incorporating grassroots social inclusion procedures using online tools and multicriteria assessment methods. In this way, the analysis of the differences between energy project types on local community or national sustainability, such as large scale vs small scale or centralized vs distributed generation systems could be more easily examined, also providing substantial information for important ethics discussions on energy usage.

A sustainability assessment framework should cover impacts in all dimensions: environment, society, economy as well as human well-being. In order to address the issue of the imperfect coverage of indicators, linking the framework with a dynamic model of the energy system would provide decision-makers with an additional tool that enables comprehensive impact assessment in a dynamic multidimensional environment. Further research would aim to i) complete the development of the sustainability framework into a operational system of indicators with a particular emphasis on socioeconomic implications ii) link the framework to a dynamic model of the Icelandic or other national energy system to enable simulations of alternative energy development futures and their multidimensional (environmental, social and economic) implications as well as impact on key policy areas.

In order to address the issues of differences in knowledge between stakeholders, further work could include developing more effective science communication techniques for stakeholder engagement programs. As well as this, mechanisms to further integrate stakeholder engagement mechanisms into renewable energy project life-cycles and indeed policy development should be explored. The engagement process could benefit from being conducted alongside stakeholder interviews, in particular to elicit the input of marginalised or indigenous groups such as the Maasai in Kenya.

Further research into the more effective inclusion of ethics, cultural sustainability values and the views of minorities or indigenous peoples into the assessment process should also be conducted. The potential enabling role of technology to aid the inclusion and education of stakeholders would be closely examined in this regard, as would alternatives to the Delphi and World Café methods that were used in this study.

## 6.7 Conclusion

This thesis describes the development of a customized sustainability assessment framework for geothermal energy development through case studies in Iceland, New Zealand and Kenya. The literature on the multidimensional impacts of geothermal projects, as well as currently available assessment frameworks was reviewed. Based on this, the desirable characteristics of sustainable geothermal projects were identified along with the most appropriate structure for a geothermal sustainability assessment framework.

The research resulted in the choice of a set of ten stakeholder-validated sustainability goals, 21 core and 18 optional indicators which form a flexible assessment tool that has potential to be used or developed further in a variety of ways. When compared with that of currently available assessment frameworks, the thematic coverage of the tool in terms of sustainability themes differed with regard to local or energy-specific (i.e. geothermal) environmental and economic impacts and in particular socio-economic issues coverage.

The results of the stakeholder engagment process showed a significant diversity of opinion regarding the relevance of goals and indicators between stakeholder groups. For instance, with regard to goals of sustainable geothermal developments, environmental management was a common concern among the Icelandic, New Zealand and Kenyan participants, whereas water usage was considered the most important environment-related issue for the UNU-GTP fellows. The Kenyan, New Zealand and the UNU-GTP groups rated economic management and profitability, along with research and innovation, highly, whereas the Icelandic group placed highest emphasis on resource renewability and also rated knowledge dissemination highly. The indicator development process included the engagement of a diverse array of international stakeholders and highlighted the need for context-specific consultation and assessment to capture all of the impacts of geothermal projects, as well as the need to develop better social and cultural indicators in general.

Whilst the framework produced in this research is generally intended to serve in retrospective assessment of the performance of geothermal projects in attaining sustainability goals, it may also serve as a basis for desigining qualitative tools for prospective assessments of such projects. In view of the likely expansion of geothermal capacity in coming years, we foresee an urgent need to ensure the sustainable development of geothermal resources worldwide and recommend that such tools be used by decision and policy-makers and that additional research be carried out to develop them further.

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# Appendix A

## Final list of geothermal sustainability goals produced using results of Delphis

*GOAL 1* - *Renewability:*
In order to ensure that a geothermal resource remains replenishable, sustainable production* should be the goal in all geothermal projects.

*For each geothermal area and each mode of production there exists a certain maximum level of production, E0, so that with production below E0 it is possible to sustain steady energy production from the system for at least 100-300 years. If the level of production exceeds E0 it is not possible to sustain steady production from the system for so long. Geothermal production that is less than or equal to E0 is defined as sustainable production but production exceeding E0 is not sustainable.

*GOAL 2* - *Water Resource Usage:*
Water usage of a power plant must not reduce supply of cold fresh water to communities nearby.

*GOAL 3*- *Environmental Management:*
A geothermal resource should be managed in such a way as to avoid, remedy or mitigate adverse environmental effects.

*GOAL 4* - *Efficiency:*
Geothermal utilization shall be managed in such a way as to maximize the utilization of exergy available where practical at sustainable production levels. The desired maximum efficiency for electricity generation should be based on the theoretical maximum efficiency for converting heat to electrical energy (Carnot efficiency).

*GOAL 5* - *Economic Management & Profitability:*
Energy use from geothermal power and heat plants must be competitive, cost effective and financially viable. The financial risk of the project shall be minimized. The project should carry positive net national and community economic benefits.

*GOAL 6* - *Energy Equity:*
The energy supplied by the geothermal resource is readily available, accessible and affordable to the public.

*GOAL 7* - *Energy Security & Reliability:*
The operation of geothermal power and heat plants shall be reliable and prioritize the security of supply.

*GOAL 8* - *Community Responsibility:*
The power companies should be responsible toward the community and the effect of the

utilization of the geothermal resource shall be as positive for the community as possible and yield net positive social impact.

*GOAL 9* **-** *Research and Innovation:*
Power companies shall encourage research that improves the knowledge of the geothermal resource as well as technical developments that improve efficiency, increase profitability and reduce environmental effects.

*GOAL 10* **-** *Dissemination of Knowledge:*
Information and experience gained through geothermal utilization shall be accessible and transparent to the public and the academic community alike while respecting confidential intellectual property rights.

# Appendix B

## Common indicators chosen by all stakeholders

| |
|---|
| Air quality in the surrounds of the geothermal power plant |
| Average Income Levels in Project-Affected Communities |
| Direct and indirect local job creation over lifetime of project |
| Duration of Plant Power Outages per year |
| Estimated productive lifetime of geothermal resource |
| Expenditure on heat and electricity as a percentage of household income |
| Impact on important or vulnerable geothermal features |
| Imported energy as a percentage of total (national level) |
| Income-to-expenditure ratio for project-affected municipalities |
| Level of induced seismicity per year |
| Noise levels in working, recreation and residential areas in the surrounds of the geothermal power plant. |
| Number of accidents leading to work absence in the energy company per year |
| Percentage of community residents that must be relocated due to energy project |
| Percentage of energy company expenditure given to R&D per year |
| Percentage of renewables in total energy supply nationally |
| Project internal rate of return (IRR) |
| Rate of subsidence in the geothermal field |
| Resource reserve capacity ratio of the geothermal resource |
| Tons of greenhouse gas emissions resulting from geothermal operations |
| Utilization efficiency for the geothermal power plant |
| Water quality of water bodies impacted by geothermal power plant operations |

## Optional / Satellite Indicators

| Indicator | Present in Delphi |
|---|---|
| EBIDTA ratio per project | Iceland |
| Percentage of protected area removed/affected due to geothermal project | Iceland |
| Number of threatened species that may be affected by the geothermal project. | New Zealand, Kenya |
| Rate of literacy of existing population in project-affected areas | New Zealand, UNU-GTP, Kenya |
| Cost per MW of power produced compared to price per MW from other sources | UNU-GTP |
| Income Equity in Project-Affected Communities | UNU-GTP, Kenya |
| Infant mortality rates in the project-affected area | UNU-GTP, Kenya |
| Life expectancy at birth in project-affected area | UNU-GTP |
| Percentage of mass of fluid reinjected and/or cascaded compared to total extracted fluid mass | UNU-GTP, Kenya |
| Percentage of satisfied workers in the energy company per year | UNU-GTP, Kenya |
| Ratio of average male income to female income for similar jobs for the project staff | Iceland, UNU-GTP |
| Percentage of population with access to commercial energy in project-affected area | New Zealand, UNU-GTP, Kenya |
| Amount of freshwater used during geothermal development (exploration, construction or operation activities) as a percentage of available freshwater in the project area | Kenya |
| Monetary value of socially beneficial initiatives in project-affected communities as a percentage of total project expenditure | Kenya |
| Percentage of community residents that have agreed to potential culture-changing activities relating to the energy project | Kenya |
| Unemployment rate in project-affected communities | Kenya |
| Percentage of population below poverty line in project-affected area | Kenya |
| Economic diversity of project-impacted areas | Kenya |

# Appendix C

## Indicators generated during the three rounds of each Delphi

Note: Indicators without identified metrics were not kept after the final Delphi round.

### Icelandic Delphi indicators with metrics

| Indicator | Metric (where applicable) |
|---|---|
| Air quality in the surrounds of the geothermal power plant | Metric: concentrations (µg/m3) of potentially toxic gases (hydrogen sulphide, mercury, sulphur dioxide, carbon dioxide, etc.)<br><br>Reference value: World Health Organisation reference values - Whichever is the most stringent of national regulation or WHO guideline values. For H2S, odour threshold (7µg/m3)should not be exceeded. Should take account of natural background concentrations if very high. |
| Area of land used due to geothermal energy project (including infrastructure) | |
| Average Income Levels in Project-Affected Communities | Metric: dollars per annum<br><br>Reference Value: income level before the project begins |
| Direct and indirect local job creation over lifetime of project | Metric: no. full-time employees per year<br><br>Reference Value: predicted number of jobs before the project begins |
| Duration of plant power outages per year | Metric: Use hours of unplanned interrupted service<br><br>Reference Value: zero |
| EBIDA ratio per project | Metric: ratio<br><br>Reference Value: EBITA recommended for geothermal industry |
| Economic diversity of project-impacted areas | |

*(Continued)*

*Icelandic Delphi indicators with metrics (Continued)*

| | |
|---|---|
| Energy diversity index for project-affected regions | |
| Estimated productive lifetime of geothermal resource | Metric: years<br><br>Reference Value: at least 100-300 years |
| Expenditure on heat and electricity as a percentage of household income | Metric: percentage<br><br>Reference Value: Remain below 10% |
| Housing value in the area compared to national average | |
| Impact on important or vulnerable geothermal features | Metric: value of predefined impact parameters<br><br>Reference value: condition of important or vulnerable geothermal features before exploitation of the geothermal field.<br><br>NOTE: Important features should be defined before development by relevant stakeholders, based on uniqueness, cultural and economic importance. All features should be scaled with a vulnerability metric and the most important or vulnerable be monitored, using pre-defined criteria, such as temperature and activity. It is not considered enough to measure number or diversity of features. |
| Imported energy as a percentage of total (national level) | Metric: Percentage<br><br>Reference Value: 0% is desirable |
| Income equity in project-affected communities | |
| Income-to-expenditure ratio for project-affected municipalities | Metric: ratio<br><br>Reference Value: A ratio greater than or equal to one is desirable. |
| Initial phase capacity as a percentage of estimated total capacity | |

*(Continued)*

*Icelandic Delphi indicators with metrics (Continued)*

| | |
|---|---|
| Level of induced seismicity per year | Metric: Peak ground velocity levels (PGV) during the year<br><br>Reference value: US department of energy "traffic light" system based on detectability of ground motion levels |
| Make-up holes as a function of time | |
| Noise levels in working, recreation and residential areas in the surrounds of the geothermal power plant. | Metric: dB<br><br>Reference value: Whichever is more stringent, World Health Organisation or national acceptable noise levels for working, recreational and residential areas. |
| Number of accidents leading to work absence in the energy company per year | Metric: count<br><br>Reference Value: zero |
| Odour experience from $H_2S$ gas in residential or recreational areas near the power plant | |
| Percentage of community residents that must be relocated due to energy project | Metric: percentage<br><br>Reference Value: zero |
| Percentage of energy company expenditure given to R&D per year | Metric: %<br><br>Reference Value: TBD |
| Percentage of females with university education in local energy company | |
| Percentage of population with access to commercial energy in project-affected area | |
| Percentage of protected area removed/affected due to geothermal project | Metric: Percentage<br><br>Reference value: size of protected area before energy project |

*(Continued)*

| | |
|---|---|
| Percentage of renewables in total energy supply nationally | Metric: percentage<br><br>Reference Value: 100% |
| Percentage of satisfied workers in the energy company per year | |
| Project internal rate of return (IRR) | Metric: percentage<br><br>Reference Value: IRR exceeds the cost of capital. |
| Rate of subsidence in the geothermal field | Metric: Millimeters (mm) per year<br><br>Reference values: predicted subsidence levels before development |
| Ratio of average male income to female income for the project-affected area. | Metric: ratio<br><br>Reference Value: 1:1 |
| Ratio of rate of change in housing prices to rate of change in income levels (Housing affordability) | |
| Ratio of reinjection to production | |
| Resource reserve capacity ratio of the geothermal resource | Metric: ratio<br><br>Reference Value: predicted ratio for which non-declining production can be maintained |
| Tons of acidifying air pollutants ($H_2S$, $SO_2$) emitted as a result of geothermal operations | |
| Tons of greenhouse gas emissions resulting from geothermal operations | Metric: Tons of $CO_2$ equivalents per kilowatt hour per annum<br><br>Reference Value: zero emissions |
| Total cases lost in supreme court by energy company per year | |

*(Continued)*

*Icelandic Delphi indicators with metrics (Continued)*

| | |
|---|---|
| Unemployment rate in project affected areas | |
| Utilization efficiency for the geothermal power plant | Metric: Percentage<br><br>Reference Value: best known example |
| Water quality of water bodies impacted by geothermal power plant operations | Metric: status of water bodies impacted by geothermal power plant operations, based on national water directive ratings<br><br>Reference Value: Biological, hydromorphological and physio-chemical status of the water body before geothermal exploitation |

## New Zealand Delphi indicators with metrics

| Indicator | Metric (where applicable) |
|---|---|
| (Potential) loss of earnings in impacted communities resulting from changes in land use as a result of the geothermal development | |
| Air quality in the surrounds of the geothermal power plant | Metric: concentrations (μg/m3) of potentially toxic gases (hydrogen sulphide, mercury, sulphur dioxide, carbon dioxide, etc.)<br><br>Reference value: World Health Organisation reference values - Whichever is the most stringent of national regulation or WHO guideline values. For H2S, odour threshold (7μg/m3)should not be exceeded. Should take account of natural background concentrations if very high. |
| Area of land used due to geothermal energy project (including infrastructure) | |
| Average income (purchasing power of income) | Metric: dollars per annum<br><br>Reference Value: purchasing power of income level before the project begins<br>*Note: Impacts on income levels should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Cost of food to families who originally would have sourced significant amounts of their food from the nearby areas/rivers and who now have to buy food | |
| Direct and indirect local job creation over lifetime of project | Metric: no. full-time employees per year<br><br>Reference Value: number of jobs before the project begins<br>*Note: Impacts on job creation should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |

*(Continued)*

*New Zealand Delphi indicators with metrics (Continued)*

| | |
|---|---|
| Duration of plant power outages per year | Metric: Use hours of unplanned interrupted service<br><br>Reference Value: zero |
| Economic diversity of project-impacted areas | |
| Energy diversity index for project-affected regions | |
| Estimated productive lifetime of geothermal resource | Metric: years<br><br>Reference Value: at least 100-300 years |
| Expenditure on heat and electricity as a percentage of household income | Metric: percentage<br><br>Reference Value: Remain below 10%<br><br>(Note: this is a measure of energy affordability, with the reference value signifying the energy poverty threshold for a household) |
| Impact on important or vulnerable geothermal features | Metric: value of predefined impact parameters<br><br>Reference value: condition of important or vulnerable geothermal features before exploitation of the geothermal field.<br><br>NOTE: Important features should be defined before development by relevant stakeholders, based on uniqueness, cultural and economic importance. All features should be scaled with a vulnerability metric and the most important or vulnerable be monitored, using pre-defined criteria, such as temperature and activity. It is not considered enough to measure number or diversity of features. |
| Imported energy as a percentage of total (national level) | Metric: Percentage<br><br>Reference Value: 0% is desirable |
| Income equity in project-affected communities | |

*(Continued)*

*New Zealand Delphi indicators with metrics (Continued)*

| | |
|---|---|
| Income-to-expenditure ratio for project-affected municipalities | Metric: ratio<br>Reference Value: ratio before the project begins compared to afterwards<br>*Note: Geothermal projects may result in income flows to local governments through taxes or royalties.<br>Impacts on income-to-expenditure ratio should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project. |
| Infant mortality rates in the project-affected area | |
| Level of induced seismicity per year | Metric: Peak ground velocity levels (PGV) during the year<br><br>Reference value: US department of energy "traffic light" system based on detectability of ground motion levels, takes into account background levels of seismicity |
| Life expectancy at birth in project-affected area | |
| Noise levels in working, recreation and residential areas in the surrounds of the geothermal power plant. | Metric: dB<br><br>Reference value: Whichever is more stringent, World Health Organisation or national acceptable noise levels for working, recreational and residential areas. |
| Number of accidents leading to work absence in the energy company per year | Metric: count<br><br>Reference Value: zero |
| Number of threatened species that may be affected by the geothermal project. | Metric: Count<br>Reference Value: zero |
| Odour experience from H2S gas in residential or recreational areas near the power plant | |
| Percentage of community residents that must be relocated due to energy project | Metric: percentage<br><br>Reference Value: zero |
| Percentage of energy company expenditure given to R&D per year | Metric: %<br>Reference Value: TBD |

*(Continued)*

*New Zealand Delphi indicators with metrics (Continued)*

| | |
|---|---|
| Percentage of population below poverty line in project-affected area | |
| Percentage of population with access to commercial energy in project-affected area | Metric: percentage<br><br>Reference value: Percentage of population in project-affected areas with access to commercial energy before energy project.<br>*Note: Impacts on energy access should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Percentage of renewables in total energy supply nationally | Metric: percentage<br><br>Reference Value: percentage before the project begins<br>*Note: Impacts on renewable energy percentage should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Percentage of satisfied workers in the energy company per year | |
| Percentage of unlicensed teachers in the project-affected area | |
| Project internal rate of return (IRR) | Metric: percentage<br><br>Reference Value: IRR exceeds the cost of capital. |
| Rate of literacy in project-affected areas | Metric: percentage<br><br>Reference Value: literacy rates before the project began compared to afterwards<br>*Note: Impacts on literacy should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Rate of literacy of existing population in project-affected areas | |

*(Continued)*

*New Zealand Delphi indicators with metrics (Continued)*

| | |
|---|---|
| Rate of subsidence in the geothermal field | Metric: Millimeters (mm) per year<br><br>Reference values: predicted subsidence levels before development |
| Ratio of average male income to female income for the project-affected area. | |
| Ratio of rate of change in housing prices to rate of change in income levels (Housing affordability) | |
| Resource reserve capacity ratio of the geothermal resource | Metric: ratio<br><br>Reference Value: predicted ratio for which non-declining production can be maintained<br><br>Note: The reserve capacity for a geothermal resource is what remains of probable reserves once we take away proven reserves. The proven reserves in a geothermal field are taken to be the installed capacity and available capacity from existing wells, exploratory and production wells, which are not being utilized. The probable reserve can be estimated using the volumetric method or using areal production values and resistivity measurements. |
| Tons of acidifying air pollutants ($H_2S$, $SO_2$) emitted as a result of geothermal operations | |
| Tons of greenhouse gas emissions resulting from geothermal operations | Metric: Tons of $CO_2$ equivalents per kilowatt hour per annum<br><br>Reference Value: zero emissions |
| Total cases lost in supreme court by energy company per year | |
| Unemployment rate in project affected areas | |

*(Continued)*

*New Zealand Delphi indicators with metrics (Continued)*

| | |
|---|---|
| Utilization efficiency for the geothermal power plant | Metric: Percentage<br><br>Reference Value: best known example<br><br>Note: The utilization efficiency should be calculated taking into account optimal reinjection and is only relevant if comparing equivalent field and plant factors. |
| Value of land for nearby communities | |
| Water quality of water bodies impacted by geothermal power plant operations | Metric: status of water bodies impacted by geothermal power plant operations, based on national water directive ratings<br><br>Reference Value: Biological, hydromorphological and physio-chemical status of the water body before geothermal exploitation |

## Kenyan Delphi indicators with metrics

| Indicator | Metric (where applicable) |
|---|---|
| Air quality in the surrounds of the geothermal power plant | Metric: concentrations (μg/m3) of potentially toxic gases (hydrogen sulphide, mercury, sulphur dioxide, carbon dioxide, etc.)<br><br>Reference value: World Health Organisation reference values - Whichever is the most stringent of national regulation or WHO guideline values. For H2S, odour threshold (7μg/m3)should not be exceeded. Should take account of natural background concentrations if very high. |
| Amount of freshwater used during geothermal development (exploration, construction or operation activities) as a percentage of available freshwater in the project area | Metric: percentage<br><br>Reference value: The permitted amount of freshwater extraction that will not lead to water shortages in the area - i.e. use of freshwater for geothermal development does not conflict with other existing freshwater needs |
| Area of land used due to geothermal energy project (including infrastructure) | |
| Average income levels in project-affected communities | Metric: dollars per annum<br><br>Reference Value: income level before the project begins *Note: Impacts on income levels should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Direct and indirect local job creation over lifetime of project | Metric: no. full-time employees per year<br><br>Reference Value: number of jobs before the project begins<br>Impacts on job creation should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |

*(Continued)*

*Kenya Delphi indicators with metrics (Continued)*

| | |
|---|---|
| Duration of plant power outages per year | Metric: Use hours of unplanned interrupted service<br><br>Reference Value: zero |
| Economic diversity of project-impacted areas | Metric: Adjusted Shannon-Wiener Index (%)<br><br>Reference Value: Complete economic diversity (100%) |
| Energy diversity index for project-affected regions | |
| Estimated productive lifetime of geothermal resource | Metric: years<br><br>Reference Value: at least 100-300 years |
| Expenditure on heat and electricity as a percentage of household disposable income | Metric: percentage<br><br>Reference Value: Remain below 10%<br><br>(Note: this is a measure of energy affordability, with the reference value signifying the energy poverty threshold for a household) |
| Impact on important or vulnerable geothermal features | Metric: value of predefined impact parameters<br><br>Reference value: condition of important or vulnerable geothermal features before exploitation of the geothermal field.<br><br>NOTE: Important features should be defined before development by relevant stakeholders, based on uniqueness, cultural and economic importance. All features should be scaled with a vulnerability metric and the most important or vulnerable be monitored, using pre-defined criteria, such as temperature and activity. It is not considered enough to measure number or diversity of features. |
| Imported energy as a percentage of total (national level) | Metric: Percentage<br><br>Reference Value: 0% is desirable |

*(Continued)*

*Kenya Delphi indicators with metrics (Continued)*

| | |
|---|---|
| Income equity in project-affected communities | Metric: Gini coefficient<br><br>Reference Value: Income equity before the project compared to afterwards<br><br>Note: income equity should be measured considering all other things equal, that is to say that the impact of the energy project on this indicator should be clearly traceable |
| Income-to-expenditure ratio for project-affected municipalities | Metric: ratio<br><br>Reference Value: ratio before the project begins compared to afterwards<br>*Note: Impacts on income-to-expenditure ratio should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Infant mortality rates in the project-affected area | Metric: percentage<br><br>Reference Value: Infant mortality rates before the project began compared to afterwards<br>*Note: Impacts on infant mortality should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Level of induced seismicity per year | Metric: Peak ground velocity levels (PGV) during the year<br><br>Reference value: US department of energy "traffic light" system based on detectability of ground motion levels |
| Life expectancy at birth in project-affected area | |
| Monetary value of socially beneficial initiatives in project-affected communities as a percentage of total project expenditure | Metric: percentage<br><br>Reference Value: TBD *Note: socially beneficial initiatives are funded by the geothermal development and should have been approved by the local community. They may include such facilities as schools, clinics, etc. |

*(Continued)*

*Kenya Delphi indicators with metrics (Continued)*

| | |
|---|---|
| Noise levels in working, recreation and residential areas around the geothermal power plant. | Metric: dB<br><br>Reference value: Whichever is more stringent, World Health Organisation or national acceptable noise levels for working, recreational and residential areas. |
| Number of accidents leading to work absence in the energy company per year | Metric: count<br><br>Reference Value: zero |
| Number of threatened species that may be affected by the geothermal project | Species on the IUCN red list, or if not on the red list, or on any national lists of threatened species<br><br>Metric: Count<br>Target / Reference Value: zero |
| Percentage of community residents that have agreed to potential culture-changing activities relating to the energy project | Metric: percentage (e.g. from survey responses)<br><br>Reference Value: TBD<br><br>Note: culture-changing activities may include resettlement, influx of migrant workers from outside, changes in livelihoods or social structures as a result of new economic activities or land use changes, new infrastructure, access to electricity, etc. |
| Percentage of community residents that must be relocated due to energy project | Metric: percentage<br><br>Reference Value: zero |
| Percentage of energy company expenditure given to R&D per year | Metric: percentage<br><br>Reference Value: TBD |
| Percentage of mass of fluid reinjected and/or cascaded compared to total extracted fluid mass | Metric: Percentage<br><br>Reference Value: 100% is ideal (no waste fluid is released to the environment) |
| Percentage of population below poverty line in project-affected area | Metric: percentage<br><br>Reference Value: The percentage of population below the poverty line in surrounding regions. |

*(Continued)*

*Kenya Delphi indicators with metrics (Continued)*

| | |
|---|---|
| Percentage of population with access to commercial energy in project-affected area | Metric: percentage<br><br>Reference value: Percentage of population in project-affected areas with access to commercial energy before energy project.<br>*Note: Impacts on energy access should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Percentage of renewables in total energy supply nationally | Metric: percentage<br><br>Reference Value: percentage before the project begins<br>*Note: Impacts on renewable energy percentage should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Percentage of satisfied workers in the energy company per year | Metric: percentage<br><br>Reference Value: 100% |
| Percentage of unlicensed teachers in the project-affected area | |
| Project internal rate of return (IRR) | Metric: percentage<br><br>Reference Value: IRR exceeds the cost of capital. |
| Rate of literacy in project-affected areas | Metric: percentage<br><br>Reference Value: literacy rates before the project began compared to afterwards<br>*Note: Impacts on literacy should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Rate of subsidence in the geothermal field | Metric: Millimeters (mm) per year<br><br>Reference values: predicted subsidence levels before development |

*(Continued)*

| | |
|---|---|
| Ratio of average male income to female income for the project-affected area. | |
| Ratio of rate of change in housing prices to rate of change in income levels (Housing affordability) | |
| Resource reserve capacity ratio of the geothermal resource | Metric: ratio<br><br>Reference Value: predicted ratio for which non-declining production can be maintained<br><br>Note: The reserve capacity for a geothermal resource is what remains of probable reserves once we take away proven reserves. The proven reserves in a geothermal field are taken to be the installed capacity and available capacity from existing wells, exploratory and production wells, which are not being utilized. The probable reserve can be estimated using the volumetric method or using areal production values and resistivity measurements. |
| Tons of acidifying air pollutants (H2S, SO2) emitted as a result of geothermal operations | |
| Tons of greenhouse gas emissions resulting from geothermal operations | Metric: Tons of CO2 equivalents per kilowatt hour per annum<br><br>Reference Value: zero emissions |
| Total area of land that has been compacted due to geothermal development activities | |
| Total cases lost in supreme court by energy company per year | |
| Unemployment rate in project-affected communities | Metric: percentage<br><br>Reference Value: unemployment rates before the project begins *Note: Impacts on unemployment rates should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |

*(Continued)*

*Kenya Delphi indicators with metrics (Continued)*

| | |
|---|---|
| Utilization efficiency for the geothermal power plant | Metric: Percentage<br><br>Reference Value: best known example<br>*Note: The utilization efficiency should be calculated taking into account optimal reinjection and is only relevant if comparing equivalent field and plant factors. |
| Water quality of water bodies impacted by geothermal power plant operations | Metric: status of water bodies impacted by geothermal power plant operations, based on national water directive ratings<br><br>Reference Value: Biological, hydromorphological and physio-chemical status of the water body before geothermal exploitation |

# UNU-GTP Delphi indicators with metrics

| Indicator | Metric (where applicable) |
|---|---|
| Air quality in the surrounds of the geothermal power plant | Metric: concentrations (µg/m3) of potentially toxic gases (hydrogen sulphide, mercury, sulphur dioxide, carbon dioxide, etc.)<br><br>Reference value: World Health Organisation reference values - Whichever is the most stringent of national regulation or WHO guideline values. For H2S, odour threshold (7µg/m3)should not be exceeded. Should take account of natural background concentrations if very high. |
| Area of land used due to geothermal energy project (including infrastructure) | |
| Average Income Levels in Project-Affected Communities | Metric: dollars per annum<br><br>Reference Value: income level before the project begins *Note: Impacts on income levels should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Cost (price) per MW of power produced compared to price per MW from other sources | Cost should include social and environmental costs<br><br>Metric: Ratio<br><br>Reference Value: TBD |
| Direct and indirect local job creation over lifetime of project | Metric: no. full-time employees per year<br><br>Reference Value: number of jobs before the project begins<br><br>Impacts on job creation should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project. |

*(Continued)*

*UNU-GTP Delphi indicators with metrics (Continued)*

| | |
|---|---|
| Duration of plant power outages per year | Metric: Use hours of unplanned interrupted service<br><br>Reference Value: zero |
| Economic diversity of project-impacted areas | |
| Energy diversity index for project-affected regions | |
| Estimated productive lifetime of geothermal resource | Metric: years<br><br>Reference Value: at least 100-300 years |
| Expenditure on heat and electricity as a percentage of household income | Metric: percentage<br><br>Reference Value: Remain below 10%<br><br>(Note: this is a measure of energy affordability, with the reference value signifying the energy poverty threshold for a household) |
| Impact on important or vulnerable geothermal features | Metric: value of predefined impact parameters<br><br>Reference value: condition of important or vulnerable geothermal features before exploitation of the geothermal field.<br><br>NOTE: Important features should be defined before development by relevant stakeholders, based on uniqueness, cultural and economic importance. All features should be scaled with a vulnerability metric and the most important or vulnerable be monitored, using pre-defined criteria, such as temperature and activity. It is not considered enough to measure number or diversity of features. |
| Imported energy as a percentage of total (national level) | Metric: Percentage<br><br>Reference Value: 0% is desirable |

*(Continued)*

*UNU-GTP Delphi indicators with metrics (Continued)*

| | |
|---|---|
| Income Equity in Project-Affected Communities | Metric: Gini coefficient<br><br>Reference Value: Income equity before the project compared to afterwards<br><br>Note: income equity should be measured considering all other things equal, that is to say that the impact of the energy project on this indicator should be clearly traceable |
| Income-to-expenditure ratio for project-affected municipalities | Metric: ratio<br><br>Reference Value: ratio before the project begins compared to afterwards<br><br>*Note: Impacts on income-to-expenditure ratio should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Infant mortality rates in the project-affected area | Metric: percentage<br><br>Reference Value: Infant mortality rates before the project began compared to afterwards<br><br>*Note: Impacts on infant mortality should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Level of induced seismicity per year | Metric: Peak ground velocity levels (PGV) during the year<br><br>Reference value: US department of energy "traffic light" system based on detectability of ground motion levels |

*(Continued)*

*UNU-GTP Delphi indicators with metrics (Continued)*

| | |
|---|---|
| Life expectancy at birth in project-affected area | Metric: years<br><br>Reference Value: Average life expectancy before project compared to afterwards<br><br>Impacts on life expectancy should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Noise levels in working, recreation and residential areas in the surrounds of the geothermal power plant. | Metric: dB<br><br>Reference value: Whichever is more stringent, World Health Organisation or national acceptable noise levels for working, recreational and residential areas. |
| Number of accidents leading to work absence in the energy company per year | Metric: count<br><br>Reference Value: zero |
| Odour experience from H2S gas in residential or recreational areas near the power plant | |
| Percentage of community residents that must be relocated due to energy project | Metric: percentage<br><br>Reference Value: zero |
| Percentage of energy company expenditure given to R&D per year | Metric: percentage<br><br>Reference Value: TBD |
| Percentage of mass of fluid reinjected and/or cascaded compared to total extracted fluid mass | Metric: Percentage<br><br>Reference Value: 100% is ideal (no waste fluid is released to the environment) |
| Percentage of population below poverty line in project-affected area | |

*(Continued)*

*UNU-GTP Delphi indicators with metrics (Continued)*

| | |
|---|---|
| Percentage of population with access to commercial energy in project-affected area | Metric: percentage<br><br>Reference value: Percentage of population in project-affected areas with access to commercial energy before energy project.<br>*Note: Impacts on energy access should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Percentage of renewables in total energy supply nationally | Metric: percentage<br><br>Reference Value: percentage before the project begins<br>*Note: Impacts on renewable energy percentage should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Percentage of satisfied workers in the energy company per year | Metric: percentage<br><br>Reference Value: 100% |
| Percentage of unlicensed teachers in the project-affected area | |
| Project internal rate of return (IRR) | Metric: percentage<br><br>Reference Value: IRR exceeds the cost of capital. |
| Rate of literacy of existing population in project-affected areas | Metric: percentage<br><br>Reference Value: literacy rates before the project began compared to afterwards<br>*Note: Impacts on literacy should be calculated with all other things being equal, i.e. based on evidence that the impact is traceable to the energy project |
| Rate of subsidence in the geothermal field | Metric: Millimeters (mm) per year<br><br>Reference values: predicted subsidence levels before development |

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*UNU-GTP Delphi indicators with metrics (Continued)*

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|---|---|
| Ratio of average male income to female income for similar jobs for the project staff | Metric: ratio<br><br>Reference Value: 1:1 |
| Ratio of rate of change in housing prices to rate of change in income levels (Housing affordability) | |
| Resource reserve capacity ratio of the geothermal resource | Metric: ratio<br><br>Reference Value: predicted ratio for which non-declining production can be maintained |
| Tons of acidifying air pollutants ($H_2S$, $SO_2$) emitted as a result of geothermal operations | |
| Tons of greenhouse gas emissions resulting from geothermal operations | Metric: Tons of CO2 equivalents per kilowatt hour per annum<br><br>Reference Value: zero emissions |
| Total cases lost in supreme court by energy company per year | |
| Unemployment rate in project-affected communities | |
| Utilization efficiency for the geothermal power plant | Metric: Percentage<br><br>Reference Value: best known example |
| Water quality of water bodies impacted by geothermal power plant operations | Metric: status of water bodies impacted by geothermal power plant operations, based on national water directive ratings<br><br>Reference Value: Biological, hydromorphological and physio-chemical status of the water body before geothermal exploitation |