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

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A R T I C L E I N F O

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A B S T R A C T

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.

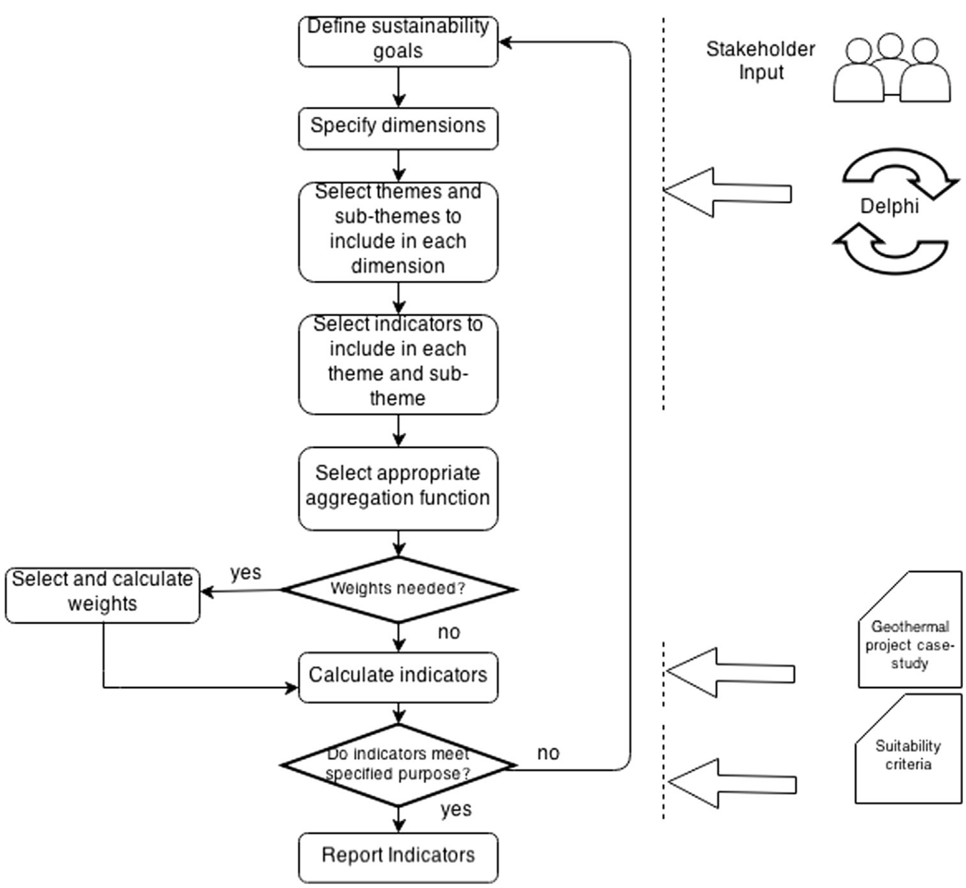

Fig. 3-1. Iterative indicator development process, modified from [11]. See also [43].

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

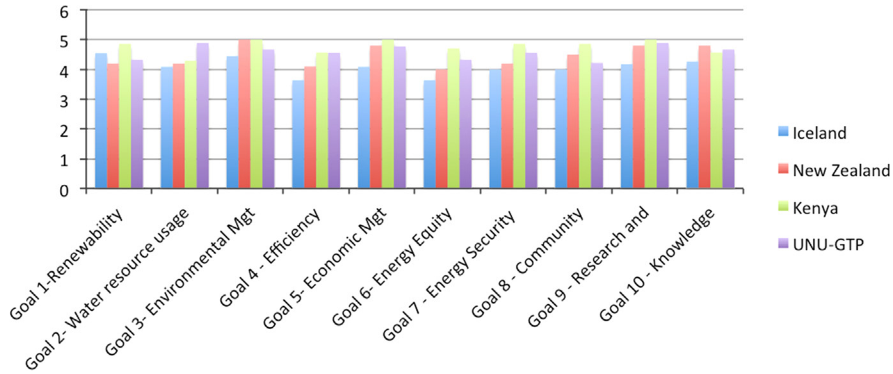

Fig. 4-1. Comparison of scores for sustainability goals after final Delphi round.

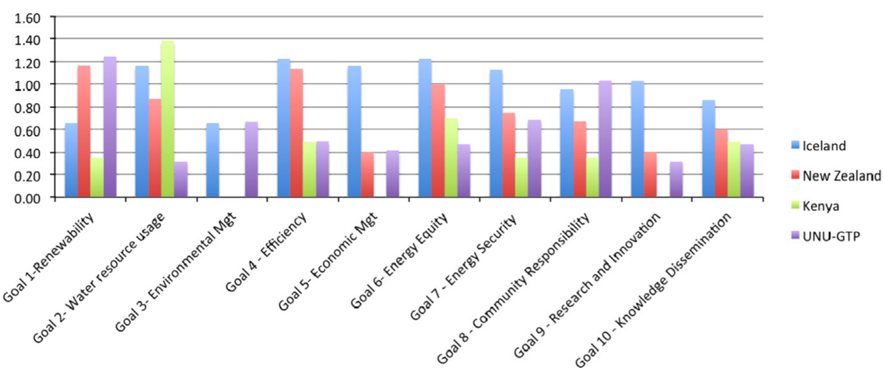

Fig. 4-2. Comparison of standard deviations for goals after final Delphi round.

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.

[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.

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

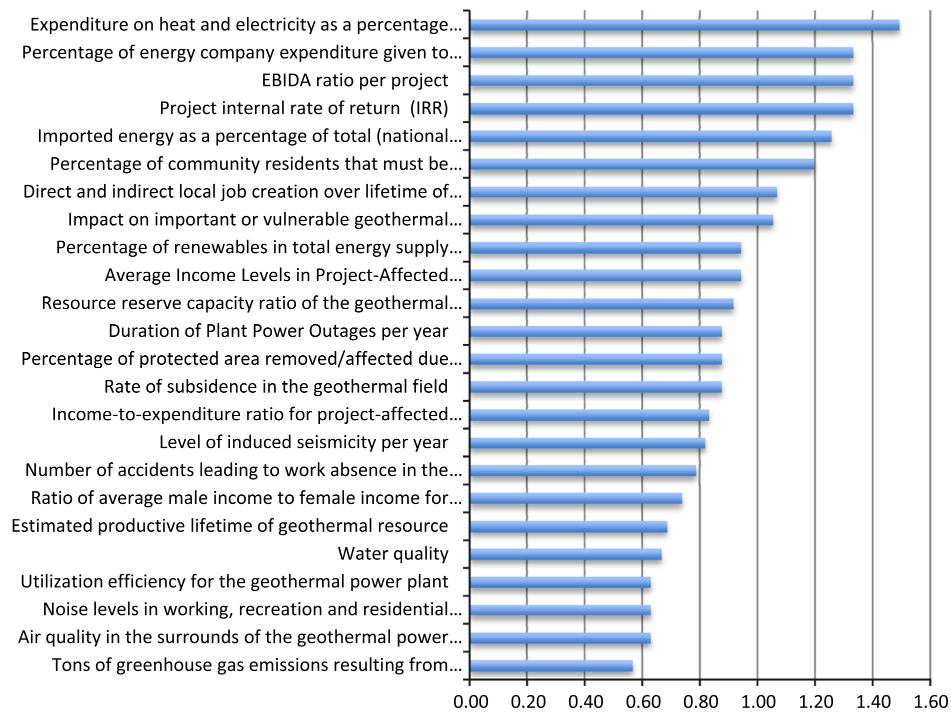

Fig. 4-3. Icelandic Delphi – standard deviations for all indicators after Round 3.

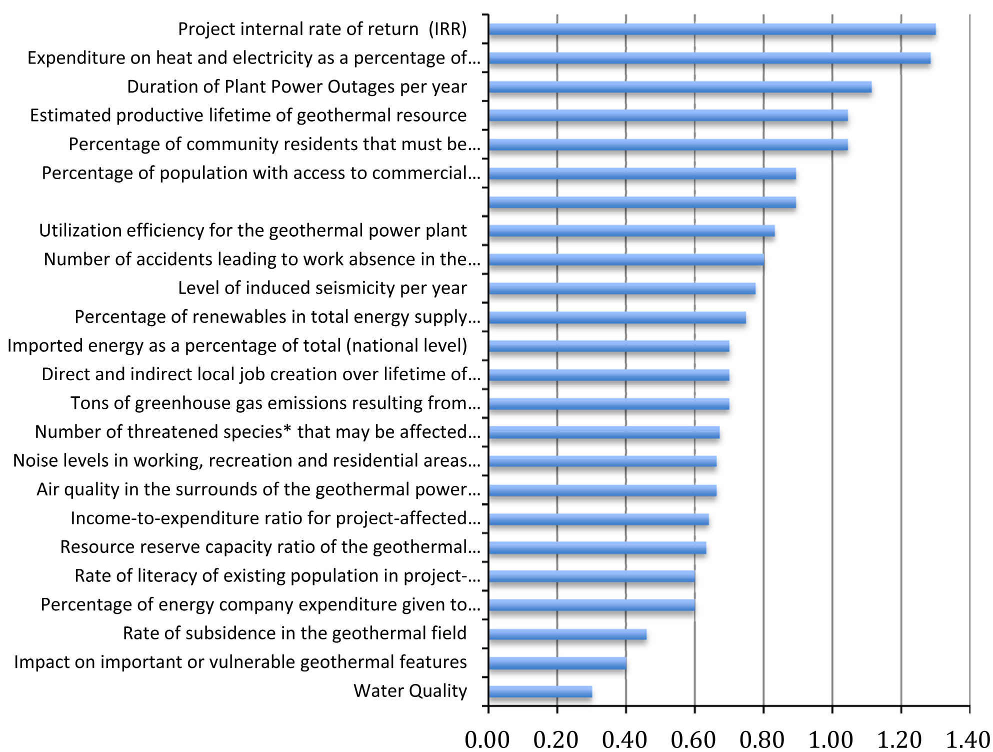

Fig. 4-4. New Zealand Delphi – standard deviations for all indicators after Round 3.

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*

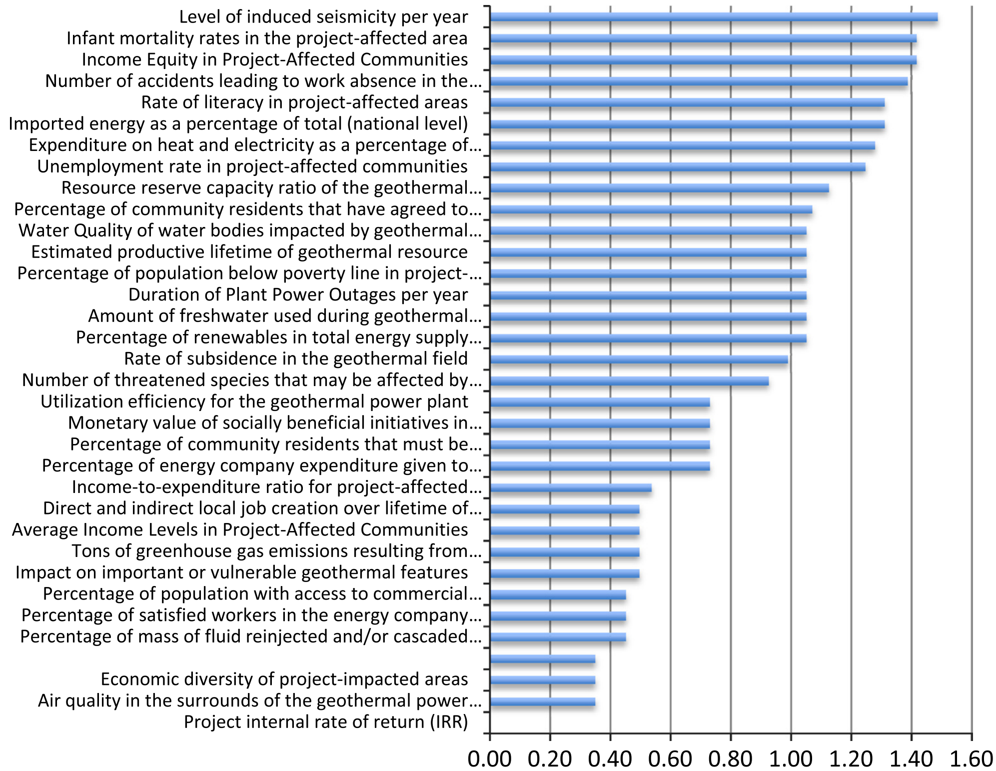

Fig. 4-5. Kenyan Delphi – standard deviations for all indicators after Round 3.

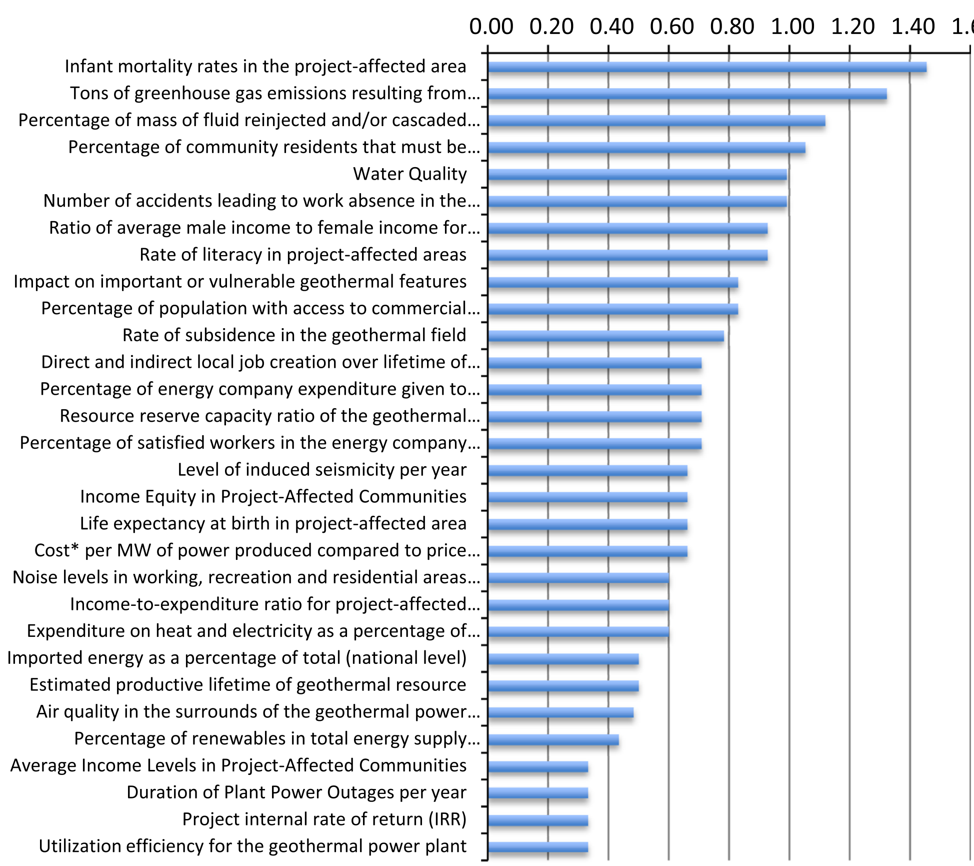

Fig. 4-6. UNU-GTP Delphi – standard deviations for all indicators after Round 3.

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.

Common Indicator	Sustainability Theme: 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.

	Sustainability Goal									
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
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

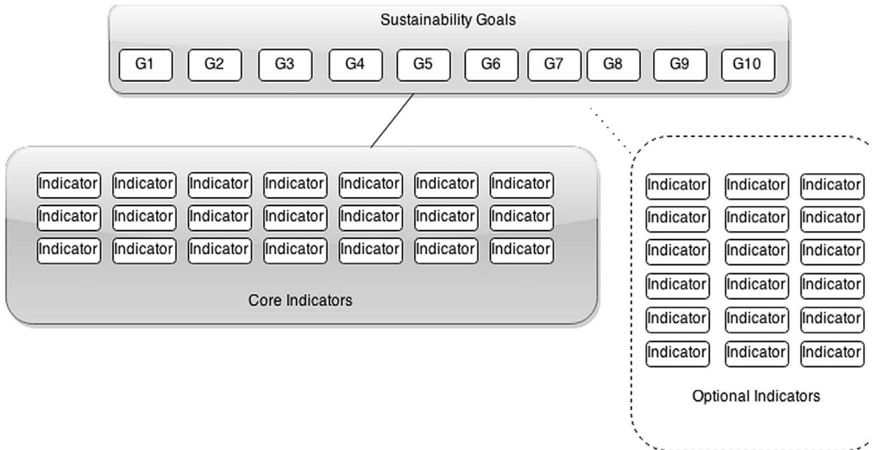

Fig. 5-1. Suggested sustainability assessment framework structure.

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
	4.59	4.5	3.9	
Estimated productive lifetime of geothermal resource				
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	
Level of induced seismicity per year	3.72	4.36	3.75	
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.) 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
Direct and indirect local job creation over lifetime of project	Metric: no. full-time employees per year Reference Value: predicted number of jobs before the project begins
Duration of Plant Power Outages per year	Metric: Use hours of unplanned interrupted service Reference Value: zero
EBIDA ratio per project	Metric: ratio 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 Reference Value: at least 100-300 years
Expenditure on heat and electricity as a percentage of household income	Metric: percentage 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 Reference value: condition of important or vulnerable geothermal features before exploitation of the geothermal field. 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 Reference Value: 0% is desirable
Income Equity in Project-Affected Communities	
Income-to-expenditure ratio for project-affected municipalities	Metric: ratio 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 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 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 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 Reference Value: zero
Percentage of energy company expenditure given to R&D per year	Metric: % 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 Reference value: size of protected area before energy project
Percentage of renewables in total energy supply nationally	Metric: percentage Reference Value: 100%
Percentage of satisfied workers in the energy company per year	
Project internal rate of return (IRR)	Metric: percentage Reference Value: IRR exceeds the cost of capital.
Rate of subsidence in the geothermal field	Metric: Millimeters (mm) per year Reference values: predicted subsidence levels before development
Ratio of average male income to female income for the project-affected area.	Metric: ratio 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 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 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 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 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.) 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 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 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 Reference Value: zero
Economic diversity of project-impacted areas	

Energy diversity index for project-affected regions	
Estimated productive lifetime of geothermal resource	Metric: years Reference Value: at least 100-300 years
Expenditure on heat and electricity as a percentage of household income	Metric: percentage Reference Value: Remain below 10% (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 Reference value: condition of important or vulnerable geothermal features before exploitation of the geothermal field. 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 Reference Value: 0% is desirable
Income Equity in Project-Affected Communities	
Income-to-expenditure ratio for project-affected municipalities	Metric: ratio Reference Value: ratio before the project begins compared to afterwards *Note: Geothermal projects may result in income flows to local governments through taxes or royalties. 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 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 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 Reference Value: zero
Number of threatened species that may be affected by the geothermal project.	Metric: Count 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 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 Reference value: Percentage of population in project-affected areas with access to commercial energy before energy project. *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 Reference Value: percentage before the project begins *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 Reference Value: IRR exceeds the cost of capital.
Rate of literacy in project-affected areas	Metric: percentage Reference Value: literacy rates before the project began compared to afterwards *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 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 Reference Value: predicted ratio for which non-declining production can be maintained 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 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 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.
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 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/m^3) of potentially toxic gases (hydrogen sulfide, mercury, sulfur dioxide, carbon dioxide, etc.) 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.
Amount of freshwater used during geothermal development (exploration, construction or operation activities) as a percentage of available freshwater in the project area	Metric: percentage 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 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 Reference Value: number of jobs before the project begins 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 Reference Value: zero
Economic diversity of project-impacted areas	Metric: Adjusted Shannon-Wiener Index (%) Reference Value: Complete economic diversity (100%)
Energy diversity index for project-affected regions	
Estimated productive lifetime of geothermal resource	Metric: years Reference Value: at least 100–300 years
Expenditure on heat and electricity as a percentage of household disposable income	Metric: percentage Reference Value: Remain below 10% (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 Reference value: condition of important or vulnerable geothermal features before exploitation of the geothermal field. 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 Reference Value: 0% is desirable
Income Equity in Project-Affected Communities	Metric: Gini coefficient Reference Value: Income equity before the project compared to afterwards 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 Reference Value: ratio before the project begins compared to afterwards ∗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 Reference Value: Infant mortality rates before the project began compared to afterwards ∗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 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 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.
Noise levels in working, recreation and residential areas around the geothermal power plant.	Metric: dB 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 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 Metric: Count 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) Reference Value: TBD 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 Reference Value: zero
Percentage of energy company expenditure given to R&D per year	Metric: percentage Reference Value: TBD
Percentage of mass of fluid reinjected and/or cascaded compared to total extracted fluid mass	Metric: Percentage 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 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 Reference value: Percentage of population in project-affected areas with access to commercial energy before energy project. ∗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 Reference Value: percentage before the project begins ∗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 Reference Value: 100%
Percentage of unlicensed teachers in the project-affected area	
Project internal rate of return (IRR)	Metric: percentage Reference Value: IRR exceeds the cost of capital.
Rate of literacy in project-affected areas	Metric: percentage Reference Value: literacy rates before the project began compared to afterwards ∗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 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 Reference Value: predicted ratio for which non-declining production can be maintained

	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 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 ⁎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 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.) 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 ⁎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 Metric: Ratio Reference Value: TBD
Direct and indirect local job creation over lifetime of project	Metric: no. full-time employees per year Reference Value: number of jobs before the project begins 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 Reference Value: zero
Economic diversity of project-impacted areas	
Energy diversity index for project-affected regions	
Estimated productive lifetime of geothermal resource	Metric: years Reference Value: at least 100–300 years

Expenditure on heat and electricity as a percentage of household income	Metric: percentage Reference Value: Remain below 10% (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 Reference value: condition of important or vulnerable geothermal features before exploitation of the geothermal field. 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 Reference Value: 0% is desirable
Income Equity in Project-Affected Communities	
Income Equity in Project-Affected Communities	Metric: Gini coefficient Reference Value: Income equity before the project compared to afterwards 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 Reference Value: ratio before the project begins compared to afterwards *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 Reference Value: Infant mortality rates before the project began compared to afterwards *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 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 Reference Value: Average life expectancy before project compared to afterwards 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 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 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 Reference Value: zero
Percentage of energy company expenditure given to R&D per year	Metric: percentage Reference Value: TBD
Percentage of mass of fluid reinjected and/or cascaded compared to total extracted fluid mass	Metric: Percentage 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

	Reference value: Percentage of population in project-affected areas with access to commercial energy before energy project. *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 Reference Value: percentage before the project begins *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 Reference Value: 100%
Percentage of unlicensed teachers in the project-affected area	
Project internal rate of return (IRR)	Metric: percentage Reference Value: IRR exceeds the cost of capital.
Rate of literacy of existing population in project-affected areas	Metric: percentage Reference Value: literacy rates before the project began compared to afterwards *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 Reference values: predicted subsidence levels before development
Ratio of average male income to female income for similar jobs for the project staff	Metric: ratio 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 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 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 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 Reference Value: Biological, hydromorphological and physio-chemical status of the water body before geothermal exploitation

References

[1] Axelsson G. Sustainable geothermal utilization – case histories, definitions, research issues and modeling. Geothermics 2010;39:283–91.

[2] Barzekar G, Aziz A, Mariapan M, Mohd Hasmadi IM. Delphi technique for generating criteria and indicators in monitoring ecotourism sustainability in Northern forests of Iran: Case study on Dohezar and Sehezar Watersheds. Folia Forestalia Pol 2011;53(2):130–41.

[3] Bauler T. An analytical framework to discuss the usability of (environmental) indicators for policy. Ecol Indic 2012;17:38–45.

[4] Bauler T. An analytical framework to discuss the usability of (environmental) indicators for policy. Ecol Indic 2012;17:38–45.

[5] Bell S, Morse S. Sustainability indicators, measuring the immeasurable? London: Earthscan; 2008.

[6] Bohringer C, Jochem PE. Measuring the immeasurable – a survey of sustainability indices. Ecol Econ 2007;63(1):1–8.

[7] Carrera DG, Mack A. Sustainability assessment of energy technologies via social indicators: results of a survey among European energy experts. Energy Policy 2010;38:1030–9.

[8] Cash DW, Clark WC, Alcock F, Dickson NM, Eckley N, Guston DH, et al. Knowledge systems for sustainable development. Proc Natl Acad Sci 2003;100 (14):8086–91.

[9] Cassara LF, Conrada EB, Morse S. Assessing the use and influence of sustainability indicators at the European periphery. Ecol Indic 2013;35:52–61.

[10] Chang P-L, Hsu C-W, Chang P-C. Fuzzy Delphi method for evaluating hydrogen production technologies. Int J Hydrog Energy 2011;36:14172–9.

[11] Davidsdottir B, Basoli DA, Fredericks S, Lafitte Enterline C. Measuring sustainable energy development: the development of a three dimensional index – the SEE index. Frontiers in Environmental Valuation and Policy. Cheltenham, UK: Edward Elgar; 2007.

[12] Devuyst D, Hens L, Lannoy W. How Green is the City? Sustainability assessment and the management of urban environments. New York: Columbia University Press; 2001.

[13] Dickie BN, Luketina KM. Sustainable management of geothermal resources in the Waikato Region, New Zealand. In: Proceedings of world geothermal congress. Antalya; 2005.

[14] Environment Waikato. Operative Waikato Regional Policy Statement (October 2000). Waikato Regional Council; 2000.

[15] Etxeberria IA, Garayar A, Sánchez JA. Development of sustainability reports for farming operations in the Basque Country using the Delphi method. Rev Contabilidad 2015;18(1):44–54.

[16] Fraser ED, Dougill AJ, Mabee WE, Reed M, McAlpine P. Bottom up and top down: analysis of participatory processes for sustainability indicator identification as a pathway to community empowerment and sustainable environmental management. J Environ Manag 2006;78 (Elsevier).

[17] Government of Kenya. Scaling-up renewable energy program (SREP). Investment plan for Kenya: final report. Government of Kenya; 2011.

[18] Grosskurth J, Rotmans J. Qualitative system sustainability index: a new type of sustainability indicator. In: Hak T, Moldan B, Dahl AL, editors. Sustainability indicators: a scientific assessment. Washington DC: Island Press; 2007.
[19] Gunnarsson G, Arnaldsson A, Oddsdóttir AL. Model simulations of the Hengill Area, Southwestern Iceland. Trans Porous Med 2011;90:3–22.
[20] Hsu C-C, Sandford BA. The Delphi technique: making sense of consensus. Pract Assess, Res Eval 2007;12:10.
[21] IISD. Measuring and assessing progress identifying approaches, patterns and practices. Retrieved November 4, 2012, from International Institute of Sustainable Development: ⟨http://www.iisd.org/measure/principles/progress/⟩; 2012.
[22] Linstone Harold A., and Murray Turoff. The Delphi Method. Techniques and applications 2002;53.
[23] Lund S, Banta GT, Bunting SW. Applying stakeholder Delphi techniques for planning sustainable use of aquatic resources: experiences from upland China, India and Vietnam. Sustain Water Qual Ecol 2014;3–4:14–24.
[24] Lyon Dahl A. Achievements and gaps in indicators for sustainability. Ecol Indic 2012;17:14–9.
[25] Mariita NO. The impact of large-scale renewable energy development on the poor: environmental and socio-economic impact of a geothermal power plant on a poor rural community in Kenya. Energy Policy 2002;30:1119–28.
[26] McGeary J. A critique of using the Delphi technique for assessing evaluation capability-building needs. Eval J Australas 2009;9(1):31–9.
[27] Meadows D. Indicators and information systems for sustainable development: a report to the Balaton Group. VT: The Sustainability Institute; 1998.
[28] Miller G. The development of indicators for sustainable tourism: results of a Delphi survey of tourism researchers. Tour Manag 2001;22:351–62.
[29] Ministry of Business, Innovation and Employment. Energy in New Zealand. Ministry of Business, Innovation and Employment; 2014.
[30] Molle F, Mollinga P. Water poverty indicators: conceptual problems and policy issues. Water Policy 2003;5:529–44.
[31] Moreno-Pires S, Fidelis T. A proposal to explore the role of sustainability indicators in local governance contexts: the case of Palmela, Portugal. Ecol Indic 2012;23:608–15.
[32] Mwangi, M. Environmental and socio-economic issues of Geothermal Development in Kenya. GRC Bulletin; 2010, Mar/Apr.
[33] New Zealand Government. New Zealand Energy Strategy 2011–2021. Ministry of Economic Development; 2011.
[34] O'Sullivan M, Yeh A, Mannington W. Renewability of geothermal resources. Geothermics 2010;39:314–20.
[35] OECD. Core set of indicators for environmental performance reviews. OECD; 1993.
[36] Ogola PA, Davidsdottir B, Fridleifsson IB. Lighting villages at the end of the line with geothermal energy in eastern Baringo lowlands, Kenya – steps towards reaching the millennium development goals (MDGs). Renew Sustain Energy Rev 2011;15:4067–79.
[37] Pinfield G. Beyond sustainability indicators. Local Environment 1996;1(2):151–63.
[38] Pinter L, Hardi P, Bartelmus P. Indicators of sustainable development: proposals for a way forward. IISD; 2005.
[39] Powell C. The Delphi technique: myths and realities. J Adv Nurs 2003;41(4):376–82.
[40] Rametsteiner E, Pulzl H, Alkan-Olsson J, Frederiksen P. Sustainability indicator development—science or political negotiation. Ecol Indic 2011;11:61–70.
[41] Shields D, Šolar S, Martin W. The role of values and objectives in communicating indicators of sustainability. Ecol Indic 2002;2:149–60 (Elsevier).
[42] Shortall R, Davidsdottir B, Axelsson G. Geothermal energy for sustainable development: a review of sustainability impacts and assessment frameworks. Renew Sustain Energy Rev 2015;44:391–406 (Elsevier).
[43] Shortall R, Davidsdottir B, Axelsson G. A sustainability assessment framework for geothermal energy projects. Energy Sustain Dev 2015;27:28–45 (Elsevier).
[44] Statistics Iceland. Iceland in Figures 2014. Reykjavik: Statistics Iceland; 2014.
[45] The Pastille Consortium. Indicators into action a practitioners guide for improving their use at the local level. The Pastille Consortium; 2002.
[46] Thompson K. Delphi collective group intelligence tool: powerful and free. Retrieved October 21, 2012, from bioteams.com: ⟨http://www.bioteams.com/2007/04/27/delphi_collective_group.html⟩; 2007April 27.
[47] UNDP. Energy for sustainable development: a policy agenda. New York: UNDP; 2002.
[48] United Nations. Indicators of sustainable development: guidelines and methodologies, 3rd ed. United Nations; 2007.
[49] Wilhelm WJ. Alchemy of the Oracle: The Delphi Technique. Delta Pi Epsil J 2001;43:6–26.