Towards Comparative Environmental Sustainability Metrics for Geothermal Energy

A Camenzuli, G M Mudd[#]

Environmental Engineering / Department of Civil Engineering,
Monash University, Clayton, Melbourne, Australia
[#]Gavin.Mudd@eng.monash.edu.au

Major Themes : Delivering Sustainable Infrastructure / Designing Sustainable Global Solutions

Sub-themes : Energy / Addressing Climate Change

Abstract

The spectre of climate change is a fundamental driver of sustainability policy, technology and associated research – especially so in the primary energy sector. At present, many industrialised countries obtain the majority of their energy from fossil fuels, mainly coal, oil and gas, with a variable extent from nuclear power or renewables such as hydroelectricity, wind power and biomass. The use of fossil fuels is a major contributor to greenhouse emissions and climate change, and low carbon intensity and renewable energy sources are being viewed more favourably for the future. Although not widely utilised at present, geothermal energy for electricity is clearly well positioned to meet this opportunity. However, there are very few assessments of the environmental sustainability metrics for geothermal electricity to facilitate sound comparison to other electricity sources, such as the embodied water costs or effective greenhouse emissions of geothermal versus wind energy. This paper will present a detailed literature review of the environmental sustainability metrics for geothermal electricity, including research on aspects such as water costs, greenhouse emissions and energy costs. The sustainability metrics are then compared to the various estimates for other renewable energy sources, fossil fuels and nuclear power, thereby providing a unique basis for assessing the sustainability of geothermal electricity.

1 Introduction

An environmentally sustainable energy source is a fundamental component of modern infrastructure – especially so when considering the spectre of climate change impacts and associated issues. At present, there is extensive debate about various sources of energy and their relative merits as a long-term sustainable energy supply (eg. Aubrecht, 2006; Hinrichs & Kleinbach, 2006; Diesendorf, 2007). This paper focuses on geothermal energy used to produce electricity, reviewing the basic technical features of geothermal energy for electricity and major environmental aspects with respect to critical sustainability issues such as carbon dioxide emissions, land use and water consumption. Available data is compiled from published sustainability reports or literature covering numerous geothermal fields or energy companies, and compared to similar reported indices for other sources of electricity supply. The paper is therefore a unique and up-to-date review of the environmental sustainability metrics for geothermal energy-derived electricity.

2 Geothermal Energy for Electricity

At its simplest, geothermal energy taps into and extracts heat energy from the earth's crust, which is then used to create steam and drive electric turbines. By 2007, there was about 9.73 GW_e of geothermal capacity operating at 8.59 GW_e to generate 75,251 GWh of energy (Bertani, 2007). A breakdown is summarised in Table 1, shown by country in Figure 1.

Table 1: Global geothermal capacity (MW_e) and energy generation (GWh) (Bertani, 2007)

Country	Installed	Operating	Energy
USA	2,687	1,935	16,951
Philippines	1,970	1,856	16,255
Indonesia	992	992	8,688
Mexico	953	953	8,348
Italy	811	711	6,228
Japan	535	530	4,645
Iceland	421	421	3,687
New Zealand	472	373	3,268
El Salvador	204	189	1,656
Costa Rica	163	163	1,424
Kenya	129	129	1,128

Country	Installed	Operating	Energy
Russia	79	79	692
Papua New Guinea	56	56	491
Nicaragua	87.4	52.5	460
Guatemala	53	49	429
Turkey	38	29.5	258
Portugal	23	23	201
China	27.8	18.9	166
France	14.7	14.7	129
Germania	8.4	8.4	74
Ethiopia	7.3	7.3	64
Miscellaneous	1.6	1.1	9.6
TOTAL	**9,732**	**8,590**	**75,251**

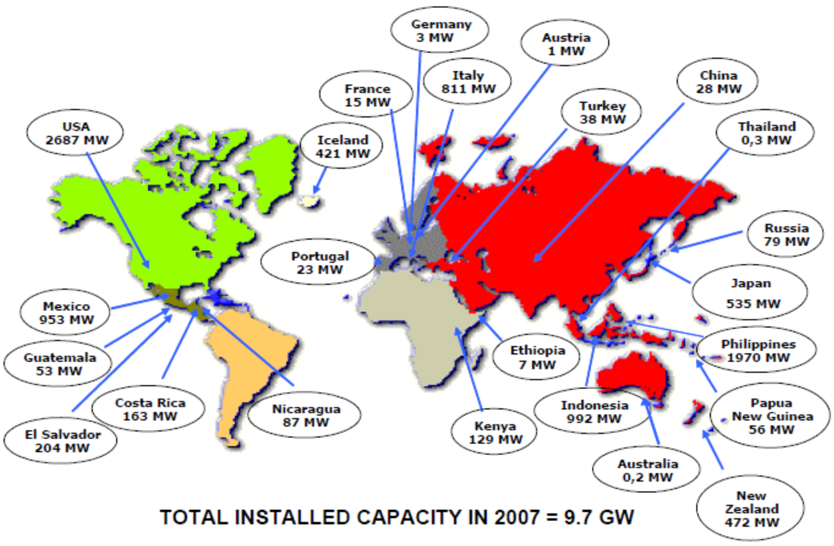

Figure 1: Global installed geothermal capacity (Bertani, 2007)

2.1 Geothermal Resources

There are a number of ways that geothermal energy can be implemented, depending on the nature of the geothermal heat resource itself and the power plant design. This review is only brief, with further details given in key studies or texts such as Dickson & Fanelli (2005), Tester et al. (2006) and DiPippo (2008).

Inside the earth, heat is generated by the radioactive decay of numerous elements, mainly potassium-40 (^{40}K), uranium (^{235}U, ^{238}U) and thorium (^{232}Th) (Tester et al., 2005). This heat in turn leads to planetary scale processes such as continental or tectonic plate movements, volcanism and so on (Dickson & Fanelli, 2005). The average heat flux of the earth's surface is 60 $\mu W/m^2$ (Ungemach, 1987).

Due to crustal and tectonic processes, the elevated temperature from depth is sometimes concentrated in particular places at shallow depths, even expressing itself at the surface through volcanoes or hot springs. The definition of a geothermal resource is a reservoir in the Earth from which heat can be extracted economically and utilised for generating electric power (Gupta & Roy, 2007). An exploitable geothermal resource has four prerequisites (Ungemach, 1987):

1. A heat source, which could be a magma body or simple hot rocks at depth;
2. A heat carrier fluid;
3. Permeable or fractured rocks acting as a reservoir;
4. Cap rocks providing an impermeable and insulating cover.

Geothermal resources can be divided up into five categories:

(i) *Vapour-dominated* (Gupta & Roy, 2007) – these geothermal fields contain water at high pressures and temperatures in excess of 100 °C. When this water is bought to the surface, the lower pressure leads to the formation of saturated steam and water vapour. The steam can in turn be classified as wet or dry. Vapour-dominated geothermal resources include an extensive cap rock, providing a low permeability barrier to the escape of hot reservoir fluids.

(ii) *hot water* (Gupta & Roy, 2007) – in contrast to vapour-dominated resources, in hot water systems the primary control on water pressure is liquid water more than temperature.

(iii) *geopressured* (DiPippo, 2008) – these are resources contained in high pressure and temperature systems. Historically they have been inaccessible due to the problems in drilling at such high pressures, although recent advances in geological and drilling technology is making these resources viable, primarily due to the pressure which can be used to power a hydraulic turbine, the high temperature and the presence of dissolved methane which can be also be combusted for additional electricity.

(iv) *hot dry rock (HDR)* (Gupta & Roy, 2007) – at depths up to several kilometres, most rocks are low permeability and have no naturally occurring fluid to store or transport heat. The heat can be derived from either igneous rocks (eg. granites), upper mantle or more local (eg. radioactive decay, faults or fracture zones). In general, hot dry rocks first need to be artificially fractured to allow for the flow of water through the heat zone.

(v) *magma* – depending on pressure and composition, magma can range from 600 to 1400 °C. Magma's are found in vicinity of volcanic regions, such as near plate tectonic boundaries (eg. New Zealand, Japan).

At present, vapour-dominated are the most exploited geothermal resource type, followed by hot water, with geopressured, hot dry rocks and magma not being exploited commercially. A schematic of a typical geothermal project is shown in Figure 2.

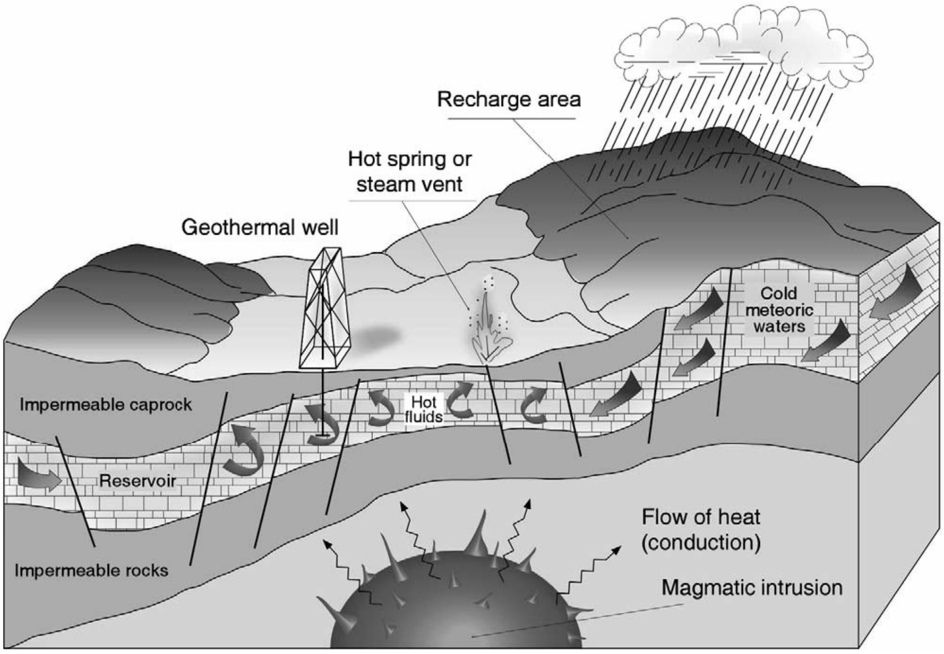

Figure 2: Schematic of a typical geothermal project (Barbier, 2002)

2.2 Geothermal Power Generation Technologies

Most modern geothermal electric power plants are essentially composed of two major parts (Arnórsson, 2004):

1. Injection/extraction wells for steam gathering and/or waste fluid disposal;
2. A power house with turbines, generators and cooling towers.

There are various power plant systems for harvesting geothermal power, including the relative proportion of capacity for each type of power plant in the world in 2005 (Bertani, 2005):

- Single-flash (37%)
- Double-flash (26%)
- Back-pressure (1%)
- Dry-steam (28%)
- Binary/combined cycle/hybrid (8%)

The average capacity for single-flash systems is 25.7 MW_e, dry-steam systems 43.9 MW_e, double-flash systems 34.2 MW_e, binary/combined cycle systems 3.3 MW_e and back-pressure systems about 4.1 MW_e (Bertani, 2005). The Kalina cycle power plant, a subset of binary/combined cycle plants, uses a fluid such as ammonia-water mixtures for its working thermal regime, compared to Rankine cycle plants which use hydrocarbons as their thermal fluid. Further details on all power plant systems and their respective designs can be found in DiPippo (2005), Tester et al. (2005) and USDoE (2008), among considerable other literature.

2.3 Environmental Aspects

The harnessing of geothermal energy for electricity production entails a variety of potential environmental impacts, with arguably the most important issues relative to other electricity sources being water, gaseous emissions and land use.

Water Consumption and Impacts

Geothermal energy requires water for drilling, steam generation and heat transfer, and can lead to impacts on local water resources, depending on characteristics such as temperature, gas content, heat source, rock types, permeability, age of hydrothermal system and fluid source (Barbier, 2002). These factors lead to varying water quality, though geothermal fluids are usually elevated in solutes such as salts (cations, anions), inorganics (eg. silica, ammonia), trace and heavy metals or various gases (noble gases, hydrogen sulphide, carbon dioxide). It is common for waters derived from geothermal energy to be significantly above water quality guidelines for ecosystems or potable purposes. The main approach to management of water issues is reinjection, which helps to reduce potential pollution, maintain reservoir pressures, prolong reservoir life and reduces thermal, chemical and land subsidence. Economic costs of reinjection are generally lower than alternative water regimes (Fridleifsson & Freeston, 1994).

Gaseous Emissions

Although geothermal electricity does not involve direct combustion of the primary energy resource (compared to fossil fuels), various gases are often present as impurities or 'non-condensable gases' (NCG's) in the steam (MIT, 2006) and are typically related to the hydrothermal source and its relative age. The most common gaseous emissions are entrained carbon dioxide (CO_2) and hydrogen sulphide (H_2S). The extent of gaseous emissions also depends on power plant type. For example, steam and flash plants can allow for venting to the atmosphere, whereas binary cycle plants only use the geothermal fluid for heat transfer to the working fluid, with no direct release to the environment (MIT, 2006). Although trace amounts of other important gases can be found in geothermal resources, such as methane, hydrogen fluoride or hydrogen, these are highly variable and invariably site-specific. In general, carbon dioxide comprises about 85% by volume and weight of discharged gases (Barbier, 2002).

Land Use

Geothermal electricity converts heat energy at a given site directly to electrical energy, and does not require extensive land area (Fridleifsson & Freeston, 1994). This is due to the fact that no mining, transportation or solid waste disposal is needed (eg. coal mining). Compared to other forms of electricity generation, geothermal electricity needs comparatively little land.

3 Environmental Sustainability Metrics

This study set out to investigate the environmental sustainability metrics for current geothermal electricity projects and compare this data to conventional power sources such as coal or other renewable energy technologies. The principal metrics of interest are the embodied greenhouse emissions or water per unit electrical energy output (eg. t CO_2/GWh, ML/GWh). Although the embodied energy is also of interest, the 'available energy' or energy consumed in supplying geothermal energy is very difficult to quantify, and is certainly not widely reported.

A fundamental sustainability reporting protocol is the Global Reporting Initiative (GRI, 2006) – which establishes a consistent and standard approach to reporting on most tenets of sustainability such as environmental, economic, social, governance and human rights. As the GRI is a broad regime, it can be applied to mining, oil-gas, local government, financial investment or any activity. Given the prominent role of energy in sustainable development, more energy companies over time are using the GRI protocol to report on their sustainability performance annually.

There are numerous energy companies around the world who operate geothermal power stations, principally in the United States, Philippines, Indonesia, Mexico, Italy, Japan, Iceland, New Zealand and minor capacity in numerous countries (see Table 1, Figure 1). Some of the major geothermal companies do produce GRI-style sustainability reports, however, many do not. A major problem, however, is that they sometimes also include non-geothermal power plants (eg. hydro-electric, coal, etc.) in their reports. In addition, some companies only report company totals based on primary energy source, not reporting site-based data for specific projects, such as reporting company totals for geothermal, hydro-electric, fossil fuels or even nuclear power and not individual project data. Such aggregated and limited data makes it impossible to discern the differences between geothermal resource and/or power plant types.

The available data was compiled from the following companies and their annual sustainability reports:

- *Mighty River Power* – sustainability reports 2004 to 2007 (MRP, various);
  Located in New Zealand, with two flash-binary power plants at Rotokawa and Mokai.
- *ENEL* – annual and/or sustainability reports 2002 to 2006 (ENEL, various);
  ENEL operate in 21 countries, with the majority of their projects in Italy; most plants are of the dry-steam type.
- *Orkuveita Reykjavirkur (OR)* – sustainability reports 2002 to 2006 (OR, various);
  Located in Iceland, OR has two single-flash plants at Nesjavellir and Hellisheidi.
- *Contact Energy* – sustainability reports 2003 to 2007 (CE, various);
  Located in New Zealand, with three plants at Wairakei, Poihipi Road and Ohaaki; the plants are either double-flash or dry-steam.

In addition, a wide variety of literature was reviewed to provide comparative values.

4 Results and Discussion

4.1 Greenhouse Emissions

The available greenhouse emissions data reported by various companies in sustainability reports is summarised in Table 2, including additional literature data for comparison. The high degree of variability is evident in reported data as well as the literature.

Table 2: Reported carbon dioxide metrics (t CO_2/GWh) for geothermal electricity (number of data points in brackets), including compilation of literature values

Company	Country	Average	Minimum	Maximum	Reference
Mighty River Power	New Zealand	95.4 (4)	88.3	102.5	MRP, various
ENEL	various	4.2 (5)	2.1	5.9	ENEL, various
Contact Energy	New Zealand	87.8 (5)	68.1	113.1	CE, various
Orkuveita Reykjavirkur	Iceland	20.5 (5)	10.6	27.5	OR, various

Geothermal Project/Type	t CO_2/GWh	Reference
Steam[#1]	96	Ármannsson & Kristmanndóttir (1992)
Hot dry rock	11	Ármannsson & Kristmanndóttir (1992)
The Geysers (dry steam, USA)	40.3	MIT (2006), Kagel & Gawell (2005)
Flash-steam liquid dominated	27.2	MIT (2006), Kagel & Gawell (2005)
Closed loop binary	0	MIT (2006), Kagel & Gawell (2005)
Krafla	152	Ármannsson et al. (2005)
Svartsengi	181	Ármannsson et al. (2005)
Nesjavellir	26	Ármannsson et al. (2005)
Geothermal (USA average)	26.6	EIA (2008)
Binary/combined cycle	24	World Energy Council (2004)
Steam[#2]	120	World Energy Council (2004)

[#1, #2] Specific details not given.

For Australia, unit CO_2 emissions for various states with predominantly coal-fired electricity range from 980 t CO_2/GWh for South Australia to 1,310 t CO_2/GWh for Victoria (low quality brown coal) (DCC, 2008). For Tasmania, dominated by hydro-electricity, unit CO_2 emissions are 130 t CO_2/GWh (DCC, 2008).

The data in Table 2 demonstrates, as expected, that geothermal electricity has a considerably lower greenhouse intensity than fossil fuel-fired electricity.

4.2 Other Gaseous Emissions

At present, there is inconsistent reporting of other gaseous emissions from geothermal electricity. Excluding carbon dioxide, the principal gases include sulphur dioxide (SO_2), hydrogen sulphide (H_2S), methane (CH_4) and nitrous oxides (‘NO_x’). The presence and extent of releases for each of these gases is highly site-specific, as it depends both on the nature of the geothermal resources and the power plant design and operation on the surface.

Sulphur Dioxide (SO_2)

No companies reported sulphur dioxide emissions. According to MIT (2006), unit emissions for some select projects in the USA are: (i) hydrothermal (flash-steam, liquid dominated) - 0.159 t/GWh; (ii) hydrothermal (The Geysers, dry steam field) - 0.000098 t/GWh; and (iii) hydrothermal (closed-loop binary) - 0 t/GWh. All of these values are considerably lower than for coal or oil-fired power stations, which unit emissions of 4.71 and 5.44 t/GWh, respectively (MIT, 2006).

Hydrogen Sulphide (H_2S)

The only company which reported hydrogen sulphide emissions was ENEL. Over 2002 to 2006, unit H_2S emissions ranged from 4.04 to 4.79 t/GWh, averaging 4.54 t/GWh (ENEL, various). A gradual decline over time is evident. Unfortunately, given that ENEL report total company data, it is not possible to assess the extent to which this data is resource-type and power plant specific. For comparison, coal or oil have unit H_2S emissions of about 11 t/GWh, while the Krafla and Nesjavellir geothermal projects in Iceland have unit H_2S emissions of about 6.1 and 1.3 t/GWh, respectively (Ármannsson & Kristmannsdóttir, 1992; Gislason, 2000; Arnórsson, 2004).

Methane (CH_4)

The only company which reported methane emissions was Orkuveita Reykjavirkur (OR). Over 2002 to 2006, unit emissions ranged from 0.019 to 0.072 t/GWh, averaging 0.046 t/GWh (OR, various). Based on a global warming potential for methane of 21 (DCC, 2008), this equates to an average CO_2-equivalent emission of 0.96 t/GWh. Methane is therefore a relatively low factor in the greenhouse emissions of geothermal energy.

4.3 Water Consumption

The production of energy and electricity requires significant amounts of water, and is therefore inextricably linked to sustainability (Inhaber, 2004). Only OR and ENEL consistently reported water consumption data, with Contact Energy only reporting water consumption for a single year. The available data is presented in Table 3. There is a significant decline over time for OR. A difficulty with OR is that it is also a water utility, and the degree of separation between energy and water supply is not clear in the reported data.

Table 3: Reported water consumption metrics for geothermal electricity (ML/GWh) (number of data points in brackets)

Company	Country	Average	Minimum	Maximum	Reference
ENEL	various	2.83 (5)	2.29	3.27	ENEL, various
Contact Energy	New Zealand	21.5 (1)	-	-	CE, various
Orkuveita Reykjavirkur	Iceland	125.4 (5)	84.4	144.4	OR, various

Determining the ‘consumption’ in a geothermal electricity project is clearly a vexed issue, in many ways similar to the challenges in assessing the consumed or embodied water in mining (see Mudd, 2008). For binary/closed loop cycles, water consumption could be argued to be close to zero, however, it would be hard to believe that it could ever be perfectly zero (eg. allowing for steam, reservoir and power plant losses). Reinjection is commonly used, both to minimise water used but also to help prolong reservoir life, and this can help to explain the apparently lower water consumption of ENEL. Based on the data in Table 3, it is apparent that geothermal electricity could be likely to use more water than coal but this is highly dependent on a project’s configuration (especially if it is a closed loop cycle). At present, reported data and other literature is insufficient to accurately quantify water consumption.

The extent of impacts on water resources is also a vague area for geothermal energy. The nature of the impacts is often localised, commonly in water resources or regions that otherwise have little other active use. However, given the noted issues with water quality and the amount of water used, impacts on water resources need to be addressed explicitly and not overlooked. At present, like other aspects, there is little reported to facilitate an accurate assessment of impacts on water resources.

4.4 Land Use

No company reported the active land area in use for their respective geothermal energy projects. The most comprehensive study of land use is MIT (2006), shown in Table 4, including estimates for coal, nuclear and solar power plants. Although the estimates are approximate only and not directly comparable (eg. coal includes mining while nuclear does not), they do show clearly that geothermal electricity requires considerably less land than other forms of electricity.

Table 4: Estimated land requirements for geothermal and other power plants (MIT, 2006)

Energy source	Land use m^2/MW	Land use m^2/GWh
110 MW geothermal flash plant (excluding wells)	1,260	160
20 MW geothermal binary plant (excluding wells)	1,415	170
49 MW geothermal FC-RC plant [(1)] (excluding wells)	2,290	290
56 MW geothermal flash plant (including wells [(2)], pipes, etc)	7,460	900
2258 MW coal plant (including strip mining)	40,000	5,700
670 MW nuclear plant (plant site only)	10,000	1,200
47 MW (average) solar thermal plant (Mojave Desert, CA)	28,000	3,200
10 MW (average) solar PV plant [(3)] (Southwestern US)	66,000	7,500

[1] Typical Flash-Crystalliser/Reactor-Clarifier plant at Salton Sea, California.
[2] Wells are directionally drilled from a few well pads.
[3] New land would not be needed if, for example, rooftop panels were used in an urban environment.

5 Conclusions

This paper set out to review and update the critical environmental sustainability metrics for geothermal energy-derived electricity production. The spectre of climate change is encouraging the world to examine the potential for a variety of low greenhouse intensity sources of electricity – a key attractive feature of geothermal electricity. Overall, the study found that geothermal electricity is growing significantly, but the available reported sustainability data by key companies operating geothermal plants is still somewhat limited. The available data analysed did show that the greenhouse intensity varied significantly, ranging from 2.1 t CO_2/GWh for ENEL from Italy to 95.4 t CO_2/GWh for Mighty River Power in New Zealand. Although the variability is expected to be due to different geothermal resources being tapped, as well as differences in power plant designs (especially if a closed loop cycle is present or not), the data was not sufficiently detailed to allow such clarity of interpretation. For other gaseous emissions, geothermal electricity is generally much lower in unit emissions compared to coal or oil-derived electricity. With regards to water consumption, the limited data suggests that geothermal energy is likely to be higher than conventional power sources, but that this could be reduced significantly with measures such as closed loop cycles and reinjection. In summary, the available data analysed from recent sustainability reports, as well as an extensive array of technical literature, continues to support the highly attractive environmental sustainability metrics for geothermal energy-derived electricity.

6 References

Ármannsson, H & Kristmannsdóttir, H, 1992, *Geothermal Environmental Impact*. Geothermics, 21(5/6), pp 869-880.

Ármannsson, H, Fridriksson, T & Kristjánsson, B R, 2005, *CO_2 Emissions From Geothermal Power Plants and Natural Geothermal Activity in Iceland*. Geothermics, 34(3), pp 286-296.

Arnórsson, S, 2004, *Environmental Impact of Geothermal Energy Utilization*. In "Energy, Waste and Environment: A Geochemical Perspective", Editors R Gieré & P Stille, Geological Society (London), UK, Special Publication 236, pp 297-336.

Aubrecht, G J, 2006, *Energy: Physical, Environmental, and Social Impact*. 3rd Edition, Pearson/Prentice Hall.

Barbier, E, 2002, *Geothermal Energy Technology and Current Status: An Overview*. Renewable and Sustainable Energy Reviews, 6(1-2), pp 3-65.

Bertani, R, 2005, *World Geothermal Power Generation 2001–2005*. Geothermics, 34(6), pp 651-690.

Bertani, R, 2007, *World Geothermal Generation in 2007*. GHC Bulletin, September, pp 8-19.

CE, various, *Annual Sustainability / Environment Reports*. Contact Energy Ltd (CE), Years 2002 to 2007, Auckland, New Zealand.

Dickson, M & Fanelli, M, 2005, *Geothermal Power Plants: Principles, Applications and Case Studies*. Elsevier, Kidlington.

Diesendorf, M, 2007, *Greenhouse Solutions With Sustainable Energy*. UNSW Press.

DiPippo, R, 2008, *Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact*. 2nd Edition, Butterworth Heinemann, 520p.

EIA, 2008, *Official Energy Statistics From the US Government*. Energy Information Administration (EIA), US Department of Energy, USA, Accessed 28 May 2008, www.eia.doe.gov.

ENEL, various, *Annual / Sustainability Reports*. ENEL SpA, Years 2002 to 2006, Rome, Italy.

Fridleifsson, I & Freeston, D, 1994, *Geothermal Energy Research and Development*. Geothermics, 23(2), pp 175-214.

Gislason, G, 2000, *Nesjavellir Co-Generation Plant, Iceland: Flow of Geothermal Steam and Non-Condensable Gases*. In "World Geothermal Congress 2000", Kyushu-Tohoku, Japan, 28 May-10 June 2000, pp 585-590.

Gupta, H & Roy, S, 2007, *Geothermal Energy: An Alternative Resources for the 21st Century*. Elsevier, Amsterdam, The Netherlands.

Hinrichs, R A & Kleinbach, M H, 2006, *Energy – Its Use and the Environment*. 4th Edition, Thomson/Brooks Cole.

Kagel, A & Gawell, K, 2005, *Promoting Geothermal Energy: Air Emissions Comparison and Externality Analysis*. The Electricity Journal, 18(7), pp 90-99.

MIT, 2006, *The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century*. Massachusetts Institute of Technology (MIT), Cambridge, USA.

MRP, various, *Annual Sustainability Report*. Mighty River Power Ltd (MRP), Years 2004 to 2007, Auckland, New Zealand.

Mudd, G M, 2008, *Sustainability Reporting and Water Resources: a Preliminary Assessment of Embodied Water and Sustainable Mining*. Mine Water and the Environment, DOI 10.1007/s10230-008-0037-5.

OR, various, *Annual Sustainability Report*. Orkuveita Reykjavirkur (OR), Years 2002 to 2006, Auckland, Iceland.

Testser, J, Drake, E et al., 2005, *Sustainable Energy: Choosing Among Options*. Massachusetts Institute of Technology (MIT), Cambridge, USA.

Ungemach, P, 1987, *Applied Geothermics*. John Wiley & Sons.