Promoting Geothermal Energy: Air Emissions Comparison and Externality Analysis

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GEOTHERMAL ENERGY ASSOCIATION

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Photo courtesy of Ormat

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Brief Summary

This analysis updates a 2005 paper published by Alyssa Kagel and Karl Gawell of Geothermal Energy Association (GEA) in the Electricity Journal. That report explored the beneficial externalities associated with using geothermal power instead of fossil fuels by comparing emissions levels of different fuel sources. The 2005 paper found roughly 1.6 cents/kWh of unrecognized value in the market price of geothermal power. Since that time new information has become available. This analysis expands upon the methodology of the 2005 paper by taking advantage of information not available over a decade ago and by incorporating more atmospheric pollutants into the calculation. As a result, this report finds the externality benefits of producing electricity using geothermal resources, as opposed to fossil fuels to be \$0.01 for natural gas, and \$0.035 for coal per kWh. Additionally, GEA estimates that geothermal provides approximately \$278 million in externality benefits per year to the entire U. S. or \$117 million per year to the states of Nevada and California by avoiding fossil fuel emissions.

Introduction

When compared to other energy sources such as coal, natural gas, and even some renewables, geothermal energy emerges as one of the cleanest and most environmentally benign forms of energy. In general, geothermal plants have small land footprints and low air emissions. Of the three types of geothermal power plants currently in operation, dry-steam and flash plants produce only trace amounts of gaseous emissions, while closed-cycle Organic Rankine Cycle (ORC or binary) plants produce near-zero greenhouse gas (GHG) emissions during generation. However, the cooling towers used for some binary plants may produce miniscule amounts of atmospheric pollutants depending on the type of cooling tower and the amount of cooling needed. Additionally, Argonne National Laboratories found in their 2010 life-cycle analysis of geothermal systems that hydrothermal binary plants have some of the lowest lifecycle emissions of any generating technology, including other renewables. Argonne calculated the life-cycle GHG emissions from binary power plants to be 5.7 gCO_2eq/kWh. This value is lower than that of both wind and solar, which have life-cycle GHG emissions of 8.0 and 62.3 gCO_{2eq}/kWh, respectively.[1]

This report updates a 2005 analysis published by Alyssa Kagel and Karl Gawell of GEA in the Electricity Journal. That study explored the externalities associated with using geothermal power instead of fossil fuels by comparing emissions levels of different fuel sources. The 2005 paper found roughly 1.6 cents/kWh of unrecognized value in the market price of geothermal power. Since that time new information has become available. This analysis expands upon the methodology of the 2005 paper by taking advantage of information not available over a decade ago, and it incorporates more atmospheric pollutants into the calculation.

An externality is defined as a cost or benefit that is not transmitted through market prices of a good or service. For our purposes, an externality is interpreted as the benefit of generating electricity from geothermal power instead of fossil fuels by estimating those “costs” not included in current fossil fuel market prices. As a result, this report finds that the external benefit from geothermal generation equivalent to 1.0 cent per kWh for natural gas and 3.5 cents per kWh for coal.

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[1] Sullivan et al. 2010

Additionally, the benefits of geothermal energy include other positive externalities not included in this analysis. For example, geothermal power requires a smaller footprint (measured as kWh/acre) than other energy sources and has a reduced impact on transportation infrastructure due to the absence of a fuel cycle. Additionally, geothermal power plants can utilize recycled waste water to reduce environmental impacts on water resources and treatment costs.

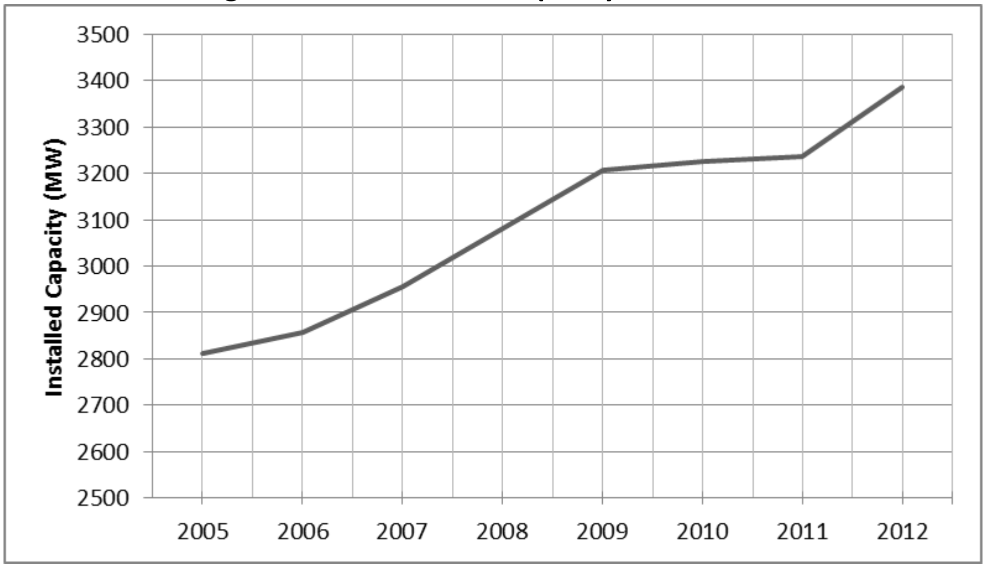
Historical Context and Recent Developments

Geothermal development in the U.S. boomed in the early 1980s due to a number of factors, including the 1973-74 Organization of the Petroleum Exporting Countries (OPEC) oil embargo, the enactment of energy tax incentives for renewables, the implementation of the Public Utility Regulatory Policies Act of 1978, and substantial research funding from the Department of Energy (DOE). Geothermal resources were developed in California, Nevada, and Utah during this period. Between 1980 and 1985, 17 geothermal plants went online in the U.S., totaling 1.15 gigawatts (GW) of installed capacity.[2] But declines in fossil fuel prices, waning public interest in energy policy, expiration of tax credits and other incentives, and substantially decreased government funding precipitated a dramatic decline in new geothermal development during the late 1980s and into the 1990s. Very little geothermal development took place between 1990 and 2005; only 148 MW came online during this span of fifteen years. For comparison, that is roughly equivalent to the generating capacity that came online from new geothermal plants in 2012.[3]

Despite the setbacks of the 1990s, new developments in geothermal power resumed in 2005 as shown in Figure 1. This surge in growth is attributed to the extension of the federal production tax credit in 2005 to geothermal facilities, the ITC cash grant program, and the American Recovery and Reinvestment Act, coupled with growing state-level recognition of the value of renewable portfolio standards. Twenty-seven plants came online between 2006 and 2012 in seven Western states, bringing the total installed capacity in the U.S. to 3.38 GW. Today, geothermal power plants are currently online in eight states: Alaska, California, Hawaii, Idaho, Nevada, Oregon, Utah, and Wyoming. Additionally, a staggering 175 geothermal projects are currently in development, which could add ≈2,500 MW to U.S. installed capacity in the next decade or so.[4]

[2] GEA
[3] *Ibid.*
[4] *Ibid.*

Figure 1: U.S. Installed Capacity 2005 – 2012



Source: GEA

Today, geothermal power is underutilized for a number of reasons. Federal tax credits, which tend to be modified every few years, are reaching their end dates. For geothermal plants with long lead times, the legislative uncertainty means the effects of the incentive are diminished. At the state level, there is a failure to recognize the system values of geothermal power and a misconception that geothermal energy can only provide base-load service. On the contrary, geothermal energy can provide both firm and flexible power with almost no system integration costs. [5]

While renewable energy procurement practices tend to compare renewable energy resource alternatives against one another on a cost per kilowatt-hour (kWh) basis without considering the full range of system costs that competing technologies offer, the lack of uniformity among geothermal plants is actually a strength, because geothermal projects can provide the highest value of service tailored to the operating environment and operational needs of the market. Geothermal energy offers significant benefits in addition to a competitive cost per kilowatt-hour.[6]

Geothermal Technology

The breadth of geothermal plant designs, which vary based on resource temperature and chemistry, operational needs, and other factors can sometimes blur the lines between geothermal plant categories. There are three main types of geothermal plants: dry-steam, binary, and flash. Technological advances in geothermal plants to utilize different types of geothermal resources are on the horizon as Enhanced Geothermal Systems (EGS) and Small Power or Co-production systems develop their market and technology potential.

[5] Linvill et al. 2013
[6] *Ibid.*

Flash Power Plant

In a geothermal flash power plant, high-pressure and high- temperate geothermal water separates into steam and water as it rises from underground and pressure drops. The steam and liquid are separated in a surface vessel, called a steam separator. The steam is delivered to the turbine, and the turbine powers a generator. The liquid is injected back into the reservoir.

Dry-Steam Power Plant

In a geothermal dry-steam power plant, steam is withdrawn directly from an underground geothermal reservoir and used to run the turbines that power the generator. Because there is no water, the steam separator used in a flash plant is not necessary. These plants composed about half of U.S. installed capacity in 2012 and are all located in California.[7]

Binary Power Plant

Binary geothermal plants have made it possible to produce electricity from resources lower than 150°C. These new plants have greatly expanded the U.S. industry's geographical footprint, especially in the last decade. In binary systems, geothermal water is passed through a heat exchanger in order to heat another liquid called a working fluid, which boils at a lower temperature than water. When the working fluid vaporizes, the force of the expanding vapor turns the turbines to power the generators. The geothermal water is then injected back into the reservoir in a closed loop system that is separated from groundwater sources. Because binary plants use closed-loop systems, these plants boast near-zero GHG emissions. However, some particulate matter (PM) is emitted from the cooling systems of these power plants. Recently, most new plants that have come online in the U.S. have been binary systems.[8]

Enhanced Geothermal Systems

Enhanced geothermal systems (EGS) refer to the engineering of conditions at a site to create a reservoir which then has the potential to produce geothermal energy. A geothermal system requires heat, permeability, and water, so EGS techniques make up for reservoir deficiencies in any of these areas. EGS technologies enhance existing fracture networks in rock, introduce water or another working fluid, or otherwise build on a geothermal reservoir that would be difficult or impossible to derive energy from using only conventional technologies.

Distributed Generation, Small Power, Co-Production

Traditional geothermal power can be used in small community-based power systems, such as the campus at Oregon Institute of Technology or the community system envisioned for Canby, California. Additionally, geothermal water is a natural byproduct of oilfield production processes. Much of the 25 billion barrels of water produced at oil wells each year in the U.S., long considered unusable "wastewater," is hot enough to produce electricity through geothermal co-production. Many oil or gas wells could have clean energy capacities of up to 1 MW. A 1 MW power generator is small in conventional power generation terms, but the potential for hundreds of these to be brought on line within a short period of time is promising.[9] It appears likely that most small power and EGS systems will utilize binary power cycles or a similar advanced power system technology.

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[7] GEA

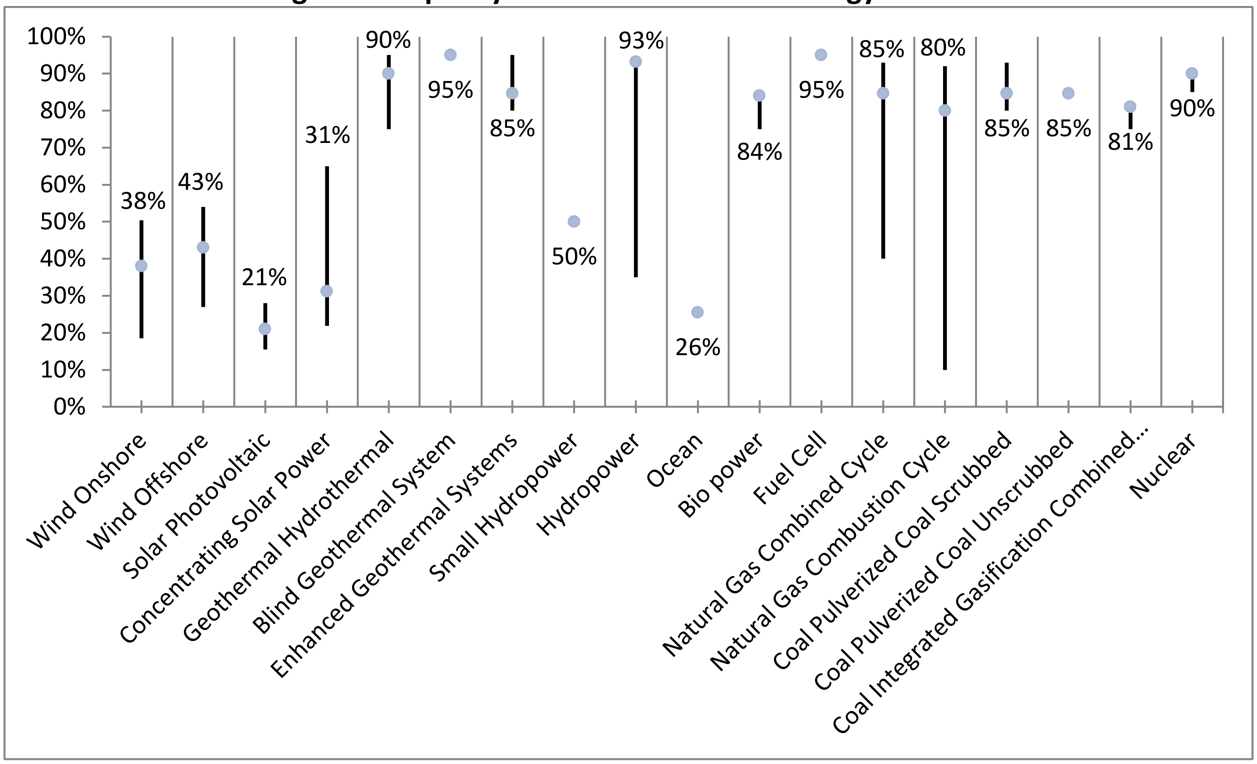
[8] *Ibid.*

[9] *Ibid.*

Capacity Factor

The capacity factor of a power plant is the ratio of its actual output over a period of time to its potential output if it were possible for it to operate continuously at full capacity. Figure 2 provides national capacity factor information for assorted energy sources. As Figure 2 demonstrates, geothermal plants have higher capacity factors than most other renewables and even higher capacity factors than coal or natural gas.

Figure 2: Capacity Factors for Assorted Energy Sources



Source: DOE and NREL "Transparent Costs Database"
Note: Blue dots represent estimate for the average capacity factor of each technology.

Geothermal Air Emissions

One of the significant benefits of geothermal energy, besides its incredibly high capacity factor, is its extremely low air emission rate. Flash and dry-steam plants emit about 5% of the carbon dioxide, 1% of the sulfur dioxide, and less than 1% of the nitrous oxide emitted by a coal-fired plant of equal energy capacity, and binary geothermal plants produce near-zero emissions.[10]

Geothermal power does not involve direct combustion of the primary energy resource. Flash and dry-steam geothermal plants release some gases into the atmosphere during the power conversion process due to the presence of naturally-occurring dissolved gases contained in geothermal fluids. However, it is difficult to distinguish between natural and anthropogenic emissions associated with geothermal resource development. There is a lack of baseline data for naturally-occurring GHG emissions released

[10] Holm et al. 2012

from undeveloped geothermal sites.[11] These questions are explored further in GEA's November 2012 paper, "Geothermal Energy and Greenhouse Gas Emissions."

Of the three types of geothermal power plants online today – dry-steam, flash-steam, and binary – only the first two are likely to emit any measurable amounts of GHGs. When comparing the CO_2 emissions data obtained from the Environmental Protection Agency (EPA) and Energy Information Administration (EIA) for coal and natural gas power plants, the average rate of carbon dioxide emissions for coal-fired power plants and natural gas power plants are 2200 lbs CO_2/MWh and 861 lbs CO_2/MWh, respectively. Geothermal systems, on the other hand, produce significantly less emissions, approximately ≈197 lbs CO_2/MWh.[12]

Table 1 shows more information on emissions levels for Carbon Dioxide, Methane, Particulate Matter, Sulfur Dioxide, and Nitrous Oxide and how emissions from geothermal compare to natural gas and coal.

Carbon Dioxide (CO_2)

As with natural geothermal emissions, the most commonly released gas from geothermal power plants is carbon dioxide as shown in Table 1. Because geothermal systems are natural sources of CO_2, isolating the CO_2 attributable to human activities is often difficult. The amount of carbon dioxide found in the geothermal fluid can vary depending on location, and the amount of carbon dioxide actually released into the atmosphere can vary depending on plant design. This makes it difficult to generalize about the amount of carbon dioxide emitted by an average geothermal power plant. For example, binary plants with air cooling are a closed-loop system and emit no carbon dioxide, as geothermal fluids are never exposed to the atmosphere. However, even without discounting the non-anthropogenic emissions the overall comparative amount of CO_2 from geothermal plants is from small to nil, depending on technology utilized with binary power technology emitting essentially zero GHG emissions.

Methane (CH_4)

Methane is another common greenhouse gas emitted naturally from geothermal systems, but those emissions are minimal. In Table 1, methane emissions from geothermal plants do not even register on the table because they are several orders of magnitude smaller than coal and natural gas methane emissions.

Particulate Matter (2.5 and 10 micrometers)

Particulate matter is a complex mixture of extremely small particles and liquid droplets. Particle pollution is made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles. Particles that are 10 micrometers in diameter or less can pass through the human throat and nose, enter the lungs, and cause severe negative health consequences.[13] Geothermal plants emit small amounts of PM from cooling towers, but these emissions are negligible compared to the PM emissions from fossil fuels.

Nitrous Oxide (N_2O) and Nitrogen Oxides (NO_X)

Nitrous Oxide is part of a larger family of atmospheric pollutants referred to as the Nitrogen Oxides, or NO_X. Since geothermal power plants do not burn fossil fuels, they emit very low levels of nitrous oxide.

[11] *Ibid.*
[12] Based on publicly available CARB emissions data and net generation data from CEC, this value is the average emissions rate calculated from fifteen reporting geothermal facilities in California for reporting year 2010.
[13] EPA 2013a

Geothermal plants are generally required by law (with some variation from state to state) to capture hydrogen sulfide emissions and either burn the gas or convert it to elemental sulfur. If burned, the combustion process creates small amounts of nitrogen oxides, but these amounts are several orders of magnitude smaller than the N_2O emissions generated by coal or natural gas.[14]

Sulfur Dioxide (SO_2) and Hydrogen Sulfide (H_2S)

While geothermal plants do not emit sulfur dioxide directly, once hydrogen sulfide is released as a gas into the atmosphere, it disperses in the air and oxidizes to sulfur dioxide and sulfuric acid. Hydrogen sulfide, identifiable by its distinctive rotten egg smell, remains the pollutant of greatest concern for geothermal energy production. Since 1976, geothermal power plants have tackled this problem by installing Hydrogen Sulfide Abatement Systems, Stretford or LoCAT, which can remove over 99.9 percent of the hydrogen sulfide from geothermal non-condensable gases.[15] These systems convert hydrogen sulfide to elemental sulfur, which can then be used as a soil amendment and fertilizer feedstock. Today, geothermal dry-steam and flash power plants produce only minimal sulfur dioxide emissions or about 0.0002 lbs/MWh for dry-steam and about 0.35 lbs/MWh for flash plants.[16] Meanwhile, binary geothermal power plants generally release no hydrogen sulfide or sulfur emissions.

Table 1: Emissions Levels by Pollutant and Energy Source

[lbs/MWh]	DRY STEAM	FLASH	BINARY	NATURAL GAS	COAL
CO_2	59.82	396.3	-	861.1	2200
CH_4	0.0000	0.0000	-	0.0168	0.2523
$PM_{2.5}$	-	-	-	0.1100	0.5900
PM_{10}	-	-	-	0.1200	0.7200
SO_2	0.0002	0.3500	-	0.0043	18.75
N_2O	0.0000	0.0000	-	0.0017	0.0367

Source: Climate Registry 2012, EIA 2013c, EPA 2009, EPA 2011, NRC 2010

Geothermal plants emit such miniscule amounts of CH_4 and N_2O[17] that while they were used in calculations, they do not appear in Table 1. There are some $PM_{2.5}$ and PM_{10} emissions for geothermal plants from the cooling towers, however, they are insignificant when compared to fossil fuel PM emissions. Lastly, binary power plants emit essentially zero GHG emissions except for the miniscule amounts of PM emissions from the cooling towers.

Benefits of Geothermal Power

Decisions about electricity choices are often based upon the lowest consumer cost. This does not take into account a variety of other factors including: value of the reliability of the power system, cost to integrate the resource into the power system, future prices and price volatility, land use, conflict with competing social values, the cost of subsidies paid by governments or taxpayers, security implications, and more. Properly accounting for these factors demonstrates the advantages of geothermal power.

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[14] Holm et al. 2012

[15] *Ibid.*

[16] CARB 2012

[17] CH_4 emissions $\approx 2.2 \times 10^{-6}$ and $\approx 7.9 \times 10^{-6}$ lbs/MWh for dry steam and flash respectively, N_2O emissions $\approx 3.1 \times 10^{-7}$ and $\approx 1.4 \times 10^{-6}$ lbs/MWh for dry steam and flash respectively

Geothermal energy provides both base-load and flexible power. Since geothermal plants generate power at high capacity factors they require much less transmission capacity to deliver the same amount of energy as other types of renewable resources. While using geothermal as a base-load operation is typical, geothermal plants can also operate in a flexible mode. Once the plant is operational it can be expected to provide electricity for many decades if maintained properly.

Geothermal energy's ability to provide both base-load and flexible power means it can support unpredictable changes in electricity. In contrast, natural gas is not configured to support unpredictable changes because of its expensive transmission and distribution infrastructure.[18] Moreover, if natural gas exports increase, US prices will increased toward world market levels which are significantly higher.

Geothermal projects involve considerable on-site capital investment, typically pay substantial property taxes, and involve significant long-term local employment. Additionally, geothermal project developers sign long-term fixed price or price formula contracts, so they don't present the risk of price shocks and help counter-balance the volatility of some other resources. In geothermal financing, the project developer pays the "fuel costs" upfront when developing a power plant. Therefore, geothermal power plants operate at a low levelized cost if the plant is operated at a high capacity factor. When operating at nearly full capacity, the costs can go as low as 4-5 cents/kWh (USD) on average.[19]

Unfortunately, government subsidies provided to fossil fuels move the cost of emissions onto the consumer instead of the emissions producers themselves, a trend that distorts the market. Environmental costs brought on by emissions from fossil fuel sources can be difficult to quantify, but are rarely borne by the fossil fuel companies themselves. These costs include land degradation as a result of mining or the natural gas well fields, emissions of toxic chemicals, the unfortunate extinction of wildlife due to climate change, and negative health consequences including rising healthcare costs.

While recent regulatory changes and a renewed interest in a national climate policy rehabilitated investment in geothermal power, production continues at only a fraction of its potential. If public policy begins to account for geothermal energy's positive externalities, the resulting expansion of geothermal energy could bring about fewer environmental impacts, better air quality, greater fuel diversity, and improved national security through the use of a domestic energy source.

Methodology

There are only two significant differences between the calculation made in the 2005 analysis and the calculations made in this analysis. First, this analysis uses more recent emissions data than the 2005 analysis. Second, this analysis goes into more depth by factoring in several more atmospheric pollutants and two fossil fuels: natural gas, and coal. The specific steps involved in the calculation are described below. More information on the calculations can be found in the Appendix I.

Variables Defined

Avg. Geo Energy	The average total yearly amount of electricity generated from geothermal from 2002 to 2012

[18] Linvill et al. 2013
[19] Gehringer et al. 2012

Geo Emissions	Geothermal emissions data from California Air Resource Board (CARB) and EPA
GHG Emission Factors	A value that relates the quantity of a pollutant released with an activity associated with the release of that pollutant (e.g., pounds of CO_2 per MWh of electricity generated from a power plant, lbs CO_2/MWh)

Step 1

The average yearly power generated was broken down into the electricity produced by each geothermal plant type based on fraction of installed capacity: 47% from dry-steam (DS) plants, 29% flash, and 24% binary.[20]

$$\text{Avg. Geo Energy} \approx 14{,}982 \text{ GWh}$$

Step 2

In Step 2, the average yearly power generated was broken down by electricity produced by each geothermal plant type. For example 47% of installed capacity is dry-steam. So it was assumed 47% of power generation also came from dry-steam or 7,041 GWh of the 14,982 GWh.

Avg. Geo Energy = 14,982 GWh

7,041 GWh	4,344 GWh	3,595 GWh
DS Power	Flash Power	Binary Power

Step 3

Step 3 is divided into two parts. First, actual emissions of geothermal plants were taken from two sources, the California Air Resource Board (CARB), and the Environmental Protection Agency (EPA). Because of the difficulty of obtaining complete information on actual geothermal emissions, using two data sets was necessary to create a complete picture of geothermal emissions. Information on SO_2 emissions was taken from the EPA data and information on CO_2, N_2O and CH_4 emissions was taken from the CARB data.[21]

Second, actual geothermal emissions (lbs/MWh) were multiplied by MWh generated by plant type estimated in Step 2 to estimate total yearly emissions from geothermal energy.

Emissions (lbs/MWh) X DS Power (MWh) = DS Emissions (lbs)
Emissions (lbs/MWh) X Flash Power (MWh) = Flash Emissions (lbs)
Emissions (lbs/MWh) X Binary Power (MWh) = Binary Emissions (lbs)

Step 4

Using a variety of sources from the EIA and EPA, a series of emission levels were chosen or estimated for each fossil fuel. If a value for each gas in convertible units to lbs/ MWh was not found, one was estimated by multiplying the emissions factor by consumption and dividing by net generation.

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[20] EIA 2013b, GEA
[21] CARB 2012, EPA 2012

Figure 3: Greenhouse Gas Emissions Level Calculations

Coal	Emission Factor (Per Unit Mass or Volume)	Unit	Consumption for Electricity Generation	Unit	Net Generation [MWh]	Emission Level [lbs/MWh]
CO_2	1862.12	kg CO2 / short ton	928,857,000	short tons	1,733,430,000	2200
SO_2	35	lbs / short ton	928,857,000	short tons	1,733,430,000	18.75
N_2O	0.0016	kg N2O/ mmBTU	18,035,200,000	mmBtu	1,733,430,000	0.0367
CH_4	0.011	kg CH4 / mmBTU	18,035,200,000	mmBtu	1,733,430,000	0.2523
Natural Gas	**Emission Factor (Per Unit Mass or Volume)**	**Unit**	**Consumption for Electricity Generation**	**Unit**	**Net Generation [MWh]**	**Emission Level [lbs/MWh]**
CO_2	0.0545	kg CO2 / scf	7,265,194,000,000	cubic feet	1,013,689,000	861.1
SO_2	0.6	lbs /mmcf	7,265,194	mmcf	1,013,689,000	0.0043
N_2O	0.0001	kg N2O/ mmBTU	7,712,100,000	mmBtu	1,013,689,000	0.0017
CH_4	0.001	kg CH4 / mmBTU	7,712,100,000	mmBtu	1,013,689,000	0.0168

Source: EPA 2009, EPA 2013b, Climate Registry 2012, EIA 2013c, EIA 2013d, EIA 2013e, EIA 2013f

After the emission levels were estimated, these values were multiplied by the amount of electricity produced in a given year by geothermal technology type to identify if the same electricity were to be produced by natural gas or coal, the equivalent GHG emissions.

The calculation below was made for coal and gas:

GHG Emission Level (lbs/MWh) X DS Power (MWh) = GHG Emissions (lbs)

GHG Emission Level (lbs/MWh) X Flash Power (MWh) = GHG Emissions (lbs)

GHG Emission Level (lbs/MWh) X Binary Power (MWh) = GHG Emissions (lbs)

Step 5

Total Geo Emissions of all atmospheric pollutants and GHGs from geothermal were subtracted from the emissions estimated in Step 4.

The calculation below was made for coal and gas:

GHG Emissions (lbs) – DS, Flash, or Binary Emissions (lbs) = Adjusted GHG Emissions

Step 6

Step 6 is a list of market values for the 'cost' [$/ metric ton] for each GHG. The next section contains a list of these sources. For consistency, in the final calculation the lowest market price available for each atmospheric pollutant is used in GEA's estimation. Additionally, choosing low prices for the calculation eliminates bias. Most of these market prices are in 2007 dollars, so a simple calculation using the U.S. Bureau of Labor Statistics (BLS) inflation calculator adjusted the prices to 2013 dollars.

Step 7

Lastly, the price per metric ton is multiplied by the estimated emissions from a specific fuel source in Step 5, thus providing a total dollar figure that represents the benefit per year of using geothermal power to generate the electricity instead of a fossil fuel. By dividing that value by the total average yearly power generated determined in Step 1, a $/kWh figure is determined.

The calculation below was made for coal and gas:

"Cost" x Adjust GHG Emissions = Total Cost in terms of US$

Total Cost in terms of US$ / Avg. Geo Energy = Benefit of Geo Energy (cents/kWh)

Market Prices of Fossil Fuels

Costs ($/metric ton) were determined for four externality sources, summarized below. These market prices take into account the externality or cost/benefit that is not transmitted through market prices for geothermal power. By using these market prices, the environmental, health, and security costs associated with generating power from fossil fuels instead of geothermal are factored into the methodology of this analysis.

The Social Cost of Carbon: Trends, Outliers and Catastrophes (2008)

This paper presents an update of an earlier meta-analysis of Tol's 2005 paper of the social cost of carbon. Using more data and more advanced statistical analysis, this paper confirms the findings of Tol's 2005 paper and estimates that the social costs of carbon are driven to a large extent by the choice of the discount rate, and equity weights. With the conservative assumptions above, the mean cost of carbon equals $23 per ton of carbon. Additionally, Tol writes there is a 1% probability that the social cost of carbon is greater than $78 per ton of carbon.

Estimating the Social Cost of Non-CO_2 GHG Emissions: Methane and Nitrous Oxide (2011)

This paper uses a simplified integrated assessment model that combines the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) and the Dynamic Integrated Climate Change Model (DICE) to estimate the social costs of the three most important greenhouse gases, —CO_2, CH_4, and N_2O—for the years 2010 through 2050. The model is based on the assumptions and input parameters of the recent U.S. government interagency SCC working group.

Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use (2010)

Chapter 2 of this reference, "Energy for Electricity," provides detailed analyses of electricity generation from coal, natural gas, nuclear fission, wind, and solar. The first three sources were chosen because they together account for 88% of all electricity generated in the U.S. when this publication was written in 2009-2010.

Measuring the Damages of Air Pollution in the United States (2007)

"Measuring the Damages of Air Pollution in the United States" estimates the damages due to emissions of air pollution in the U.S. An integrated assessment model is used to calculate the marginal damage associated with emitting an additional ton of pollution from nearly 10,000 sources in the U.S. Gross Annual Damages (GAD) in 2002, resulting in a range from $71 billion to $277 billion (0.7% to 2.8% of GDP). The range of values depends largely on the value of health, source location, and the concentration-response function relating exposures to particulate matter to adult mortality rates. Urban emissions constitute 52% of total emissions by weight, yet they cause nearly three-quarters of the GAD.

Results

Using the methodology described above, GEA found the benefit of producing power using geothermal sources, as opposed to fossil fuels is $0.01 for natural gas, and $0.035 for coal per kWh.

These two values can be interpreted in two ways. First, they can be viewed as benefits associated with using geothermal energy in place of fossil fuels. For example, society gains 3.5 cents in value for every kWh of geothermal energy generated instead of using coal. Alternatively, these values can be viewed as a cost incurred from using fossil fuels. If the same amount of electricity was generated in the U.S. from coal instead of geothermal energy, the resulting cost would be 3.5 cents per kWh.

It is important to note that because the lowest cost available for each atmospheric pollutant is used in GEA's estimation, the true benefit from geothermal power could actually be much greater than the values estimated above.

GEA estimates that geothermal provides approximately $278 million in externality benefits per year to the entire U. S. or $117 million per year to the states of Nevada and California by avoiding fossil fuel emissions. Using the externality values 3.5¢/kWh and 1.0¢/kWh for coal and natural gas and the system power distributions from the EIA and CEC[22] for California in 2011 and Nevada in 2010, we estimate the externality benefit per year is about $87.5 million per year for California and $29.1 million per year for Nevada. This assumes California obtains ≈ 44% (8% coal and 36% NG) and Nevada ≈ 87% (20% coal and 67% NG) of its electricity from fossil fuels.

Regardless of how these results are considered (i.e., as benefit derived from using geothermal as a power source, or as costs that must be absorbed in addressing the consequences of non-geothermal power production), it is clear that indirect economic consequences result from specific energy choices regarding how power is generated. This analysis provides a partial measure of the positive attributes that geothermal power production can provide relative to other power generation sources.

Furthermore, the economic benefits of geothermal power outlined in this report can be interpreted as minimum values, since they do not consider other positive externalities of geothermal energy utilization. The main conclusion from this analysis is that geothermal energy is a high-value energy source that can provide substantial economic and societal benefits if deployed at sufficient scale to penetrate U.S. power markets.

Acronyms

BLS	U.S. Bureau of Labor Statistics
C_2O	Carbon Dioxide
CARB	California Air Resource Board
CGEC	California Geothermal Energy Collaborative
CEC	California Energy Commission
CH_4	Methane
DICE	Dynamic Integrated Climate Change Model
DOE	U.S. Department of Energy
DS	Dry-Steam
EESI	Environmental and Energy Study Institute
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
GAD	Gross Annual Damages
GEA	Geothermal Energy Association
GHG	Greenhouse Gas
LBS	Pounds (mass)
MAGICC	Model for the Assessment of Greenhouse-gas Induced Climate Change
OPEC	Organization of the Petroleum Exporting Countries
ORC	Organic Rankine Cycle

[22] EIA 2013a, CEC 2013

NG	Natural Gas
NRC	National Research Council
N_2O	Nitrous Oxide
$PM_{2.5}$	Particulate Matter that is two and a half microns or less in width
PM_{10}	Particulate Matter that is about ten microns or less in width
SCC	Social Cost of Carbon

Appendix I: Calculations

Step 1

	Total Yearly kWh of Electricity Generated from Geothermal Facilities From EIA						
	2002	2003	2004	2005	2006	2007	
Geothermal (GWh)	14,491	14,424	14,811	14,692	14,568	14,637	
Geothermal (MWh)	14,491,000	14,424,000	14,811,000	14,692,000	14,568,000	14,637,000	
	2008	2009	2010	2011	2012		
Geothermal (GWh)	14,840	15,009	15,219	15,316	16,791	Average [GWh]	14,982
Geothermal (MWh)	14,840,000	15,009,000	15,219,000	15,316,000	16,791,000	Average [MWh]	14,981,636

Step 2

Estimate of Yearly MWhs of Electricity Generated from Geothermal Power		
Dry Steam	**Flash**	**Binary**
47%	29%	24%
7,041,369	4,344,675	3,595,593

Step 3

	Total Yearly Geothermal Emissions of Atmospheric Pollutants		
		Step 1	
[lbs/MWh]	**Dry Steam Total**	**Flash Total**	**Binary Total**
CO_2	59.81834898550	396.32234473896	-
SO_2	0.00020000000	0.35000000000	-
N_2O	0.00000031977	0.00000139787	-
CH_4	0.00000223838	0.00000792125	-
$PM_{2.5}$	-	-	-
PM_{10}	-	-	-
		Step 2	
[lbs]	**DS Yearly Emissions**	**Flash Yearly Emissions**	**Binary Yearly Emissions**
CO_2	421,203,074	1,721,891,603	-
SO_2	1,408	1,520,636	-
N_2O	2	6	-
CH_4	16	34	-
$PM_{2.5}$	-	-	-
PM_{10}	-	-	-

Step 4

Emissions Levels for Comparable Coal and Gas Generation				
	Emission Level	Comparable Emissions		
	Natural Gas [lbs/MWh]	Dry Steam [lbs]	Flash [lbs]	Binary [lbs]
CO_2	861.1	6,063,590,119	3,741,364,116	3,096,301,337
SO_2	0.004	30,280	18,683	15,462
N_2O	0.002	11,810	7,287	6,031
CH_4	0.017	118,102	72,872	60,308
$PM_{2.5}$	0.11	774,551	477,914	395,515
PM_{10}	0.12	844,964	521,361	431,471
	Emission Level	Comparable Emissions		
	Coal [lbs/MWh]	Dry Steam [lbs]	Flash [lbs]	Binary [lbs]
CO_2	2,200	15,489,630,823	9,557,431,784	7,909,598,718
SO_2	18.75	132,058,909	81,483,156	67,434,336
N_2O	0.04	258,420	159,450	131,959
CH_4	0.25	1,776,635	1,096,222	907,218
$PM_{2.5}$	0.59	4,154,408	2,563,358	2,121,400
PM_{10}	0.72	5,069,786	3,128,166	2,588,827

Step 5

Adjustment for Geothermal Generation Emissions			
	Natural Gas		
	Dry Steam [tonnes]	Flash [tonnes]	Binary [tonnes]
CO_2	2559344	916017	1404459
SO_2	13	-681	7
N_2O	5	3	3
CH_4	54	33	27
$PM_{2.5}$	351	217	179
PM_{10}	383	236	196
	Coal		
	Dry Steam [tonnes]	Flash [tonnes]	Binary [tonnes]
CO_2	6834924	3554141	3587734
SO_2	59900	36270	30588
N_2O	117	72	60
CH_4	806	497	412
$PM_{2.5}$	1884	1163	962
PM_{10}	2300	1419	1174

Step 6

Market Values of Emissions Allocations												
	CO_2 [$/tonne]		SO_2 [$/tonne]		N_2O [$/tonne]		CH_4 [$/tonne]		$PM_{2.5}$ [$/tonne]		PM_{10} [$/tonne]	
Source	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
(NRC 2010)			5262	5262					8618	8618	417	417
(Tol 2008)	23	25										
(Muller et al. 2007)			816	1361	272	272						
(Marten & Newbold 2011)	9	52			3500	20000	370	1100				
GEA Choice of Price	23		816		272		370		8618		417	
Market Price Adjusted for Inflation	27		906		303		410		9569		463	
PM Natural Gas Prices								(NRC 2010) Natural Gas Price	29030		1542	
								Natural Gas Price adjusted for Inflation	32242		1713	

Step 7

Externality Benefit of Geothermal Power Production						
	Natural Gas			Coal		
	Dry Steam	Flash	Binary	Dry Steam	Flash	Binary
CO_2	$68,436,851	$24,494,303	$37,555,225	$182,765,864	$95,037,737	$95,935,997
SO_2	$11,868	-$617,419	$6,356	$54,285,822	$32,870,766	$27,720,715
N_2O	$1,622	$1,000	$829	$35,505	$21,907	$18,130
CH_4	$21,961	$13,546	$11,216	$330,403	$203,861	$168,718
$PM_{2.5}$	$11,327,590	$6,989,364	$5,784,301	$18,032,236	$11,126,273	$9,207,950
PM_{10}	$656,540	$405,099	$335,255	$1,065,021	$657,141	$543,841
Estimated Total Cost by Tech. & Fossil Fuel [$]	$80,456,433	$31,285,894	$43,693,181	$256,514,851	$139,917,684	$133,595,352
Estimated Total Cost by Fossil Fuel [$]	$155,435,507			$530,027,886		
Externality Cost per kWh [$/MWh]	10			35		
Externality Cost per kWh [$/kWh]	0.0104			0.0354		

Appendix 2: US Externality Benefit Calculation

Externality Benefit of Geothermal Per Year

Energy Source	2012 (GWh)	% of Total US Power	
Geothermal	16,791	0.4%	
Coal	1,517,203	37%	
Petroeum Coke and Liquids	22,900	1%	
Natural Gas	1,230,708	30%	
All Fuels	**4,054,485**		
Energy Source	**(GWh)**	**(kWh)**	**Benefit per Energy Source**
Coal	6,283.25	6,283,253,132	$ 222,292,098
Natural	5,096.78	5,096,779,993	$ 52,879,443
Oil	94.84	94,836,681	$ 2,514,347
		Total Benefit	**$ 277,685,888**

Source: EIA 2013g

The externality benefit of geothermal power per year to the U.S. is estimated to be $278 million per year by avoiding fossil fuel emissions. Likewise, if the same electricity was generated from natural gas, coal, and petroleum instead of geothermal the “cost” to the U.S. would be about $278 million per year.

This calculation is based on the conservative assumptions that if geothermal power were removed from the electrical grid, the same percentage of natural gas, coal and petroleum would replace geothermal. When in reality, the electricity generated from these fuel sources would likely increase to replace the geothermal generation. The same methodology was used to estimate the numbers for two leading geothermal states, California and Nevada.

Appendix 3: Externality Benefit of Oil

This analysis finds the externality benefits of producing electricity from geothermal resources opposed to petroleum to be 2.7 cents per kWh. The oil calculation was omitted from the main body of the paper for two reasons. First, few western states generate substantial electricity from petroleum. The fossil fuels used in electricity generation in the west are normally coal and natural gas. A few exceptions exist like Hawaii. Second, we did not find reliable emissions factors for petroleum particulate matter. Therefore, particulate matter emissions were not used to calculate the 2.7 cents per kWh number. The result is significantly more conservative than the other fossil fuel calculations in this analysis. The methodology for calculating this externality benefit is the exact same as described in the methodology section of this paper and shown in Appendix 1. The tables below show this result in more detail.

Emissions Levels for Oil

Oil	Emission Factor (Per Unit Mass or Volume)	Unit	Consumption for Electricity Generation	Unit	Net Generation [MWh]	Emission Level [lbs/MWh]	Summed Emission Level [lbs/MWh]
CO_2 Liquids	74.06	kg CO_2/mmBtu	157,300,000	mmbtu	14,096,000	971	
CO_2 Coke	102.41	kg CO_2/mmBtu	145,700,000	mmbtu	16,086,000	955.1	1,926
SO_2 Liquids	0.16	lbs per gallon	26,477,000	Barrles	14,096,000	6.601	
SO_2 Coke	39.00	lbs per ton	4,726,000	tons	16,086,000	5.351	11.95
N_2O	0.0006	kg N_2O/ mmBTU	303,000,000	mmbtu	30,182,000	0.0133	
CH_4	0.0030	kg CH_4 / mmBTU	303,000,000	mmbtu	30,182,000	0.0664	

Source: EIA 2011, EIA 2013c, EPA 2009, EPA 2013b, EIA 2013h, EIA 2013i, EIA 2013j

Externality Benefit of Geothermal Power Production from Oil

	OIL		
	DRY STEAM	FLASH	BINARY
CO_2	$ 159,389,083	$ 80,613,766	$ 83,998,918
SO_2	$ 34,596,396	$ 20,721,971	$ 17,666,540
N_2O	$ 12,847	$ 7,926	$ 6,560
CH_4	$ 86,944	$ 53,642	$ 44,399
Estimated Total Cost by Tech. & Fossil Fuel [$]	$ 194,085,271	$ 101,397,305	$ 101,716,417
Estimated Total Cost by Fossil Fuel [$]	$ 397,198,992		
Externality Cost per kWh [$/MWh]	$ 27		
Externality Cost per kWh [$/kWh]	$ 0.027		

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