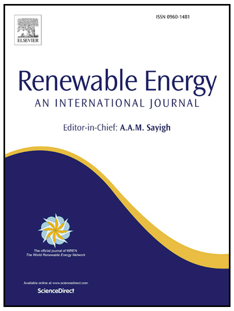

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Life Cycle Analysis of Geothermal Energy for Power and Transportation: A Stochastic Approach

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Abstract

Increasing awareness of environmental issues surrounding power generation and transportation has increased interest in renewable energy sources such as geothermal. Renewable energy extraction is not without environmental cost, however; drilling operations and construction of the facilities required for utilization can be resource intensive. Complete life cycle analysis (LCA) allows for impact comparison between competing methods of power generation. The results are modular, allowing for use in other product life cycles. One such life cycle is that of the transportation vehicle. An analysis of vehicle life cycles involving geothermal energy is performed employing the The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model. Geothermal power has large variations between plants owing to differences in the hydrothermal reservoir chemistry and thermodynamic conditions. Due to these variations, a stochastic approach was used to determine the amount of variation that is likely to be seen using this energy source. The results show geothermal power to have low environmental impact relative to other methods of energy production for use in transportation.

Keywords: LCA, environmental, energy, impacts, Monte-Carlo, simulation, geothermal

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Abbreviations

- LCA: Life Cycle Analysis

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- ISO: International Organization for Standardization
- EPA: Environmental Protection Agency
- TRACI: Tool for the Reduction and Assessment of Chemical and other environmental Impacts
- DALY: Disability-Adjusted Life Year
- NCG: Non-Condensable Gas
- PM10: Particulate Matter 10μm or less in diameter
- GREET: The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model

1. Introduction

One of the most important and yet ill-understood aspects of renewable energy is the environmental impact of the construction, operation, and recultivation of renewable energy power generation facilities. Understanding the full environmental costs of the entire "life-cycle" allows renewable energy technologies to be compared directly to either traditional forms of power generation or to other competing renewable energy technologies. The purpose of this work is to better understand the environmental impacts of geothermal energy via a LCA assessment methodology. This work uses the standards and procedures created by the ISO for Life Cycle Analysis [1] (LCA) along with a statistical treatment of inputs using stochastic methods. The analysis shows that geothermal power to be orders of magnitude cleaner than fossil fuel methods.

There have been several reports comparing the operating impacts for the three common geothermal plant types (single flash, double flash, and binary), as well as assessing common difficulties and emission abatement systems [2]. Other environmental assessments aim to promote development by addressing geothermal energy's impact with regards to governmental regulations. These are often coupled with economic viability and emerging technology assessments [3, 4].

Other analyses are more specific; referring to particular cases with unusual impacts or hazards, or addressing particular technologies [5, 6, 7]. The environmental effects of geothermal energy are highly dependent on the condition of the geothermal field; therefore, there are efforts to analyze and implement solutions for certain plants unique issues such as high carbon dioxide output from flashing used in soft drink manufacture [5]. These analyses often look into single issue impact categories such as global warming [6, 7].

Typical geothermal environmental impact assessments only look at operating emissions and do not assess the impact of the life cycle. They are also typically less concerned with environmental costs, in favor of approaching plant design from a more economic and regulatory perspective. This leaves room for a more detailed methodological approach to assessing geothermal energy production environmental impacts.

Geothermal power is subject to a high degree of environmental impact variability between plants due to the complex nature of geothermal reservoirs [8]. To address the uncertainty around life cycle analysis, there has been a move to more statistical methods of LCA in which distributions of inputs to the life cycle model are assessed with a Monte-Carlo approach [9, 10]. Recently this has been applied to a dry steam flash geothermal plant [11]. The coupling of an uncertainty analysis of life cycle inputs with a thermodynamic model of the process to assess the potential distribution of multiple environmental impacts allows for a much stronger basis of comparison for competing renewable or traditional energy production plants. In this work, this robust set of methods are applied to a modern binary cycle power plant.

A recent plant in northern Nevada (Blue Mountain) was selected as a case study. The facility provides a modern system for study and it is situated in a region of promising future geothermal energy development. When this study was performed, the Blue Mountain geothermal power plant had recently gone through start up. The production wells for Blue Mountain have had considerable decline since that point [12, 13]. The results of this paper assumes that the case study is able to maintain nameplate capacity. Blue Mountain was expected to far exceed nameplate capacity after start up [14]. The changing expectations over time demonstrate the uncertain nature of geothermal power production. Nevada has the second largest geothermal potential in the United States, which could provide 60% of the state's electricity by 2015 (1,488MW) [15]. This potential geothermal expansion could meet the energy needs of almost two million homes in Nevada. Currently, Nevada has over 21 power plants, with a capacity of approximately 484 MW of geothermal power [15].

As an extension of this case study, the life cycle of transportation vehicles making use of geothermal energy was analyzed. Transportation is another area under intense investigation for renewable fuels, but it is unique in that the fuels considered have many more constrains placed upon them such as high energy density, easy refueling, and stability in an impact event. Electric vehicles, however, are source agnostic, and can be fueled with any electricity generating renewable resource. We compare the environmental impact of an electric vehicle running on power provided via the plant in the case study with some other common vehicle fuel types and proposed renewable vehicle systems. To do this, we use the GREET model [16]. It is a life cycle assessment tool for vehicles, and provides a detailed model for both traditional and advanced transportation technologies.

2. Methods

2.1. LCA Methodology

The analysis framework used is based on traditional guidelines of LCA practice given by the International Organization for Standardization (ISO) through the standards ISO 14040:2006 and ISO 14044:2006. The proposed LCA framework used includes:

1. definition of scope, objectives, functional units, and system boundaries,
2. life-cycle inventory analysis including data collection, qualitative and quantitative description of unit processes, calculation procedures, data validation, and sensitivity analysis,
3. life-cycle impact analysis including impact category definitions, classification and characterization of impact categories, valuation/weighting of impact categories, and
4. interpretation and conclusions including identification of significant environmental issues, evaluation and recommendations.

2.1.1. Scope and Inventory

A complete geothermal system includes three primary stages: (a) exploration and drilling, (b) power production, and (c) post-production recovery. These primary stages undergo their own separate life cycle analysis; the impacts and emissions of which are summed together to get a complete cradle-to-grave analysis of the process. The first stage system, (a) exploration and drilling, is shown in Figure 1. Flow quantities and other parameters are given in Table 1.

Description	Quantity	Unit	Stage
Diesel Fuel	5680	L	Exploration
Trucks	2	t	Exploration
Diesel Fuel	37.9	L/m	Test Drilling
Drilling Fluid	11.4	L/m	Test Drilling
Concrete	5	kg/m	Test Drilling
Drilling Bore (fabricated steel)	7	kg/m	Test Drilling
Trucks	8	t	Production Drilling
Diesel Fuel	75.7	L/m	Production Drilling
Drilling Fluid	22.7	L/m	Production Drilling
Concrete	25	kg/m	Production Drilling
Drilling Bore and Casing (fabricated steel)	13	kg/m	Production Drilling

Table 1: Exploration and drilling stage flows into the system boundary inventory items. Values per meter drilling are from [17]. Data specific to Blue Mountain plant via [18, 19]. Exploration data derived from relative cost of exploration drill verses production drilling via [4].

Figure 1 shows the system boundary and the primary processes involved in this stage. This stage is further divided into sections: exploration, test drilling and production drilling. The exploration unit in this work is limited to site exploration and study using trucks on unimproved roads. This work does not include the many other aspects that can be associated with exploration, such as aerial surveys or other geological exploration as those are highly dependent on geography and site history. The test drilling section contains the drilling of multiple test wells in order to determine the viability of a geothermal field and where to best place the production wells. The test drilling section includes the flows involved in transport, the actual drilling, and the casing required to prevent geothermal water from entering the water table. Finally, production drilling section contains the drilling of full size production wells with similar flows as those associated with test drilling. The system boundary also separates processes that are independent of geothermal energy production. For instance, this analysis does not extend to the manufacturing of the tools and equipment needed to produce the facility. These components have their own life-cycles and are well studied outside of this work, which includes the environmental costs of these pieces of equipment that are required for the construction and operation of the facility from external studies. This work also only focuses on major materials flows, such as diesel fuel and drilling fluid, or concrete and steel for construction.

To be able to quickly compare design alternatives and the act of drilling is the largest source of emissions, we select meters drilled as the unit of production to which all environmental impacts are put in terms of. This unit allows rapid evaluation of the environmental impact that would be required for developing a geothermal site.

The second stage of operation, (b) power production, is shown in Figure 2. Many of the modules are similar for this stage as the first stage, because the impacts of modules such as transportation are universal, the major difference will be in the quantity used. The infrastructure module encompasses the process of building the power production facility which for this work include the production and

Description	Quantity	Unit	Stage
Diesel Fuel	37855	L	Infrastructure
Trucks	15	t	Infrastructure
Concrete	750	kg/MW	Infrastructure
Piping, Structure and Unit Operations (fabricated steel)	900	kg/MW	Infrastructure
Heat Exchanger (fabricated aluminium)	350	kg/MW	Infrastructure
Diesel Fuel	18927	L/year	Startup and steady-state production
Trucks	3	t/year	Startup and steady-state production

Table 2: Power production stage flows into the system boundary inventory items. Values per MW scaled from material values provided via [20]. Data specific to Blue Mountain plant via [18, 19].

transportation of the unit operations to the site, and the use of construction equipment. Power production and start-up production are defined differently because many plants will not immediately go to their installed capacity. For the purpose of this work, however, it was assumed that the plant will not start up in stages.

The third stage of operation, (c) post-production recovery, does not have a defined functional unit. It is instead meant to separate the recovery stage from the production stage to minimize allocation assumptions. This stage consists of transportation of the dismantled facility to disposal and recycling sites, and sealing the wells.

2.1.2. Environmental Impact Definitions

To define and assess impacts, the EPA provides TRACI: Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts [21]. TRACI is a program for computing a number of environmental impacts and will serve as the basis for analyzing the effect geothermal energy production has on the environment in several categories. The categories of importance were determined as follows:

- Global warming: This indicator can be determined by summing the mass flows of all emissions by their respective global warming potential. Geothermal energy has several sources of global warming emissions including non-condensable gases that escape from the well, leaked secondary fluid and burning fossil fuels for transportation and drilling operations [22].
- Acidification: This indicator can be determined by summing the mass flows of all the emissions by their respective acidification potentials. Acidification from geothermal energy production comes largely from escaped H_2S gas and from burned fossil fuels during plant construction [23].
- Ecotoxicity: Leaked geothermal gases, and drilling fluid are the primary contributors to this category [24].
- Human Toxicity: Using the DALY index [25]. Similar to ecotoxicity, this measures lost human health in terms of man-hours from exposure to toxic substances released by the process of building or operating a geothermal power facility. In this work, the primary pollutants effecting human health are lead, SO_2, H_2S, and NO_x.
- Fossil Fuel Depletion: Fossil fuel is consumed during transportation and drilling operations. This metric will allow useful comparison to traditional power generation methods. Depletion is calculated on an energy use basis [21]

Many of these impacts are a function of varying parameters such as well fluid composition, drilling time, and geothermal well life. These can be estimated, but have large uncertainties before beginning energy extraction and continue to have non-negligible variability thereafter. Assessing impacts with these variations in input cannot simply be approximated with averages for they have non-linear relationships with one another. In this work, variation in process inputs is handled using a Monte-Carlo approach. A program for simulating the impact of a geothermal power facility using static input parameters was written using FORTRAN 90; which will be described in more detail in the next section. This simulation was run iteratively making use of a random selection for those static inputs from a distribution of values from existing well data and plant life statistics.

2.2. *Case Study: Blue Mountain, Nevada*

Blue Mountain “Faulkner 1” geothermal power project is located in Humboldt County, Nevada. The property covers 44.5 square km and it is 34 km from the state electrical transmission grid. The electricity generation capacity of the geothermal power project is 49.5 MW. Blue Mountain “Faulkner 1” geothermal power plant has been in service since 2009, with the 20-year power purchase agreement with NV Energy [15].

Blue Mountain “Faulkner 1” project is a binary cycle power plant, which is shown in Figure 3. The hot brine is extracted from the geothermal reservoir through six production wells (Figure 4). The flow rate from each production well is about 9,500 liters per min. The temperature and pressure of the brine at well heads are between 182-188°C and 11-12 bar respectively [18]. The brine heat is transferred using a heat-exchanger with isopentane, which acts as a secondary fluid. The cooled brine exits the heat exchanger about 16°C. It is then re-injected through rejection wells to recharge the reservoir. In the heat exchanger, isopentane is vaporized and used to drive a turbine to produce electricity. Out of the turbine, isopentane is cooled and condensed by cooling water and then pumped back to the vaporizing heat exchanger. The temperature of cooling water is maintained by a air cooling tower near ambient temperature conditions [15]. For the binary cycle, geothermal fluids and the working fluid are not directly exposed to the atmosphere, but venting and leakage are estimated [26] at approximately 1% of the volume cycling per year. The vented gases are then evaluated for their respective environmental impacts. The TRACI impact factors were obtained from a dataset provided by the EPA [21] and can be seen in Table 4.

The binary cycle is simulated by first determining the fluid properties of the working fluid isopentane at the saturation conditions found in the boiler and the condenser. The saturation points were determined using the following vapor-pressure equation [27]:

$$\ln\left(\frac{p_s}{p_c}\right) = \frac{T_c}{T}(n_1\nu^{\theta_1} + n_2\nu^{\theta_2} + n_3\nu^{\theta_3} + n_4\nu^{\theta_4}) \text{ where } \nu = 1 - \frac{T}{T_c} \tag{1}$$

With p_s begin the saturation vapor pressure and T_c and p_c being the critical temperature and pressure of isopentane respectively. The enthalpy (H_1) and entropy (S_1) of the isopentane gas in the boiler is determined by using Peng-Robinson departure functions from the ideal gas enthalpy and entropy as determined by the Shomate equation. Next, the condition of the gas is determined by finding the isoentropic point at the condenser pressure by simultaneously solving the Peng-Robinson equation of state and the entropy departure function for the temperature and density of the fluid. The algorithm for simultaneous solution of these two equations is the Powell hybrid method as implimented in MINPACK [28]. The enthalpy (H_{2s}) is then calculated at this condition and corrected to the real enthalpy (H_2) by adjustment with the turbine efficiency via the following equation:

$$H_2 = H_1 - \eta_{turbine}(H_1 - H_{2s}) \tag{2}$$

where $\eta_{turbine}$ is the turbine efficiency. The turbine efficiency is assumed to be fixed at 85% for the purposes of this paper. The vapor and liquid enthalpies and entropies can then be evaluated at the saturated condenser condition (H_3 and S_3 for vapor and H_4 and S_4 for liquid). The liquid is then pumped back up to pressure for reintroduction into the boiler. The isentropic pump enthalpy is given in the following equation:

$$H_{5s} = H_4 + \frac{p_5 - p_4}{\rho_4} \tag{3}$$

where ρ_4 is the saturated liquid density and p_5 and p_4 are the boiler and condenser pressures respectively. The isentropric enthalpy rise is then corrected with the pump efficiency which is assumed to be a static 75%:

$$H_{5s} = H_4 + \frac{(H_{5s} - H_4)}{\eta_{pump}} \tag{4}$$

The work of the turbine (w_t) can be found by $H_2 - H_1$ and work of the pump (w_p) can be found by $H_5 - H_4$. Net power output from the cycle can be given as $\dot{m}_{wf}(w_t + w_p)$ where $\dot{m}_{wf}$ is the mass flow of the working fluid. Emissions from the binary cycle operation are scaled to the process power output.

A distribution of potential inputs is considered for this model using well test data [29] and construction reports [20, 19] for various geothermal projects that are scaled for this case study. The general procedure for determining the distribution of environmental impacts is shown in Figure 5, with inputs coming from a distribution of variables located in Table 3. The sizing of components and thermodynamic efficiency depends on the randomly selected conditions, and the resulting impacts depend on those sizings as well as the geochemistry.

For each sample in the Monte Carlo simulation, the inputs variables were first generated using the random number function built into FORTRAN90 and then scaled to fit a normal distribution. The thermodynamic efficiency of the process was then determined using the procedure described above and the equipment was size was scaled to match the required power output for the thermodynamic efficiency. The calculated flows and their composition then could be used to assess the environmental impact parameters for that given set of inputs. The simulation was run for 10,000 samples to generate the distributions of environmental impact

251 results.

Variable	average	standard deviation	distribution type
Brine Temp	167°C	7°C	normal
Operational Life	30 years	5 years	normal
Diesel Use Multiplier	1.0	0.1	normal
Mass percent NCG	3.0	0.7	normal
Fugitive emission percentage	1.0	0.4	normal
Average ambient T	20°C	3°C	random
Fraction CH_4 in NCG	0.06	0.02	normal
Fraction H_2S in NCG	0.09	0.03	normal
Fraction CO_2 in NCG	0.6	0.2	normal

Table 3: Input distributions for the stochastic simulation. Data is derived from [20, 4, 18, 19] and [17] for the facility components and [29] for the NCG distributions.

Compounds	Acidification	Global Warming	Cancer	Human Tox
CO_2	-	1	-	-
NOX	40.04	-	-	-
PM10	-	-	-	-
SO_2	50.79	-	7.42×10^{-4}	1.24×10^{-3}
Lead	-	-	3.55×10^{1}	1.50×10^{6}
H_2S	58.6	-	5.07×10^{-2}	2.33×10^{1}
CH_4	-	23.0	-	-

Table 4: Well content emission inventory and their respective weights (impact per kg) [21]

3. Model Results and Analysis of Impacts

3.1. Acidification

Geothermal power acidification impacts come largely from a mix of SO_2 and NO_X releases from materials construction and the burning of fossil fuels to power drilling and transportation as well as H_2S releases from the geothermal well itself. Figure 6 shows the distribution of acidic impacts resulting from the studied facility over its lifetime.

3.2. Fossil Fuel Use

Fossil fuel depletion from geothermal power generation stems from the manufacture of required facility components as well as from transportation and well drilling fuel use. Nothing inherent in geothermal energy extraction requires the use of fossil fuels, however, fossil fuels are still economically favorable and will play a role in the development of infrastructure. Figure 7 shows the distribution of fossil fuel impacts arrived at from the simulation. This shows a fairly broad distribution owing mostly to transportation and drilling operations with uncertainties in both.

3.3. Global Warming

Geothermal power contributes to global warming from the burning of fossil fuels for transportation and drilling, the mining and refining of materials such as steel and concrete for the construction of the facility, and the release of gases such as CO_2 and methane from the geothermal well both during drilling and production via fugative emissions. Figure 8 shows the probability distribution of global warming impacts for the case study. This distribution is very small due to the high certainty in the construction material impacts. The small variation is due to the distribution of fossil fuel use, and fugitive emissions from the geothermal well.

3.4. Human Health

Particulate releases from fuel combustion and dispersion from transportation cause respiratory and cancer concerns. Diesel use for drilling the well and transportation produce SO_2 and particulate which influence the human health impact. A small contribution from the H_2S from the NGC in the geothermal fluid also influences the human health result. Heavy metals escape from material refinement and from geothermal fluids, which also pose a risk to human health as they make it into the atmosphere or the water table. Heavy metal in the form of lead is assumed to escape the wellcasing at a low rate into the water table and the amount of lead that is emitted is a function of the brine flow rate. The risk of human health impacts are shown in Figure 9. The distribution of human health impacts is very small, with a high density around zero impact.

3.5. Ecotoxicity

Similar to human health impacts, ecotoxcity consists of heavy metal releases to the environment that can cause damage to organisms. The largest contributor to geothermal energy extraction's ecotoxicity impact is mercury stemming from steel and aluminum extraction and refining. Figure 10 shows the distribution of ecotoxicity impacts for the plant of interest. This distribution is similar in content to the human health impacts, but more material from construction is involved in this impact.

3.6. Water Consumption

Water consumption is projected from 189,270 L/day during drilling operations, and evaporative cooling can use up to 3,410 L/hour depending on the ambient temperature and humidity [19].

3.7. Overall Impact Effects from Input Variability

Inputs to the simulation such as brine temperature, mass percent NCG, and ambient temperature impact the thermodynamic efficiency of the cycle and amplify the results for multiple catagories. Increases in the brine temperature or decreases in the mass percent NGC or ambient temperature will increase the thermodynamic efficiency of the process and reduce the environmental impacts on a unit energy produced basis. Operational life does not impact the thermodynamic cycle, but it spreads the enviromental impact of the construction phase across a period of useful power production. Increases in operational life cause a decrease in the environmental impact of the construction phase of the plant on a unit energy produced basis.

3.8. Comparison of Energy Sources

Even considering the full life cycle of geothermal energy, it is three orders of magnitude less environmentally damaging than other methods of energy extraction. Figure 11 shows orders of magnitude difference between geothermal and coal energy for the same wattage over the life times of the plants. Figure 12 shows a similar relationship between coal and geothermal for ecotoxicity and Figure 13 for acidification. Geothermal and coal both share the need for processed materials for construction, and they both require extraction of their energy sources from within the earth: coal from mines, and geothermal from hot water. Geothermal energy has the advantage of not requiring burning fuel and exhausting to the atmosphere. With brine reinjection, geothermal has very limited impact on the environment.

4. Geothermal energy as a transportation energy source

Using the results from the case study, it is possible to evaluate a life cycle of other products that employ the use of geothermal energy. Transportation vehicles are another market segment in which renewable energies are sought after, and to that end, we investigated the environmental impact of a geothermal powered electric vehicle when compared to other renewable and traditional vehicle types. To do this, the GREET model is used [16]. It offers detailed life-cycle analysis of both vehicle manufacture and fuel production. Coupling the life cycle of an electric vehicle with the results of the life cycle analysis for geothermal power, we can see the full life cycle impact for a geothermal powered vehicle. This is under the assumption that an electric vehicle will operate at 1.25 kWh/km and will last about 260,000 km on average. Distributions for this vehicle can be seen in Figures 14 and 15 for green house gas and acidification potential respectively over the lifetime of the vehicle.

Most interesting is the comparison between different vehicles. Figure 16 shows the amount of green house gases released for a variety of different vehicles. Geothermal produces an exceptionally low amount of green house gases due to the relatively minor amount of combustion and geothermal fluid leaks compared with other transportation fuels. For other emissions, Figure 17 compares CO, NO_x, and SO_x for the same vehicle types. Those that rely on internal combustion produce a large amount of carbon monoxide from incomplete combustion. The electric vehicle which runs on a standard electric mix involves combustion, but large scale power plants are much more efficient with the use of their fuels, and do not produce nearly the same level of carbon monoxide; however, since coal power contributes, there is much higher releases of SO_x when compared to other methods. SO_x is also fairly high for geothermal. This is due in part to geothermal fluid releases of sulfur containing acids such as H_2SO_4 and H_2S, and also because of the diesel fueled drills which emit higher sulfur content than other fossil fuels in the comparison. NO_x emissions are also very low for geothermal power because of the near lack of combustion.

What components of the life cycle are major contributors can also be investigated. Figure 18 shows a breakdown of the emissions for the various life cycle aspects of the electric vehicle. At the bottom of the bars are the contributions from the geothermal power generation which are very small relative to the manufacture of the vehicle.

5. Conclusions and Future Work

Geothermal energy is an environmentally sound source of power generation. It has one of the lowest environmental impacts of current existing energy generation technologies due to its minimal construction and maintenance resource requirements. It compares very well to traditional fossil fuel based sources of power despite its low temperature source. While it has a lower thermal efficiency, it is still many orders of magnitude less environmentally harmful than coal by nearly all measures. Coupled with an electric vehicle, it also proves to be one of the most environmentally clean energy sources when compared to competing technologies. The results show that geothermal is an environmentally friendly way to produce energy for transportation use.

Even viewed in the light of uncertain inputs, geothermal energy produced via binary cycle has few inherent emissions. Amongst largest sources of emissions is fossil fuel use in the transportation of people and equipment to the site and from drilling, all of which can be mitigated by electrification. Since the direct emissions from a closed loop cycle are limited, items such as the thermodynamic efficiency of the process and operational life of the plant become dominant in the variation of the environmental impacts for a plant's full life cycle. Better understanding of the geothermal reservoir in terms of long term stability of the heat flux and variation in composition of the geothermal fluid can greatly reduce the uncertainty of the life cycle impact of a geothermal plant.

Geothermal power is currently limited to naturally occurring hydrothermal reservoirs which are sparse relative to modern energy demands. There are methods under investigation to mitigate this limitation, including engineering a man-made reservoir via a process similar to the "fracking" operations done for natural gas extraction. These systems show promise; however, their life cycle is not studied, and interesting problems arise out of potential ground water contamination and seismic activity from the engineering of the reservoir. By considering these additional facets, the life cycle analysis method presented in this work can be greatly expanded for future geothermal technology. In a future work, these enhanced geothermal plants could be compared to traditional plants using the method presented in this work.

In the future, this work could be applied to other systems in which uncertain or highly variable inputs impact emissions in a non-linear fashion to forecast impact or compare environmental risk between multiple options. By applying the life cycle analysis presented in this work to other energy sources, a much deeper comparison can be made between competing technologies. In addition, adding a cost component to this life cycle method would allow for a cost-benefit analysis between different power production facilities that could provide powerful insight for decisions regarding energy investment.

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Figure Captions

Figure 1: Exploration and drilling unit. This stage results in drilled wells. Transportation of human resources and drilling make up the bulk of this stage with fuel being the primary elementary flow input and trucks and drilling machinery making up the process equipment input.

Figure 2: Power production unit. This stage consists of the operational life of the plant and emissions are measured per unit power delivered. Transportation, construction, maintenance and geothermal fluid release are the primary cause of emissions.

Figure 3: Flow diagram for a binary cycle geothermal power plant.

Figure 4: Extraction wells for the Blue Mountain Area "Faulkner"

Figure 5: The general process for evaluating the distribution of environmental impacts for a geothermal energy production facility.

Figure 6: Acidification impact distribution for the Blue Mountain plant

Figure 7: Fossil fuel use distribution for the Blue Mountain plant

Figure 8: Global warming impact distribution for the Blue Mountain plant

Figure 9: Human health impact distribution for the Blue Mountain plant

Figure 10: Ecotoxicity impact distribution for the Blue Mountain plant

Figure 11: Global warming impact comparison between geothermal and coal.

Figure 12: Ecotoxicity impact comparison between geothermal and coal.

Figure 13: Acidification impact comparison between geothermal and coal.

Figure 14: Distribution of house gas emissions from a geothermal powered vehicle over the vehicle life time.

Figure 15: Distribution of acid producing emissions from a geothermal powered vehicle over the vehicle life time.

Figure 16: Comparison of green house gas emissions for different vehicle types. LNGV stands for liquified natural gas, E85 is an 85% mixture of ethanol and gasoline, HEV is a hybrid electric vehicle and FCV H2 is a fuel cell vehicle that runs on hydrogen gas. Electric vehicle in this is case is the same vehicle as in the geothermal column, but it uses a standard mix of electricity common in the US (coal, natural gas, nuclear, etc.)

Figure 17: Comparison of CO, NO_x, and SO_x for various vehicle types. See Figure 16 for label definitions.

Figure 18: A break down of the various contributions to the total amounts of green house gases, CO, NO_x, and SO_x emissions for a vehicle over its lifetime.

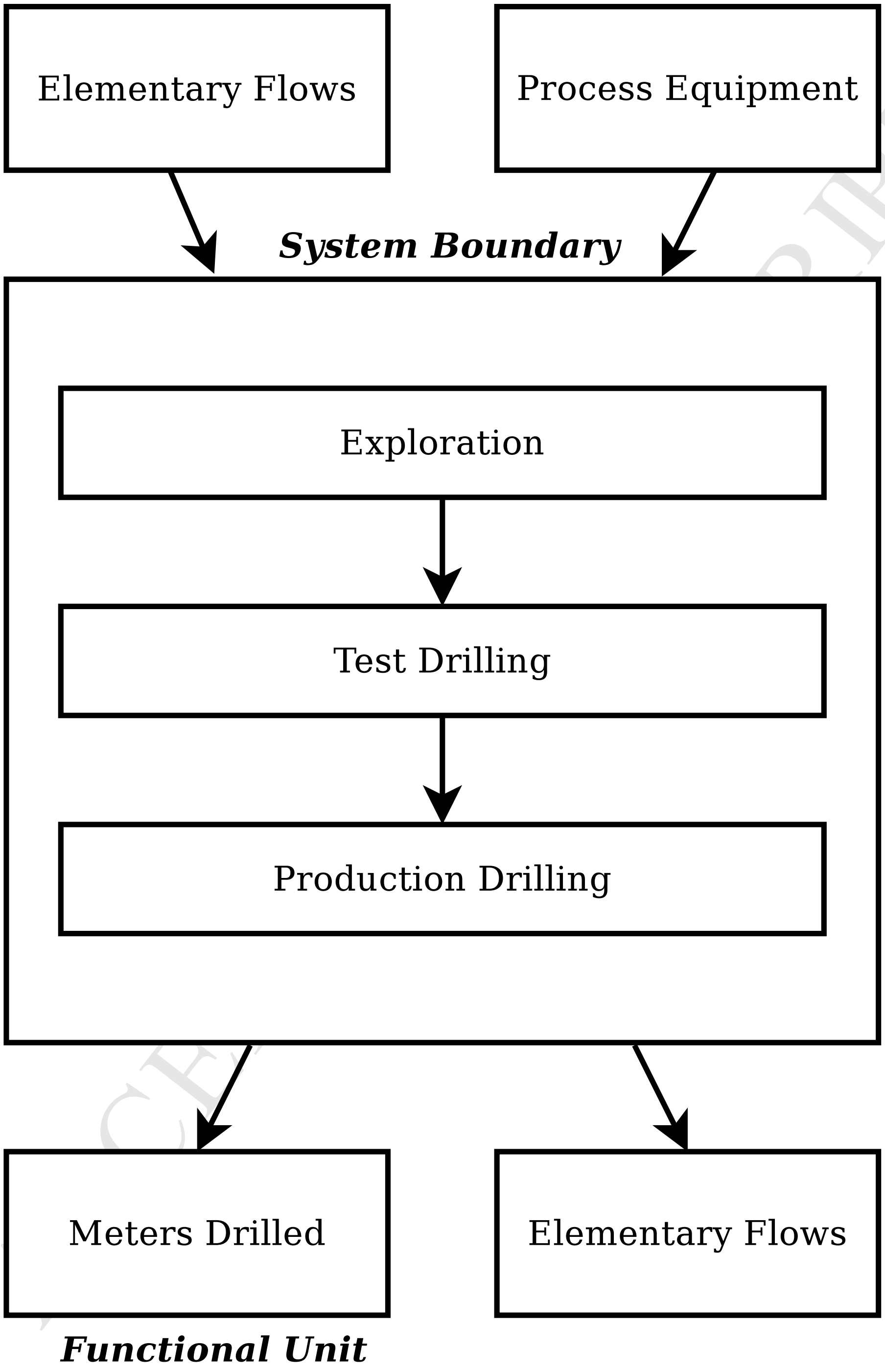

Elementary Flows
Process Equipment
System Boundary
Exploration
Test Drilling
Production Drilling
Meters Drilled
Elementary Flows
Functional Unit

Figure 1:

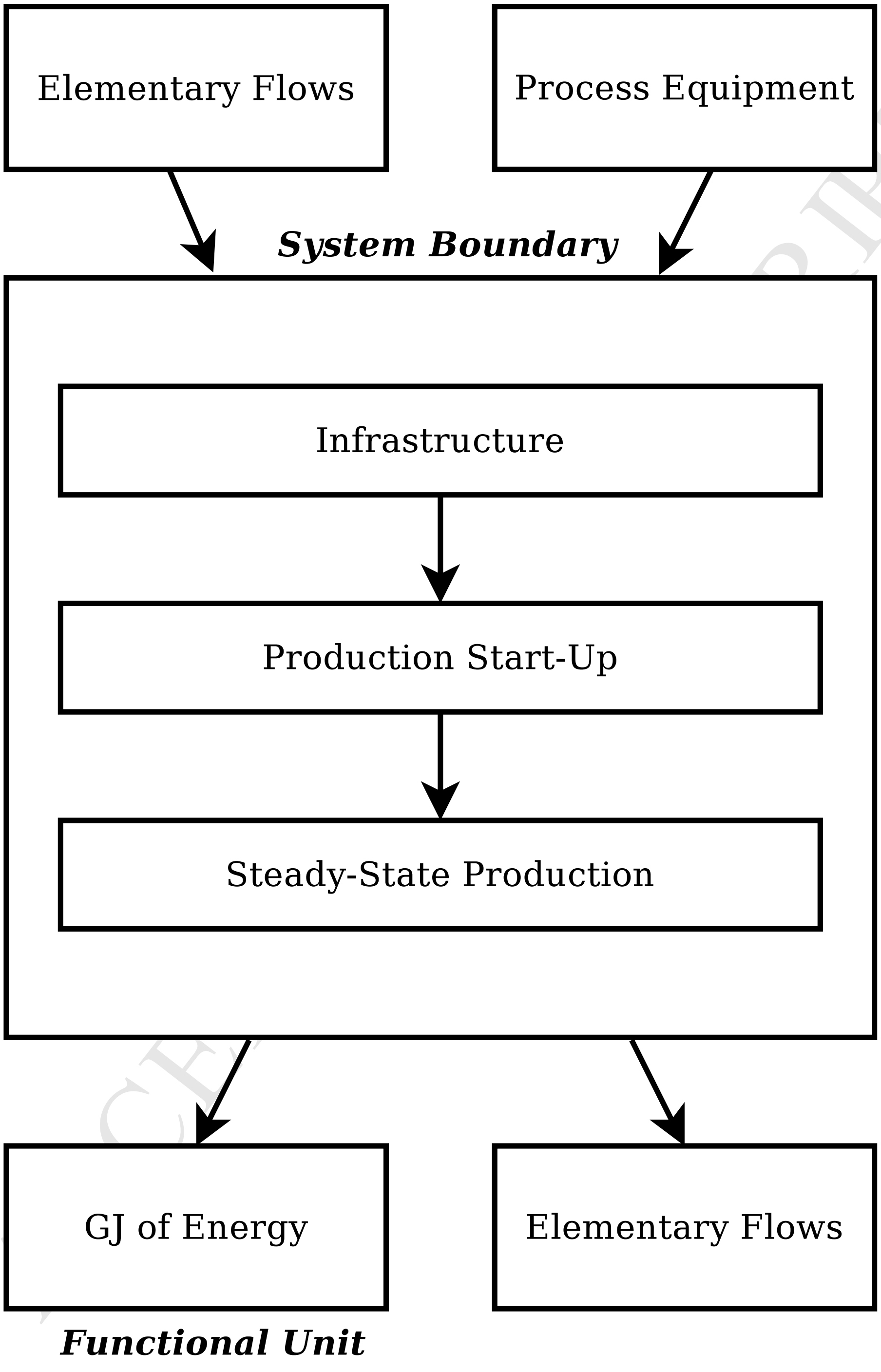

Elementary Flows
Process Equipment
System Boundary
Infrastructure
Production Start-Up
Steady-State Production
GJ of Energy
Elementary Flows
Functional Unit

Figure 2:

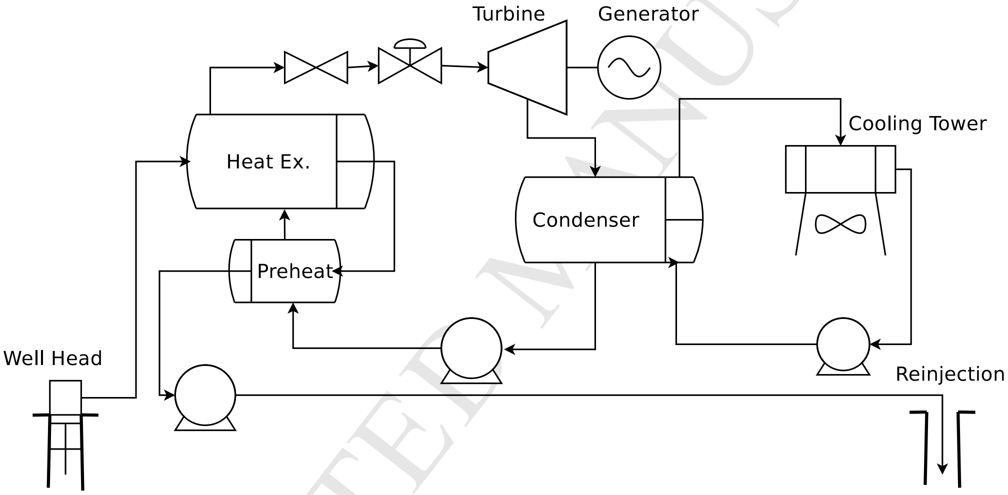

Turbine
Generator
Heat Ex.
Cooling Tower
Condenser
Preheat
Well Head
Reinjection

Figure 3:

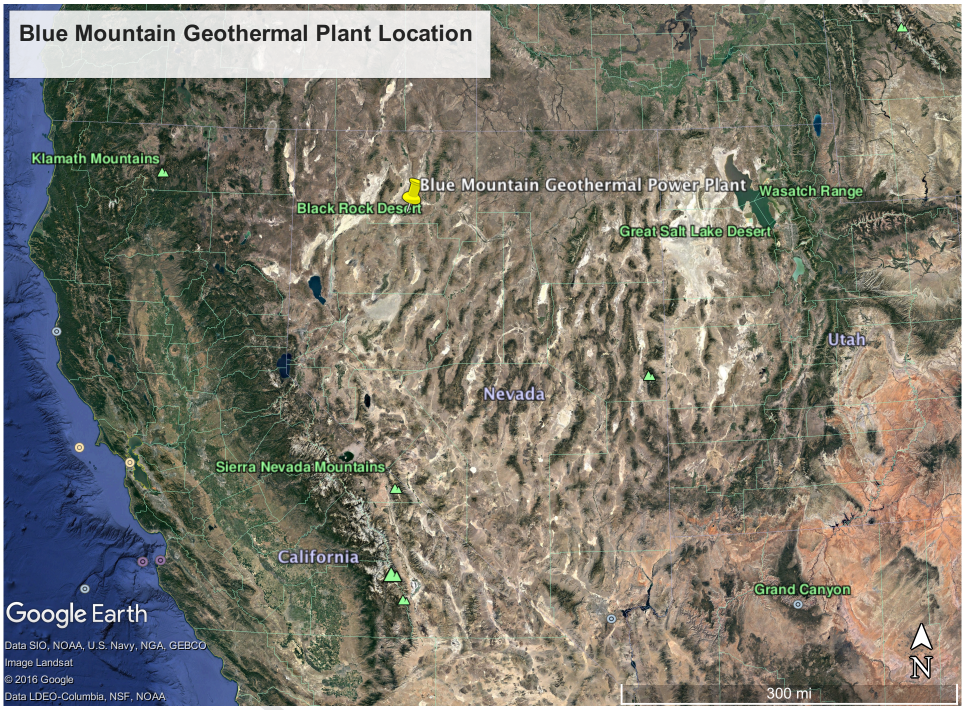

Blue Mountain Geothermal Plant Location
Klamath Mountains
Blue Mountain Geothermal Power Plant
Black Rock Desert
Wasatch Range
Great Salt Lake Desert
Utah
Nevada
Sierra Nevada Mountains
California
Grand Canyon
Google Earth
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
© 2016 Google
Data LDEO-Columbia, NSF, NOAA
N
300 mi

Figure 4:

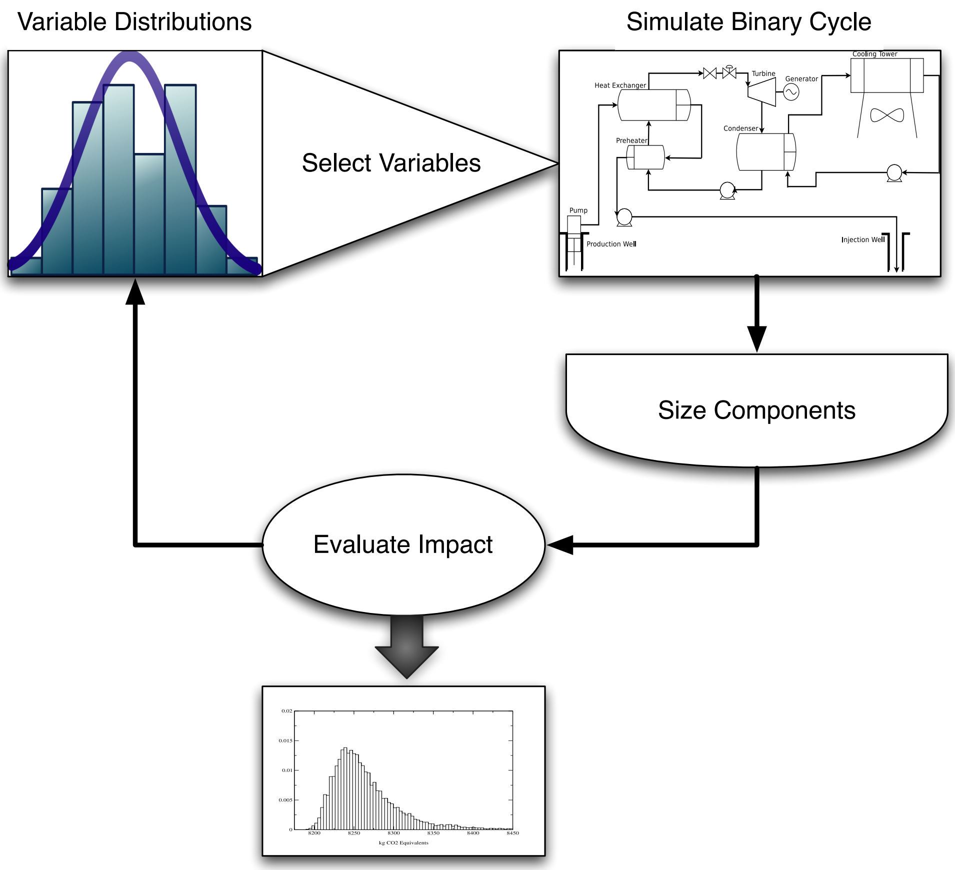

Variable Distributions
Simulate Binary Cycle
Select Variables
Heat Exchanger
Turbine
Generator
Cooling Tower
Condenser
Preheater
Pump
Production Well
Injection Well
Size Components
Evaluate Impact
0.02
0.015
0.01
0.005
0
8200
8250
8300
8350
8400
8450
kg CO2 Equivalents

Figure 5:

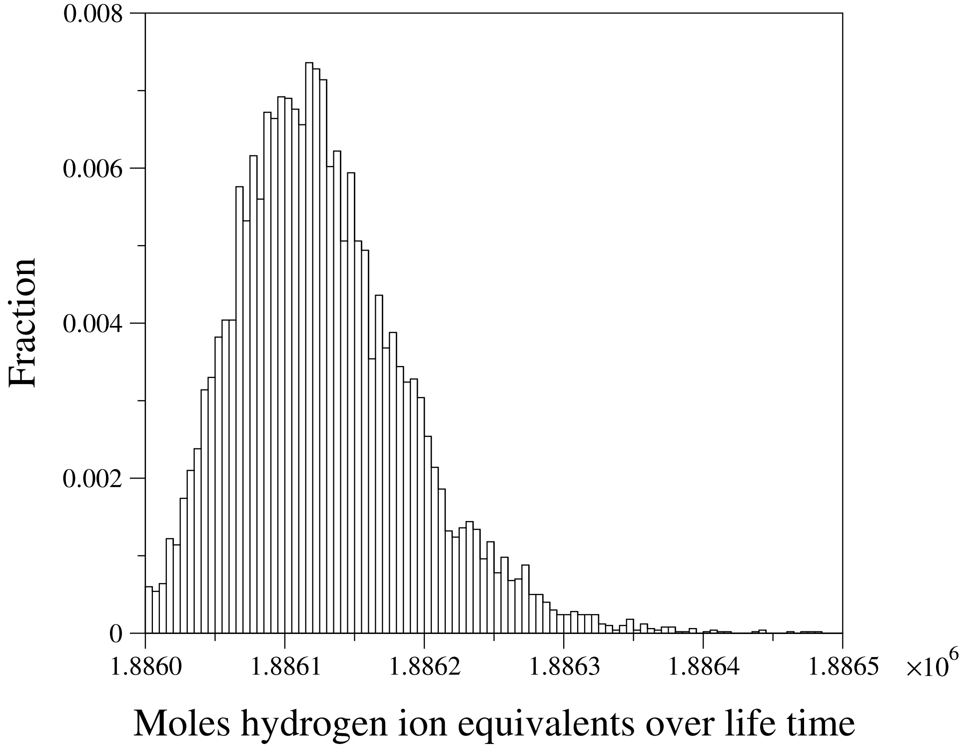

0.008
0.006
0.004
0.002
0
Fraction
1.8860
1.8861
1.8862
1.8863
1.8864
1.8865
$\times 10^6$
Moles hydrogen ion equivalents over life time

Figure 6:

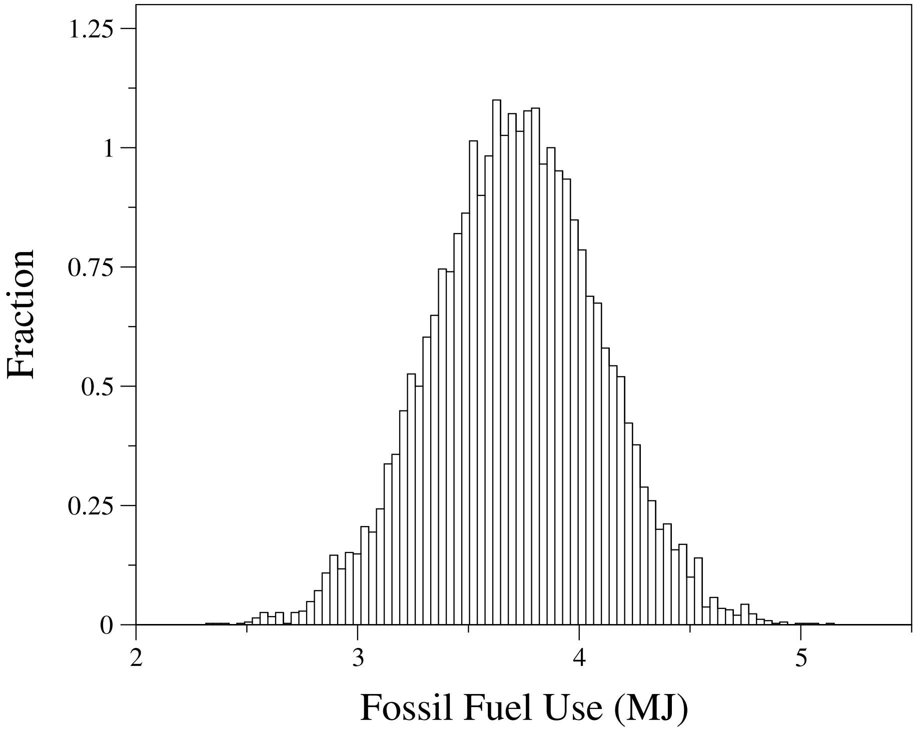


Figure 7:

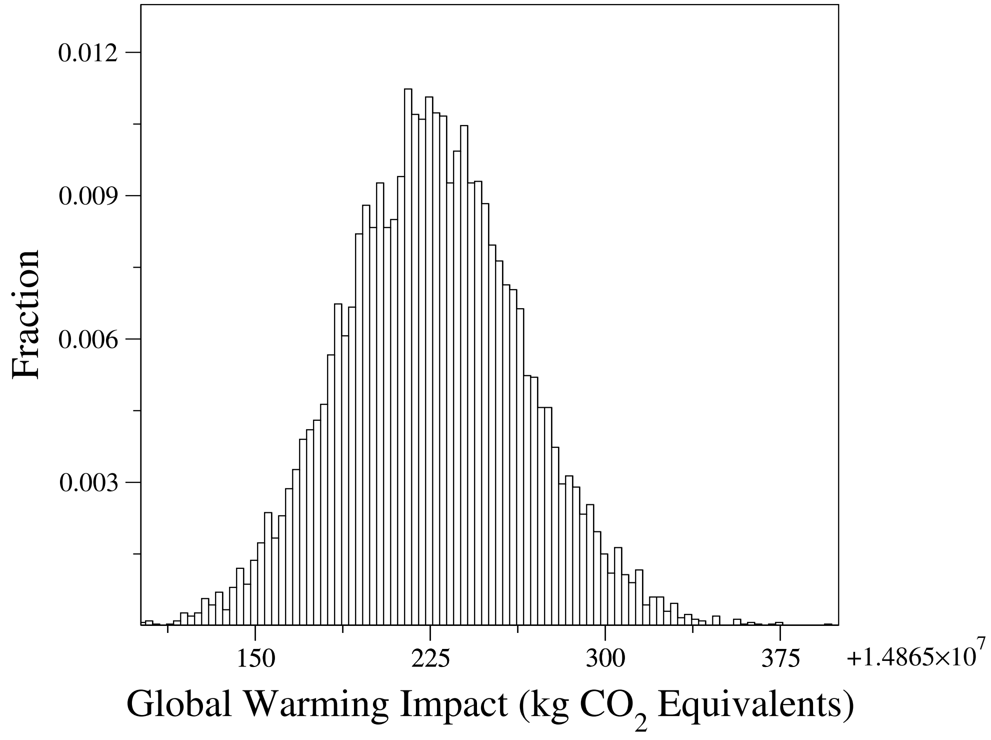

0.012
0.009
0.006
0.003
Fraction
150
225
300
375
+1.4865×10^7
Global Warming Impact (kg CO2 Equivalents)

Figure 8:

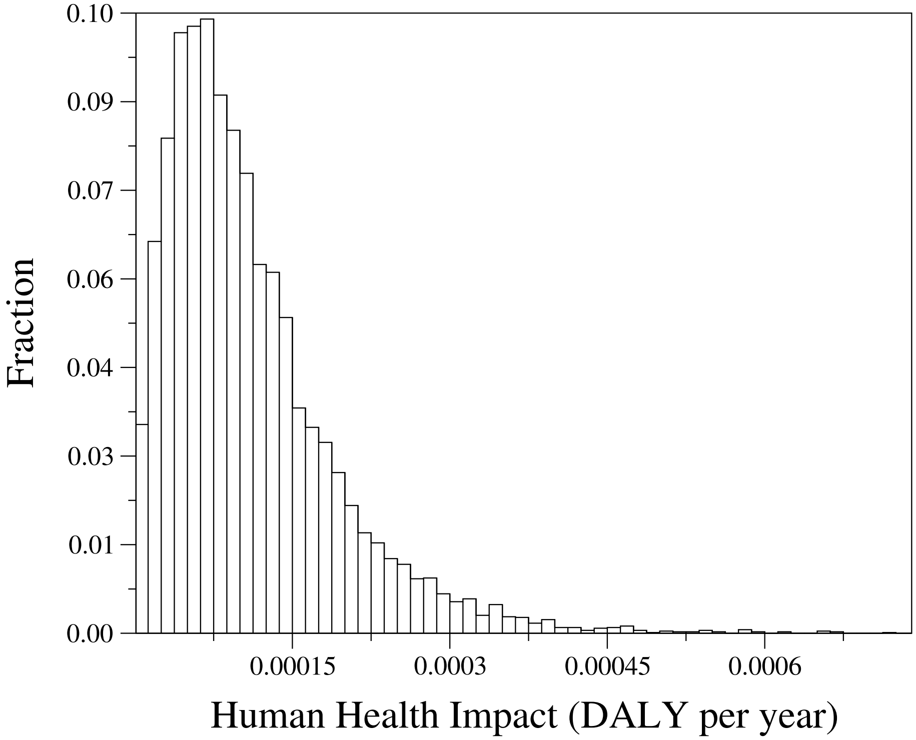

0.10
0.09
0.07
0.06
0.04
0.03
0.01
0.00
Fraction
0.00015
0.0003
0.00045
0.0006
Human Health Impact (DALY per year)

Figure 9:

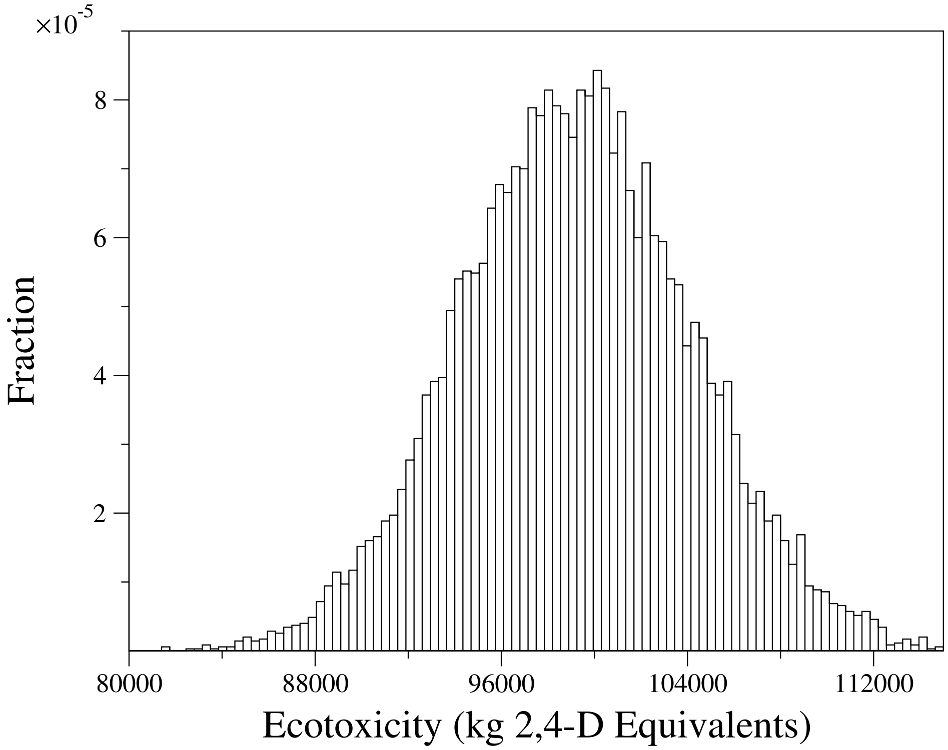

×10^{-5}
8
6
4
2
Fraction
80000
88000
96000
104000
112000
Ecotoxicity (kg 2,4-D Equivalents)

Figure 10:

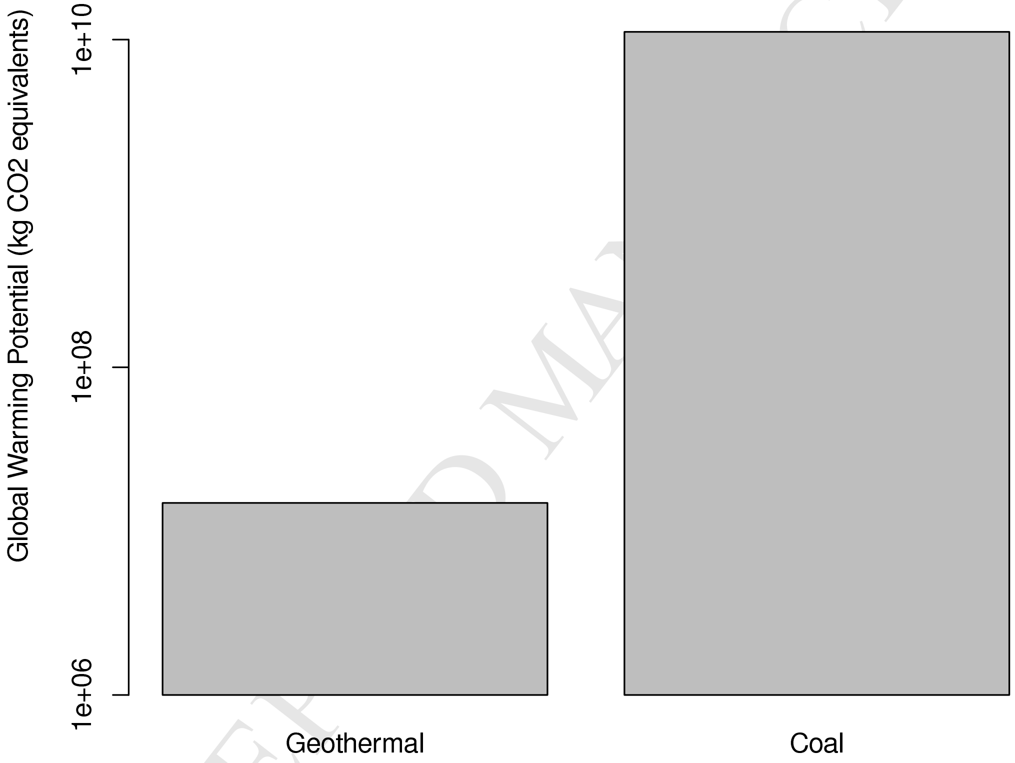

Global Warming Potential (kg CO2 equivalents)
1e+10
1e+08
1e+06
Geothermal
Coal

Figure 11:

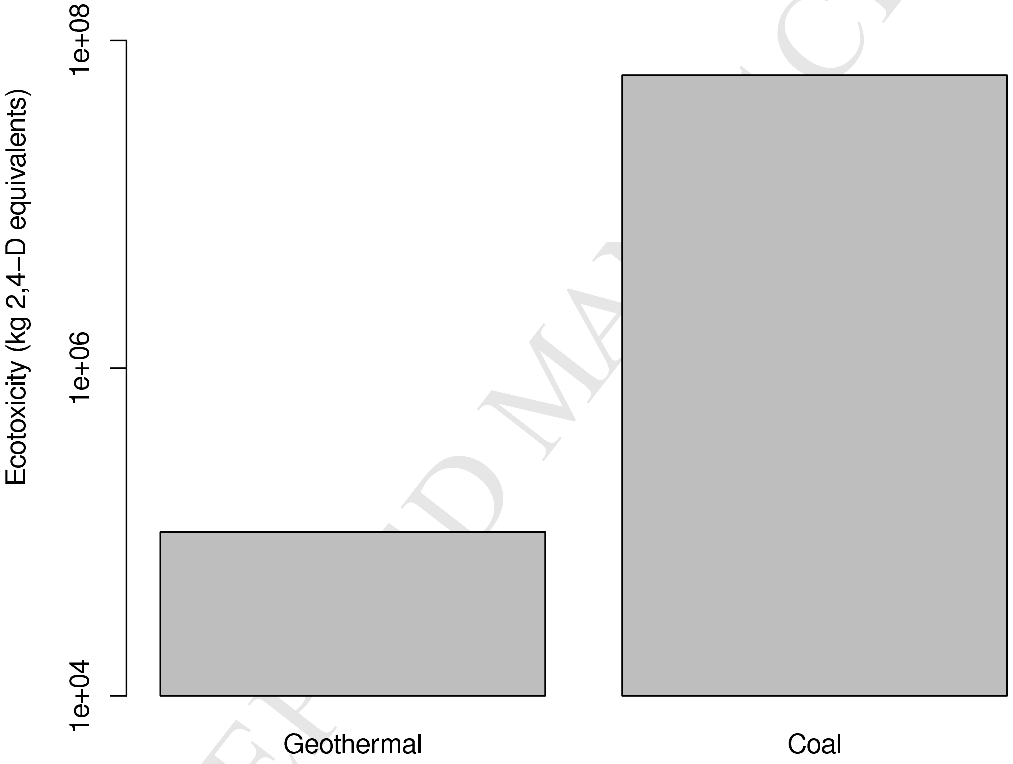

Ecotoxicity (kg 2,4−D equivalents)
1e+08
1e+06
1e+04
Geothermal
Coal

Figure 12:

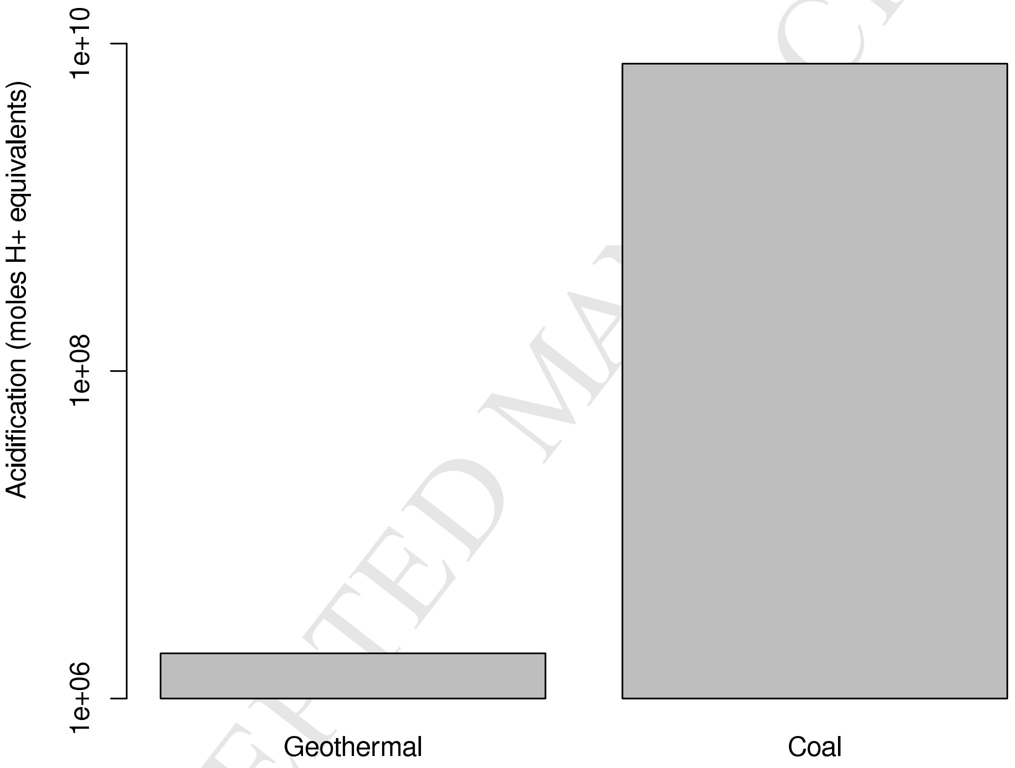

Acidification (moles H+ equivalents)
1e+10
1e+08
1e+06
Geothermal
Coal

Figure 13:

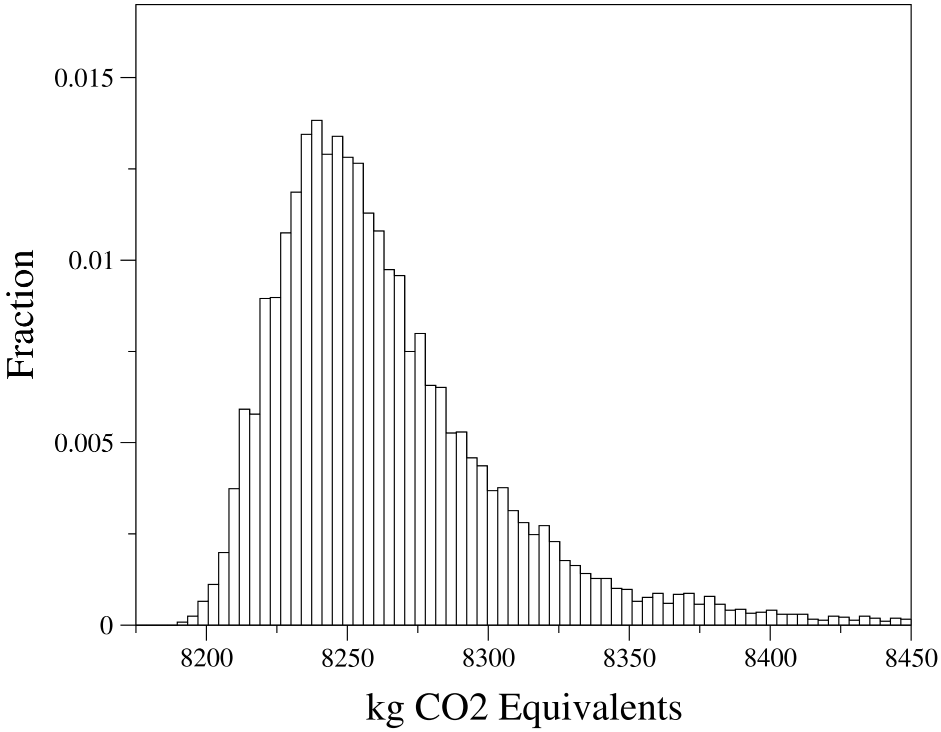
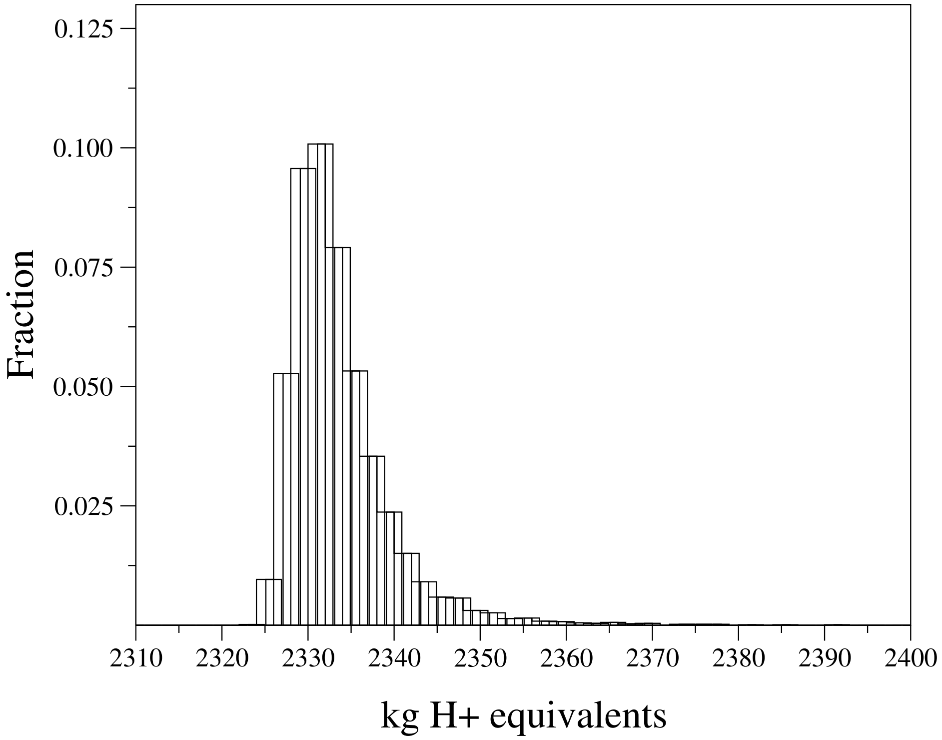

0.015
0.01
0.005
0
Fraction
8200
8250
8300
8350
8400
8450
kg CO2 Equivalents

Figure 14:



Fraction
0.125
0.100
0.075
0.050
0.025
2310
2320
2330
2340
2350
2360
2370
2380
2390
2400
kg H+ equivalents

Figure 15:

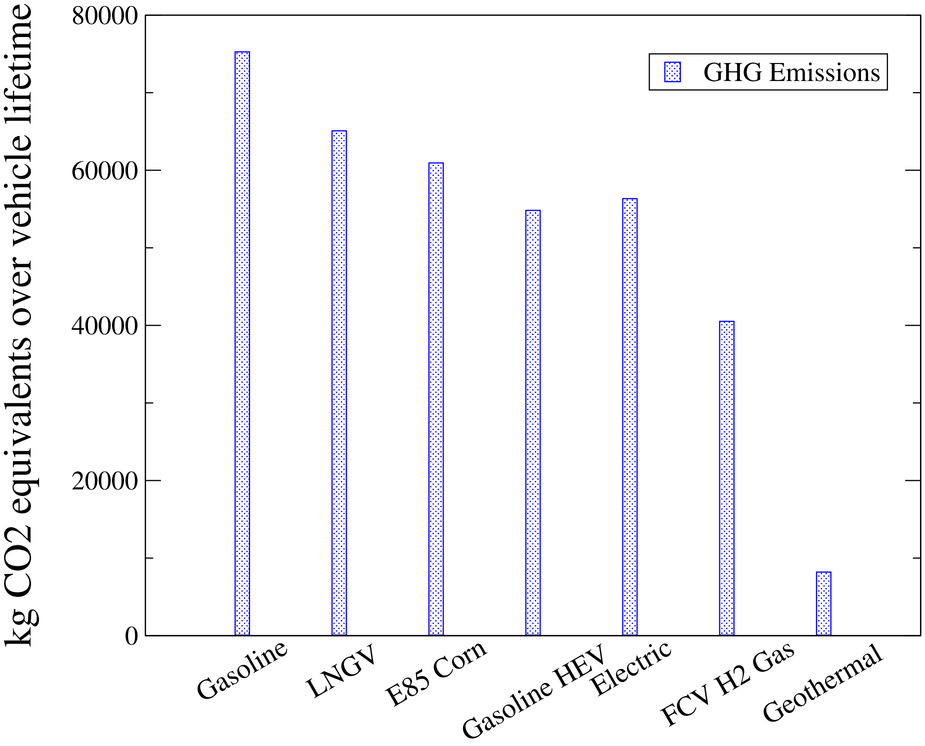

kg CO2 equivalents over vehicle lifetime
80000
60000
40000
20000
0
GHG Emissions
Gasoline
LNGV
E85 Corn
Gasoline HEV
Electric
FCV H2 Gas
Geothermal

Figure 16:

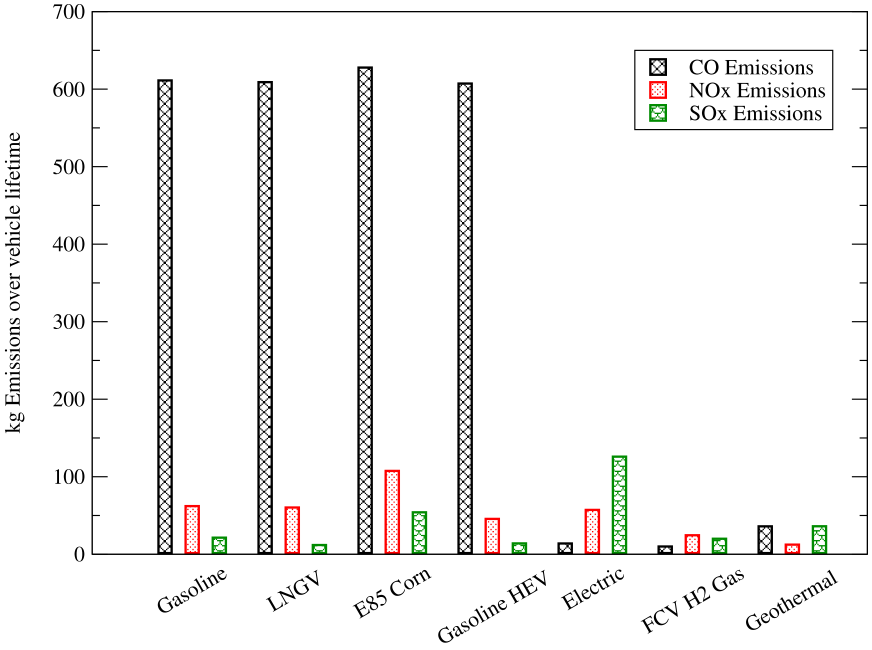

kg Emissions over vehicle lifetime
700
600
500
400
300
200
100
0
CO Emissions
NOx Emissions
SOx Emissions
Gasoline
LNGV
E85 Corn
Gasoline HEV
Electric
FCV H2 Gas
Geothermal

Figure 17:

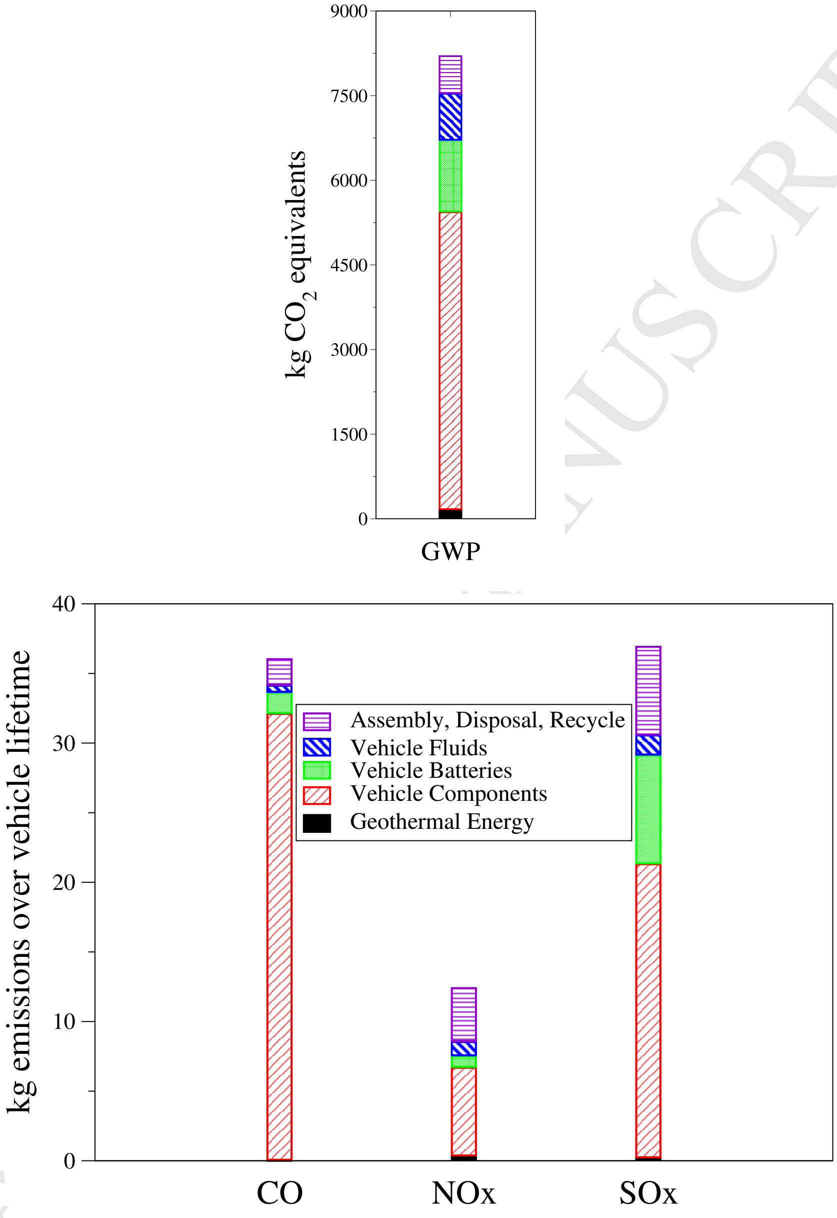

9000
7500
6000
4500
3000
1500
0
kg CO_2 equivalents
GWP
40
30
20
10
0
kg emissions over vehicle lifetime
▤ Assembly, Disposal, Recycle
▧ Vehicle Fluids
🟩 Vehicle Batteries
▨ Vehicle Components
■ Geothermal Energy
CO
NOx
SOx

Figure 18:

Research Highlights

- LCA analysis of geothermal energy as energy source for transportation
- Monte Carlo approach proposed for analysis of various environmental impacts
- Geothermal energy shows to be quite favorable as energy source for transportation from a LCA perspective.