

Life Cycle Assessment of Geothermal Sources in Kenya

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ABSTRACT

Power generation is a source of environmental pollutants globally. In Kenya, energy sources are mainly renewable. A life cycle assessment (LCA) of geothermal energy is presented for five geothermal power plants calculated using a geothermal LCA calculator developed by Argonne National Laboratory. The metrics calculated for electricity generation were greenhouse gas ratios, fossil energy, and material to power ratio (MPR). MPR values for different materials consumed were cement between 73-417 MT/MW and steel between 102-464 MT/MW. Energy input in development contributed mainly to greenhouse gas emissions of between 1.115-3.189 g/kWh. LCA in prospecting fields reduces the environmental impacts and aims at a higher drilling success rate.

1. Introduction

Geothermal energy is a baseload power source, compared to wind and solar energy, and contributes to sustainable development and a transition towards a low-carbon economy (Basosi et al., 2020; Blanc et al., 2020; Jalilinasrabady and Itoi, 2013; Pierie et al., 2016). Generally, scholars attribute global warming to fossil fuel emissions (Lijó et al., 2014). Life Cycle Assessment (LCA) investigates the environmental footprint of power plants (Parisi et al., 2019). Renewable energy impacts are lower than fossil or nuclear power plants (Hanbury and Vasquez, 2018).

Life Cycle Assessment is, according to the ISO norms (ISO 14040, 2006a; ISO 14044, 2006b), the compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system approach from cradle-to-grave (Desideri et al., 2012; Lohse, 2018; Tomasini-Montenegro et al., 2017). Life LCA is based on a system product approach of the geothermal energy sector (Lohse, 2018; Tomasini-Montenegro et al., 2017).

Dry steam has reported a global warming potential (GWP) value of 670 kg CO₂ eq/MWh (Tomasini-Montenegro et al., 2017). Flash technologies are the main techniques in geothermal power plants where two-phase fluid extracted from the reservoir is flashed in the separator once (single flash), SF, or twice (double flash), DF and or thrice (triple flash, TF). SF plants have GWP of 690 g CO₂ eq/kWh (Tomasini-Montenegro et al., 2017). The geothermal power plants

save annual CO₂ of around approximately 1, 000 million tons (Basosi et al., 2020; Desideri et al., 2012; Menberg et al., 2016). The power plant construction estimates GWP value of 74 g CO₂ eq/kWh (Tomasini-Montenegro et al., 2017). In geothermal power plants, CO₂ emissions associated with drilling and manufacturing of machinery at 64% of CO₂ for 15 g CO₂ eq/kWh (Blanc et al., 2020; Hondo, 2005).

Table 1: Nomenclature of terms applied in LCA of power plants (Sullivan, 2014).

ε_{fc}	Energy ratio of fuel cycle fossil energy input divided by E_{out}
E_{in}	Fossil energy input
E_{out}	Lifetime electricity output
ε_{pc}	Energy ratio of plant cycle fossil energy input divided by E_{out}
ε_{tot}	Energy ratio of pc + fc fossil energy input divided by E_{out}
fc	Fuel cycle
fp	Fuel production
g	Gram
GHG	Greenhouse gases
ghg_{pc}	Plant cycle GHG emissions divided by E_{out}
ghg_{fc}	Sum of fuel cycle GHG emissions from fp and fu divided by E_{out}
ghg_{tot}	Sum of fc and pc GHG emissions divided by E_{out}
REET	Greenhouse gases, regulated emissions, and energy in transportation Model
HT-F	Hydrothermal flash (and dry steam) plant
HT-B	Hydrothermal binary plant
I/P	Ratio of number of injection wells to production wells
I_well	Injection well
kWh	Kilowatt hour
MJ	Megajoule
MPR	Material to power ratio
MT	Metric ton
MW	Megawatt
pc	Plant cycle

In life cycle metrics of geothermal power plants, the key metrics are fossil energy (ε_{tot}) and ghg_{tot} . Table 1 shows the nomenclature of the metrics computed over the plant life time (Sullivan, 2014).

In this paper some single flash geothermal power plants in Kenya were studied to calculate the environmental impacts.

2. Methodology

This paper analyzes five single-flash geothermal power plants in Kenya. Table 3 shows the details of the power plants' input parameters for the LCA calculator to compute key environmental life cycle metrics. Plants' cycles are calculated from material to power ratio (MPR) for buildings and equipment, well field materials and fuel, and well exploration. For the hydrothermal SF power plants, the distance between injection and production wells specified for

the injection to production ratio (I/P) is 0.414 (Sullivan, 2014). The depths of the wells are more than 2 km. For the power plants considered, the capacity factor is 95% and the plant life is 30 years.

The important parameters in geothermal energy LCA include (Blanc et al., 2020):

- Geothermal technology (hydrothermal).
- Type of energy conversion technology (SF/DF/TF or ORC).
- Expected annual electricity/heat production or load factor (hours/year)
- Lifetime of installation/ plant cycle, pc, (years).
- Plant size (MW).
- Number of wells (production and reinjection) and depth of the wells.
- Characteristics related to the output products.

LCA analysis is usually broken down into plant cycle and fuel cycle (Sullivan, 2014).

The main input parameters into the LCA calculator are shown in Table 2. For every power plant a different number of wells are drilled, and the production wells will depend on the success rates of every geothermal field.

Table 2. Details of some single flash power plants studied.

Power plant	Capacity (MWe)	No. of wells
Olkaria I	45	24
Olkaria IV	150	21
Eburru Wellhead	2.52	3
Wellhead Olkaria	5	1
Menengai	105	22

For plant cycle, the data mainly required are for materials for computing MPR based on the net power generated. Energy ratio is calculated as the ratio of input energy (E_{in}) to energy out (E_{out}) (Sullivan, 2014). In every power plant, there is energy input from transportation, construction, exploration, and other civil works before the power plant is commissioned. The input energy is mainly from fossil fuels. Energy ratio is calculated using equation 1 (Sullivan, 2014).

$$\varepsilon = \frac{E_{in}}{E_{out}} \quad (1)$$

Greenhouse gases are emitted thus the greenhouse gas ratio is calculated (equation 2) as the sum of all incurred greenhouse gas emissions ($\sum ghg_i$) (in equivalent to CO₂ units) to energy output from the plant (Sullivan, 2014).

$$ghg = \frac{\sum ghg_i}{E_{out}} \quad (2)$$

3. Results

The LCA of the five single flash power plants was performed using a Geothermal LCA calculator. The results are presented in tables and figures for the renewable energy sources in Kenya. Table 3 shows the materials to power ratio for five of the power plants in Kenya. The

MPR for these power plants shows constant values of materials for concrete at 159 MT/MW, copper at 0.17 MT/MW, electricity at 1.3 MWh/MW, iron at 1.6 MT/MW and wood at 10.4 MT/MW. Other materials like, steel cement and water among others vary for each plant as shown in Table 3.

Table 3. Material to power ratio of the SF power plants studied.

	Cement (MT/MW)	Concrete (MT/MW)	Copper MT/MW	Electricity (Mwh/MW)	Diesel (Liters/MW)	Glass (MT/MW)	Iron (MT/MW)	Steel (MT/MW)	Wood (MT/MW)	Water (Gal/MW)
Olkaria I	187	159.0	0.17	1.3	43,160	1.1	1.6	221.7	10.4	285,539
Olkaria IV	77.581	159.0	0.17	1.3	19,080.44	0.296	1.61	117.712	10.4	140,299.8
Eburru Well head	416.792	159.0	0.17	1.3	95,056.4	2.5	1.61	464.311	10.4	632,872
Well head Olkaria	140.042	159.0	0.17	1.3	32,630.84	0.844	1.61	172.476	10.4	215,065.9
Menengai	73.355	159.0	0.17	1.3	17,588.53	0.442	1.61	102.154	10.4	114,389.8

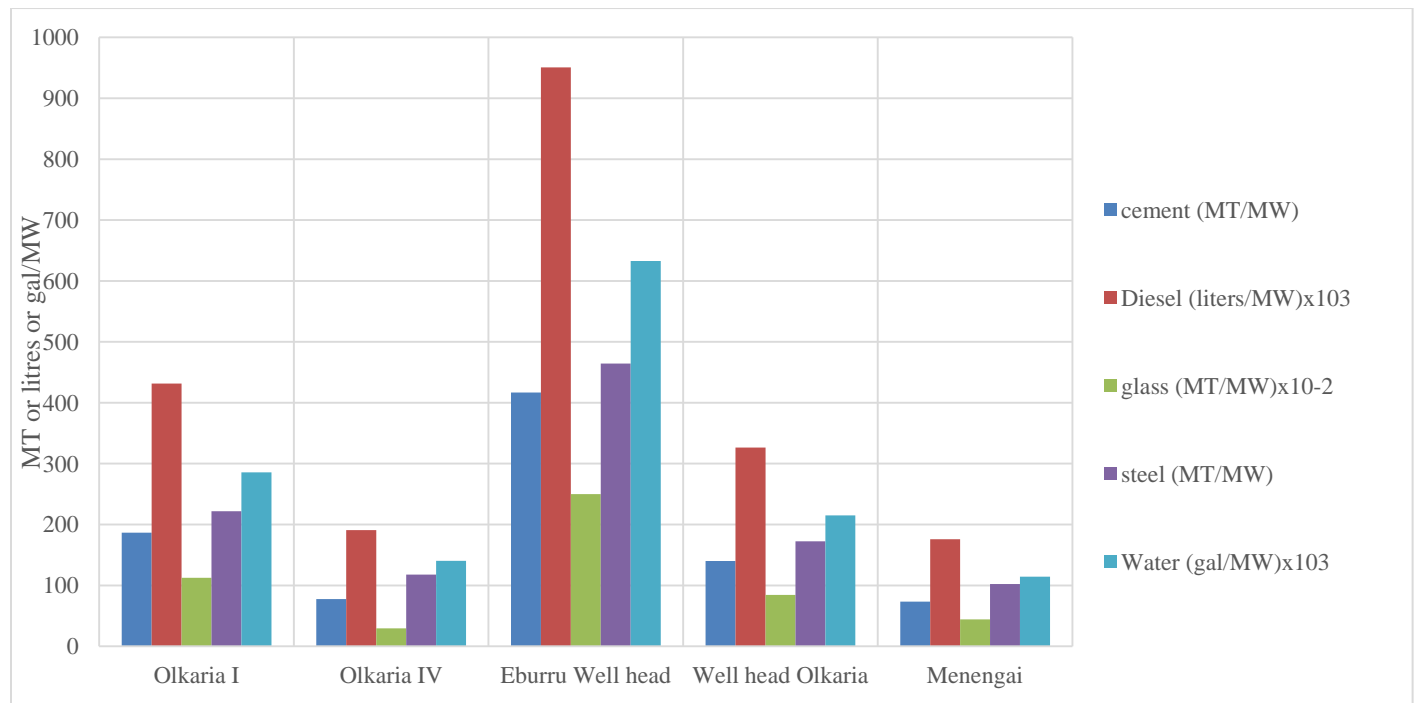


Figure 1. Bar graph showing the MPR of the geothermal SF power plants.

Figure 1 shows the MPR for each power plant. The MPR is seen to be high in case of Eburru well head unit with the highest values of diesel. Olkaria IV shows lower material consumption compared to other power plants. The main contributing factors in MPR are the net power capacity and number of wells drilled. Eburru field was assumed to have 3 wells for generating 2.52 MW. From Figure 1, the older plants like Olkaria I have higher MPR rates compared to newer plant, Olkaria IV. Due to technology advancement, the success rates in drilling has increased thus reducing the number of well drilled per MW.

Table 4 shows the greenhouse gas emissions and the energy ratios for SF power plants. The main contributing factor to global warming is the CO₂ emitted during construction and operation of the power plants.

Table 4: Plants cycle energy, energy ratio and greenhouse gases results.

	E_{in} (MJ)	ε_{pc} (MJ/MJ)	ghg _{pc} (g/kWh)
Olkaria I	7,293,349	0.00882	3.189
Olkaria IV	2,488,739	0.00301	1.115
Eburru Well head	5,625,890	0.006804	2.469
Well head Olkaria	5,664,668	0.006851	2.486
Menengai	3,337,980	0.004037	1.481

Table 4 shows Olkaria I has the highest values of energy input and energy ratio while Olkaria IV has the least. The energy input is directly proportional to the number of well drilled. Ghg_{pc} are from fossil fuels utilized during drilling operations. Once geothermal power plants are commissioned, fossil fuel input is reduced significantly.

Menengai geothermal field is at an advanced stage of development, the values used in this study are designed/projected power plant output. There is need to apply LCA in prospecting fields to reduce the environmental impacts and aim at higher drilling success rate.

4. Conclusion

Older plants have higher MPR rates compared to newer plant. Technology advancement increases success rates in drilling reducing the number of wells drilled per MW. Ghg_{pc} are from fossil fuels utilized during drilling operations. LCA should be applied in prospecting fields to reduce the environmental impacts and aim at higher drilling success rate. LCA is a good tool for environmental concerns in power development.

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