

# Binary Power Plant CO<sub>2</sub> Life Cycle Emissions Including Isobutane Fugitive Leakage

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## ABSTRACT

Geothermal energy production has one of the lowest life cycle CO<sub>2</sub> emission factors (~ 15 g-CO<sub>2</sub>/kWh) for plants producing electricity (Hondo, 2005). This life cycle factor includes indirect emissions from plant construction as well as ongoing operations such as additional well drilling and equipment replacement. Not included in this calculation are direct emissions from geothermal power production. Geothermal flash plants emit CO<sub>2</sub> at rates related to the reservoir concentration. Binary plants are typically assumed to have zero emissions of high global warming potential gases because of their closed loop system design. However, binary plants use working fluids to drive the turbine generators and leakage of these working fluids have not yet been quantified.

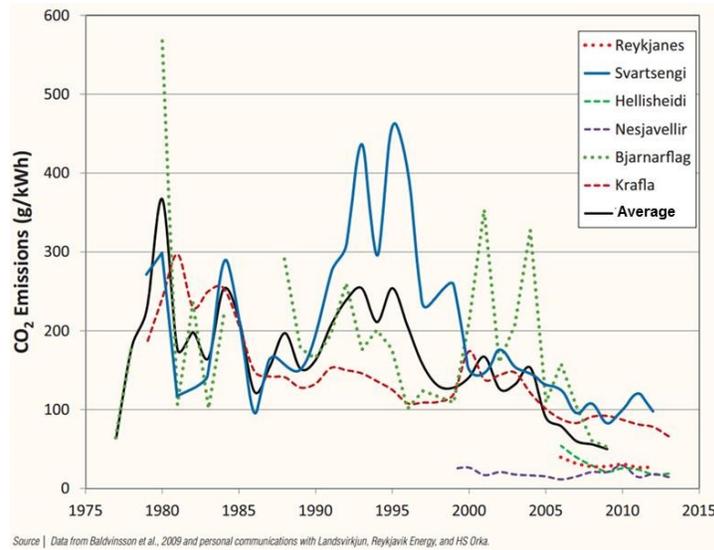
To assess the working fluid emissions from geothermal power production using an Organic Rankine Cycle, reported isobutane emissions were accessed for 3 California binary plants from the Great Basin Unified and Imperial County Air Pollution Control Districts as well as the California Air Resource Board. Each binary plant used in this study has been operating for more than 25 years. From the data, two types of isobutane emissions were accounted for over a 15 month period: 'normal' equipment leakage and equipment breakdown emissions. This preliminary analysis of working fluid emissions from these plants suggest that if a binary plant has equipment failures, the majority of the isobutane releases can be due to these events.

The results indicate that a well maintained binary plant releases approximately 0.13 g-Isobutane/kWh where as a plant with equipment failures releases approximately 1 g-Isobutane/kWh. Assuming a greenhouse warming potential of 3 for isobutane, these emission values become 0.4 and 3 g-CO<sub>2e</sub>/kWh (where CO<sub>2e</sub> is the CO<sub>2</sub> equivalent effect). Binary power plant with significant equipment issues can emit significantly more GHG via equipment breakdown that is emitted through normal leakage of valves and seals. However, even for binary plants that isobutane have fugitive emissions, these emission do not significant increase the life cycle CO<sub>2</sub> emission factor. This limited data set suggests that when direct CO<sub>2e</sub> fugitive emission are add to the indirect CO<sub>2</sub> emissions, the total CO<sub>2</sub> emissions from binary power plants are still low and equivalent or less than nuclear, as well as other renewables power production such as wind and solar.

## 1. INTRODUCTION

Although geothermal energy production is widely known as a constant renewable energy source able to produce electricity 24 hours per day, less emphasis has been placed on its low greenhouse gas (GHG) emissions despite efforts to curb GHG emissions globally. Hondo (2005) has reported indirect GHG emission factors at approximately 15 g-CO<sub>2</sub>/kWh for plants producing electricity. This life cycle factor includes emissions from plant construction as well as ongoing operations such as additional well drilling and equipment replacement. Direct emissions from flash plants can vary widely (Figure 1) and have been reported in the 100's g-CO<sub>2</sub>/kWh (Fridriksson et al., 2016). Binary plants are typically assumed to have zero emissions of high global warming potential gases because of their closed loop system design. Binary plants, however, use working fluids to drive the turbine generators and leakage of these working fluids have not yet been quantified

For binary systems, both the reservoir and the working fluid are contained in closed loop systems. The geothermal fluid in a binary system is pumped from a production well and passed through a heat exchanger, vaporizing a secondary working fluid with a lower boiling point such as pentane, isobutane or another refrigerant and returned to the subsurface reservoir via an injection well. After the working fluid leaves the heat exchanger, it drives a turbine and passed through a water- or air-cooled condenser, returning the secondary fluid into a liquid where it is reused in the next binary cycle. Because of the closed loop design, unique manipulation of Organic Rankine Cycle (ORC), and the noncondensable gases in the brine not interacting with the ambient, it is generally assumed that these plants have no GHG emissions.



**Figure 1: The CO<sub>2</sub> emissions from geothermal power plants operating in Iceland (from Fridriksson et.al. 2016).**

Existing leakage rates of isobutane have yet to be quantified and made readily available for comparisons with emissions from other power plants. Much of the equipment including pressure relief valves, flanges, fittings, packers, seals, etc., emit pressurized fluids at low rates as well as through both minor and catastrophic equipment breakdowns. Quantifying working fluid leakage rates in binary geothermal power plants would allow a more complete analysis of GHG emissions from geothermal energy production as well as provide plant operators information for potential operational improvement.

Greenhouse gas emissions, such as carbon dioxide and water vapor, trap infrared radiation from escaping the Earth’s atmosphere, causing an increase in temperature overtime. Like CO<sub>2</sub>, refrigerants that can be used in ORC also have an impact on the greenhouse effect. Table 1 lists common refrigerants and their Ozone Depletion Potential as well as their Global Warming Potential. Isobutane has a GWP of 3 (Heberle and Bruggermann, 2010), allowing leakage losses to be converted into a carbon dioxide equivalent (CO<sub>2e</sub>).

**Table 1: Common refrigerants with their corresponding Global Warming Potential (data from Goetzer et.al. 2014).**

Refrigerant	GWP (100 years)
HFC-134a	1,300
HCFC-22	1,760
R-290 (Propane)	3
R-600 (Butane)	4
R-600a (Isobutane)	3
R-744 (Carbon Dioxide)	1
R-717 (Ammonia)	0

This paper performs a preliminary assessment of isobutane emissions from three binary plants located California. Results from studies such as the one presented in this paper, can be used to assess the total amount of working fluid losses from binary plants of similar power-producing capabilities throughout the United States This will allow for a quantification of working fluid emissions from binary geothermal plants that can be more accurately compared to the emissions of other electric-producing facilities, such as coal and natural gas. A quantification of working fluid emissions can also help extrapolate future isobutane emissions for geothermal power plants as geothermal electricity production is commercialized on a larger scale.

**2. METHODS**

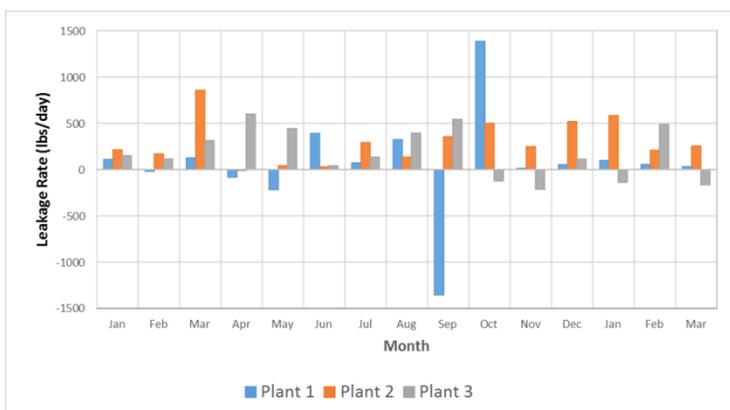
Working fluid emissions were accessed from 3 binary plants from the Great Basin Unified and Imperial County Air Pollution Control Districts as well as the California Air Resource Board (CARB, 2014) via public record requests. Emissions data was reported by the plant operators to the state regulators. Each binary plant used in the study has been operating for more than 25 years. From the data, two types

of isobutane emissions were accounted for over a 15 month period: normal equipment leakage and equipment breakdown emissions. The monthly emissions data was then organized into tables and spread sheets where it was analyzed as cumulative isobutane emissions as well as cumulative breakdown emissions as a function of time for each plant.

### 3. NORMAL ISOBUTANE LEAKAGE RATES

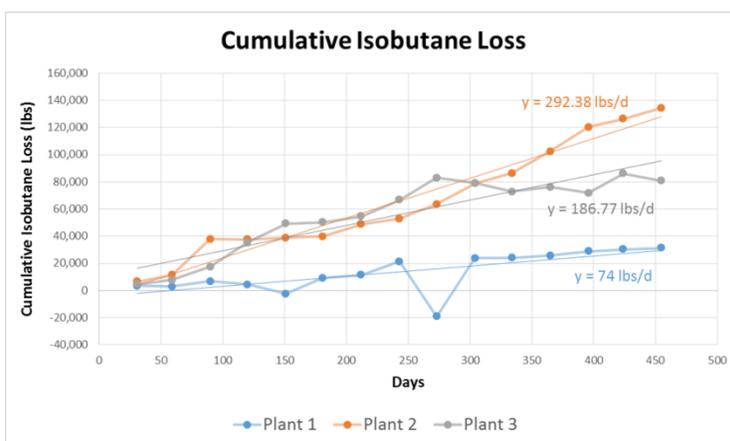
The raw data received from the state of California included starting and ending estimates of isobutane, the inventory change of isobutane, receipts of working fluid purchases, breakdown losses and overall reportable losses for each month from January 2015 to March 2016. From the data, estimated rate of isobutane loss (not including episodic breakdown emissions) were calculated monthly by dividing the pounds of isobutane lost by the number of days in the particular period for each of the three power plants.

Figure 2 illustrates the average daily isobutane leakage rate for the three plants. The typical calculated leakage rate is generally less than a few hundred pounds per day. Some of the values range beyond 500 pounds per day. The negative rates (i.e. a gain in isobutane inventory) were a result of where the ending calculated isobutane inventory was higher than the starting isobutane inventory. A ‘gain’ in the isobutane inventory is often correlated with a high leakage rate in adjacent months. We hypothesize that a negative leakage rate is due to the result of isobutane amounts being inaccurately recorded, a poor gage accuracy, or temperature related volume expansion effect corrections being incorrectly calculated.



**Figure 2: Average normal leakage rates expressed as pounds per day of isobutane for each month as a function of the 15 months of data.**

To moderate the variability in the daily leakage rate calculations, the cumulative emissions were calculated for each month. Isobutane losses were then plotted against each other for comparison as seen in Figure 3. The cumulative emission data was linearly regressed to estimate the average rate of isobutane loss in lbs/day during the 15 month period for each plant. The binary plant emission rates varied from less than 100 to almost 300 pounds per day isobutane loss.

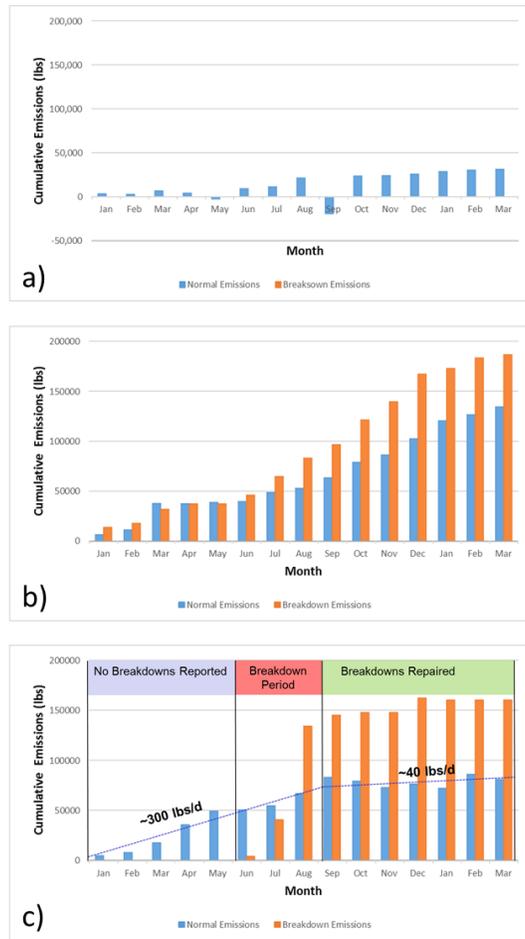


**Figure 3: Cumulative normal leakage rates expressed as pounds of isobutane lost from inventory as a function of time.**

**4. BREAKDOWN ISOBUTANE LOSSES**

Figure 4 illustrates the normal leakage emissions (i.e. leakage that has not attributed to equipment failure, shown in blue) and breakdown emissions (i.e. leakage that was attributed to particular piece of equipment malfunction shown in orange). Equipment that experienced breakdowns include; sight glass, valves, condenser tubes, seals, turbines, heat exchangers and condenser tubes.

Plant 1 did not report any breakdowns during the 15 month period (Figure 4a). Plant 2 (Figure 4b) illustrates a significant leakage of isobutane from breakdowns which are typically greater than that attributed to normal leakage. Isobutane loss from Plant 3 via equipment breakdowns was approximately twice the amount to that attributed to normal leakage (Figure 4c). Plant 3 had approximately 3 months of equipment issues in the summer that was repaired in September. It should be noted that the normal calculated leakage prior to the equipment repair was approximately 300 lbs/d and reduced to approximately 40 lbs/day after the repairs were completed.

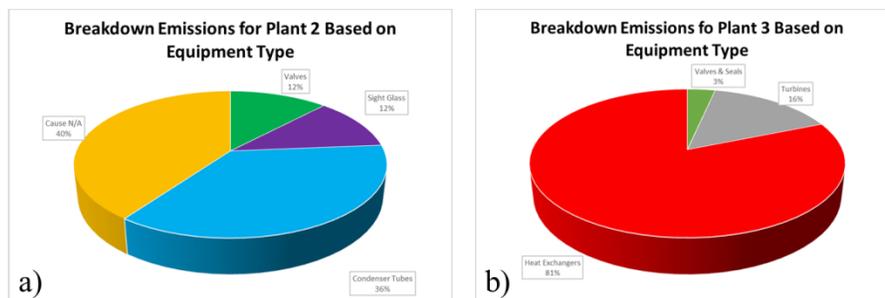


**Figure 4: Cumulative emissions as a function of emission type and by plant a) Plant 1, b) Plant 2, and c) Plant 3.**

**5. DISCUSSION**

The two pie charts in Figure 5 illustrate the equipment responsible for the episodic breakdowns within the 15 month period. Plant 1 was excluded because it did not report any breakdowns. For Plant 2, the total breakdown emissions amounted to 186,477 pounds of isobutane in addition to the normal leakage emissions. Of the total breakdown emissions, 40%, 74,591 lbs, of the equipment involved was unreported as to its type, 36%, 67,132 lbs, of the breakdown emissions were from 6 different condenser tube incidences, 12%, 22,377 lbs, of the emissions were from valves and the last 12%, 22,377 lbs were from sight glass leakage. Isobutane loss from the condenser tubes and the sight glass were directly discharged into the atmosphere.

Plant 3 had a similar total breakdown emission of 160,184 pounds of isobutane in addition to its normal leakage rate. Of the total breakdown emissions, 81%, 129,749 lbs, were due to 2 separate geothermal heat exchanger breakdowns, 16%, 25,629 lbs of the breakdown emissions were from 2 separate turbine incidences and the last 3%, 4,806 lbs, of isobutane lost were due to a combination of seal and valve breakdowns. Unlike Plant 2, the heat exchanger leakage would be to the geothermal fluid and be reinjected back into the geothermal reservoir and not directly to the atmosphere. One might conclude that this leakage would not contribute to global warming due to potential subsurface sequestration. However, for this site, Evans and others (2004) have detected isobutane from gas vents approximately 1.6 km from the plants, suggesting that some of the injected isobutane is being released to the atmosphere.



**Figure 5: Equipment breakdowns responsible for isobutane losses a) Plant 2, b) Plant 3.**

Table 2 lists the power outputs for each plant, the leakage and breakdown emissions data for the calendar year 2015 and isobutane loss rate normalized to the plant gross electrical output. The gross megawatts are calculated as if the plant was operating at full capacity for the year and did not account for lost generation to correct breakdown issues. Overall isobutane fugitive emission range over a factor of 6, from ~2,700 lbs/MW/year, from Plant 1 which experienced no additional emissions due to equipment breakdown, to ~18,000 lbs/MW/year, from Plant 2 which experienced the most emissions due to equipment breakdowns.

The table also displays the percent of emissions that are attributed to normal leakages and equipment breakdowns. It should be noted that despite breakdown emissions being plotted separately from leakage emissions rates (Figure 3), the calculated normal leakage rates from plants that experience breakdowns may also include emissions due to long-term breakdown leakage. For example, it is possible that Plant 3 leakage emissions were relatively higher because some breakdown emissions went undetected in the first half of the reported period and therefore not separately accounted for from the leakage emissions.

For plants that experience equipment failures, the breakdown emissions can be at least twice that attributed to normal leakage emissions. Using the leakage and breakdown emissions data calculated in Table 2 approximately two thirds of the isobutane emissions for Plants 2 and 3 are a result of equipment breakdowns. This ratio is likely conservative. If one assumes that Plant 1 is an accurate estimation of the a plant's normal leakage rate, Plant 2 breakdown emissions would account for 85% of the total isobutane emissions.

**Table 2: Isobutane leakage rates, and calculated greenhouse gas emissions for each plant in 2015.**

	Gross (MW)	Leakage Emissions (LBS)	Breakdown Emissions (LBS)	Total Isobutane Emissions (LBS)	Leakage Emissions %	Breakdown Emissions %	Total Isobutane Emissions LBS/MW/Yr	Greenhouse Gas Emissions (g CO <sub>2</sub> e/KWh)
PLANT 1	10	26,982	0	26,982	100	0	2,698	0.42
PLANT 2	15	102,437	167,039	269,476	38	62	17,965	2.77
PLANT 3	15	76,172	162,150	238,322	32	68	15,888	2.45

Plants 2 and 3 emit two to three times the normal leakage rate (per MW) as Plant 1. This could be due to the schedule maintenance of seals or Plants 2 and 3 normal isobutane leakage emissions may contain isobutane equipment failure mass. The linear regression of the isobutane cumulative loss for each plant was fairly good with the exception of Plant 3 (Figure 3). Prior to the repairs of the heat exchanger in Plant 3, normal leakage was calculated at 300 lbs/d (Figure 4c). After the repairs, normal leakage was calculated to be only 40 lbs/d. This data suggest that much of the normal leakage reported for the first half of the year likely was due to small leaks in the heat exchangers but not to a point of being considered and equipment issue.

These results suggest that plants that record a higher than normal leakage emissions could be used as a precursor of pending breakdowns, however, the accuracy of the monthly report illustrated in Figure 2 does not easily allow the determination of such pending equipment issues and suggest the need for a more sensitive inventory monitoring system. Besides the prevention of release of greenhouse gases, there are also economic benefits when implementing more sensitive monitoring systems for leakage rate increases. If the heat exchanger was maintained prior to the 6 condenser tube issues, an estimated \$40,000 in isobutane purchases could have been saved. It should be noted that Plants 2 and 3 each have ~758,400 ft (143.6 miles) of tubing in the air-cooled condensers and only 6 tubes out of ~12,460 total in each plant needed repair, suggesting that an efficient inspect/monitor system is needed to examine the heat exchanger.

Using Plant 1 as an example of the normal leakage rate, a well maintained binary plant emits 0.4 g CO<sub>2</sub>e/KWh (Table 2). This value is small when compared to a natural gas plant per kWh (487 g CO<sub>2</sub>/KWh [Figure 6]). Even when a binary plant is experiencing equipment failure, the binary plants emitted less than 3 g CO<sub>2</sub>e/KWh (Table 2). In contrast, geothermal power production from flash plants can emit much greater amounts of CO<sub>2</sub> depending on the reservoir as seen in Figure 1. Holm et.al. (2012) suggest a value of approximate 180 g CO<sub>2</sub>/kWh as an average geothermal flash plant value for California.

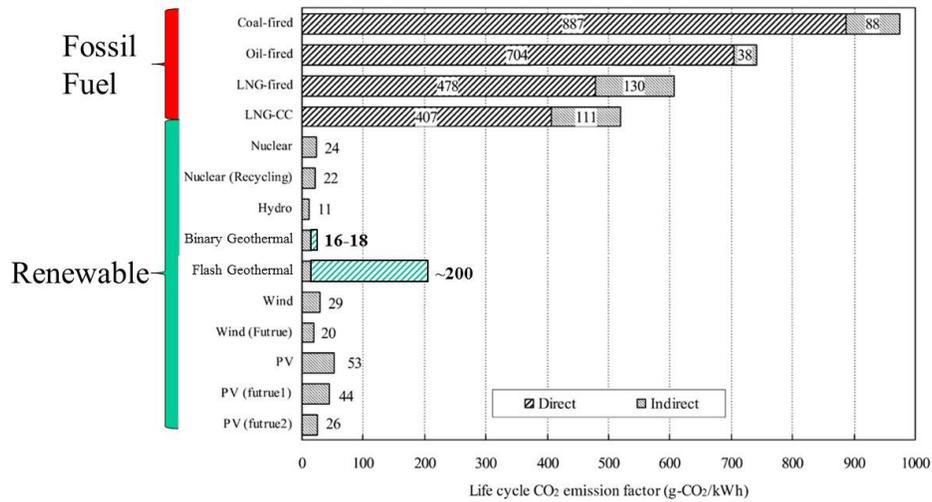


Figure 6: Direct and indirect CO<sub>2</sub> emissions from various energy sources. (modified from Hondo, 2005)

## 6. SUMMARY

Working fluid emissions were accessed from 3 binary plants from the Great Basin Unified and Imperial County Air Pollution Control Districts as well as the California Air Resource Board (CARB, 2014) via public record requests. Emissions data was reported by the plant operators to the state regulators. Each binary plant used in the study has been operating for more than 25 years. From the data, two types of isobutane emissions were accounted for over a 15 month period: normal equipment leakage and equipment breakdown emissions.

For this limited data set over a limited amount of time, the normal and equipment related isobutane emissions were calculated. Overall, binary geothermal power plants emit working fluids in small but quantifiable amounts. Older binary plants (+25 years), such as the ones used in the study, appear to experience a much higher loss of isobutane due to equipment breakdowns than normal isobutane leakage. With more improved monitoring of normal isobutane leakage rates in binary geothermal power plants, more gradual leakage issues can possibly be detected and repaired, preventing more catastrophic breakdowns in the future and reducing the overall isobutane emissions for a particular plant. The data supports that even including working fluid emissions from binary power plants with their life cycle CO<sub>2</sub> emission factor is still significantly less than fossil energy plants even when considering equipment breakdown emissions and is comparable to other renewable energy sources.

## 7. ACKNOWLEDGEMENTS

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