Life Cycle Analysis of Enhanced Geothermal Systems

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Contents

Chapter 1

Executive Summary

We conducted a Life Cycle Assessment (LCA) of Enhanced Geothermal Systems (EGS) to determine the environmental impacts of EGS as compared to other energy technologies. We compared five scenarios: EGS that produces electricity only; EGS that produces electricity and heat; electricity production by a combined cycle natural gas plant; electricity production by solar photovoltaics; and electricity production by conventional geothermal technology.

We first determined the goal and scope of our LCA and decided on our functional unit (FU), 1 kW h of electricity produced. For the EGS scenario wherein the system is producing both electricity and heat, we used the system expansion method to treat heat as a co-product, using heat production from natural gas as our comparable scenario. For our life cycle inventory phase, we found equivalences for all of the reference flows (RFs) associated with EGS in the database Ecoinvent and determined the amount of each RF/FU. We then input each RF/FU into SimaPro to create different life cycle scenarios for analysis and comparison.

In our impact assessment phase, we found that co-producing EGS, when compared to electricity-only EGS, exhibits significantly less impact on endpoint categories: resources (91.64% difference) and climate change (73.91% difference).There was an insignificant difference in impact on endpoint categories: ecosystem quality (6.38% difference) and human health (10.87% difference) between these two scenarios. These results were signified in the comparison of impacts to endpoint categories of all scenarios. We then analyzed the best case (BC) and worst case (WC) scenarios of using electricity-only EGS and co-producing EGS compared with the impacts of the other scenarios.

Chapter 2

Goal and Scope

2.1 Background and Objective

Enhanced Geothermal Systems (EGS) is a novel technology that allows for producing electricity from geothermal heat. This technology does not require an underground source of water like traditional geothermal. Instead, EGS creates its own water source by pumping water through artificial fissures in the rock, then pumping the water back out after it has been heated. This allows for electricity production in locations that are not accessible for traditional geothermal electricity production. According to the Department of Energy, EGS in the United States offers an estimated extractable capacity of more than 100 GWe (EERE). Utilization of enhanced geothermal systems could fulfil 10% of US electricity needs, so it is imperative that decision makers understand the environmental impacts generated by using this potentially widespread technology (EERE). Performing an LCA of EGS electricity production begins to address this.

The objective of this LCA is to determine the environmental and human health impacts of electricity production from EGS over the system's entire life cycle. Additionally, it is imperative to compare the environmental impacts from EGS electricity production to other methods of electricity production to determine how sustainable EGS is.

2.2 Functional Unit and Scenarios

This study uses 1 kW h of energy produced as our functional unit. This functional unit accurately captures the primary function of the service: to produce electricity.

It considers heat production from EGS as a co-product. Natural gas combustion heating was chosen as the method to accurately estimate the amount of emissions and extractions avoided by using this heat and this follows the system expansion method. We chose to use heat production from natural gas as our comparable production process because it is the cheapest and most standard technology for electricity and heat production today (UT Austin Energy Institute, 2016). When considering heat as a co-product and adhering to the system expansion method, the system is credited with the amount of associated impacts that would otherwise be produced from natural gas combustion to produce the same amount of heat.

Considering that there might not always be a convenient way to utilize waste heat, two scenarios were defined for electricity production from EGS: electricity production exclusively and combined electricity with heat production. In this second scenario, heat is treated as a co-product. The respective system boundaries for each EGS case are shown below in Figures 2.1 and 2.2. These scenarios were compared alongside three alternative scenarios that use different technologies: conventional geothermal electricity production, solar electricity production, and electricity production from combined cycle natural gas. The comparison of EGS to conventional geothermal was chosen because EGS is a new method of geothermal energy production. Specifically, the equivalence of "Electricity, high voltage — electricity production, deep geothermal — Cut-off, S" was chosen for the WECC geographic designation because the western United States is the primary region in the US that employs deep geothermal energy (EIA, 2018). Solar energy production was chosen as an alternative scenario because it is another renewable technology for electricity production. Specifically, the equivalence of "Electricity, low voltage — electricity production, photovoltaic, 570kWp open ground installation, multi-Si — Cut-off, S" was chosen for the SERC geographic region because that is the region for the current location in North Carolina. Finally, natural gas electricity production was chosen as another alternative scenario because the major processes to construct and operate a natural gas power plant are very similar to EGS, such as the plant construction, well drilling, and well stimulation. It is also useful to compare emerging renewable energy technologies to the more common fossil fuel methods. Specifically, the equivalence of "Electricity, high voltage — electricity production, natural gas, combined cycle power plant — Cut-off, S" was selected for the geographic designation SERC because a combined cycle power plant is the newest, most efficient technology available for natural gas combustion.

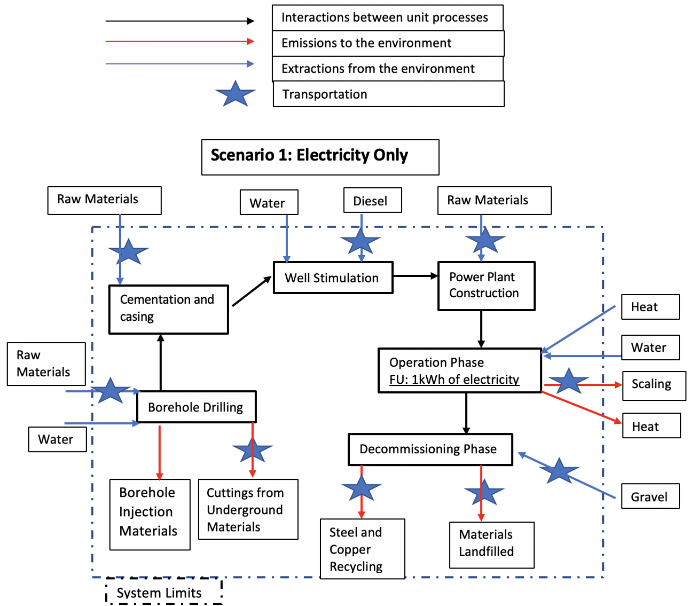

Figure 2.1: EGS electricity-only case. Borehole drilling and cementation and casing are merged to become "Well Construction" throughout the report.

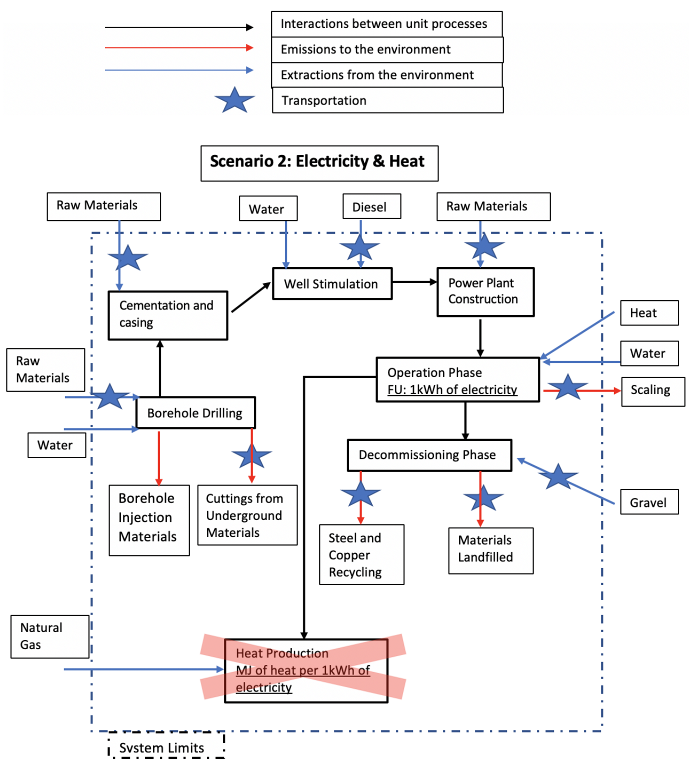

Figure 2.2: EGS electricity and heat production case. The heat is credited by system expansion - EGS would produce heat otherwise produced by natural gas.

Chapter 3

Life Cycle Inventory

For the Life Cycle Inventory (LCI) phase, we recorded all of the reference flows (RF) associated with electricity production from EGS (A). To compare the flows efficiently, each value was converted to the amount per kW h of electricity produced, which is the functional unit (FU).

Each RF value was calculated for the entire project lifetime. Then, using these values and the total kWh of electricity produced over the plant's lifetime, each RF was converted to a value per FU.

As an example, the RFs in the Well Construction Phase are given in unit per meter drilled. It was estimated that the average well depth is 7,200m, and that there are three wells at a construction site: one injection well and two production wells. Thus, there are 21,600 total meters of well dug. Accordingly, the RFs in the Well Construction Phase (unit/m drilled) were multiplied by 21,600 to get the total RF per lifetime.

The RFs in the Well Stimulation Phase are given in unit per well. Because three onsite wells are assumed, each RF was multiplied by three to get the total RF per lifetime.

The RFs in the Power Plant Construction Phase are given in MT/MW. It was determined the MT/lifetime based on the power plant's capacity. A 2.25 MW capacity was chosen for the reference case as this is in the middle of the 2-2.5 MW range given. Thus, each RF was multiplied by 2.25 to determine the MT/lifetime.

The RFs in the Operation Phase are given in unit per MW h. Each of these RFs was converted to units per kW h and multiplied each RF by the total kW h of electricity produced by the plant over its 25 year lifetime. This resulted in RF per lifetime.

The RFs in the Decommissioning Phase were given in unit per MW, besides gravel for filling, which was given in kg/m. Each of these units per MW was multiplied by hours in a year to get units per MW h, converted to units per kW h, and then multiplied by total kW h of electricity produced by the plant over its

25 year lifetime. The gravel filling was multiplied by the total well depth of all three wells to get the RF per lifetime. Each of these calculations resulted in units of the RF per lifetime.

To determine the RF/FU, the total FU over the plant's lifetime was necessary. The reference case had an assumed electrical power output of 2.25 MW because it is the average of the electrical power output range given. This power output was converted to kW h/year, and then multiplied this by 25 years. Finally, this power output over 25 years was multiplied by 0.9 to account for the fact that the plant is only able to operate up to 90% of the time. Once the lifetime energy production, 443,475,000 kW h, was found, RF/lifetime divided by FU/lifetime yielded RF/FU. By representing all of the RFs per FU, the reference flows could be compared on a common basis.

3.1 Assumptions

Assumptions were made depending on the information available and the equivalences in Ecoinvent. In the memo, the upper and lower bound of the potential temperature gradient values were 20 and 35 $°C\,km^{-1}$. In the reference case, a gradient of 27.5 $°C\,km^{-1}$ is assumed. This yields a well depth of 7.2 km required to reach the minimum temperature required of 180 °C. Also, it is assumed this project follows the industry-standard one injection well and two production wells. For transportation, a constant 100 km transportation distance for all materials is assumed, and this is kept constant for all transportation requirements over the life cycle of the EGS plant for simplicity. This assumption is based on the geothermal potential in the western United States. According to an infographic created by the National Renewable Energy Laboratory, there is a cluster of geothermal hotspots around Northern Nevada (NREL, 2009). This is a rural area: hence the 100 km distance assumption. However, all water is assumed close enough to the production site, or on-site, and transportation for water is therefore negligible. For disposal, off-site incineration is assumed, and therefore that the incinerators are 100 km away as well. The plant's lifetime of 25 years is taken from the average expected EGS plant lifetime of 20-30 years. Finally, for the heat production alternate scenario, a lifetime of 12.5 years is assumed to account for the heat production only occurring for half of the year.

Chapter 4

Impact Assessment

4.1 Methods

IMPACT 2002+ method is the main method employed, given that is assesses each service according to midpoint categories and damages categories. In Appendix C, the results according to the TRACI method are shown for a more North American-specific assessment focusing on the midpoint categories.

This LCA does not use any kind of normalization or weighting for the impacts - rather, it just presents all of the relative impacts without making any judgements on which are more or less important.

4.2 Results

4.2.1 EGS Cases Comparison

For the global warming potential characterization category, EGS falls in between 0.1 and 0.01 kg CO_2-eq/FU at just over 0.06. This is within the range of other renewable energy producers. In Figure 4.1, the highest-contributing factors are shown, with some selected lesser contributors appearing in Appendix D. Also, the TRACI method is compared to the IMPACT 2002+ method for global warming characterization in Appendix D. Transportation consistently has the highest impacts across all endpoint categories (except human health where diesel is highest). Diesel and steel consistently come in second or third. The stages that contribute the most to these impacts are the well construction and operation phases. Transportation is the largest contributor to the operation phase. For well construction, most of the impact is from diesel required to run machinery, and the transportation required to bring that diesel to construction sites. However, steel is another substance that has a significant impact on the CO_2-eq, so well depth variability is important in

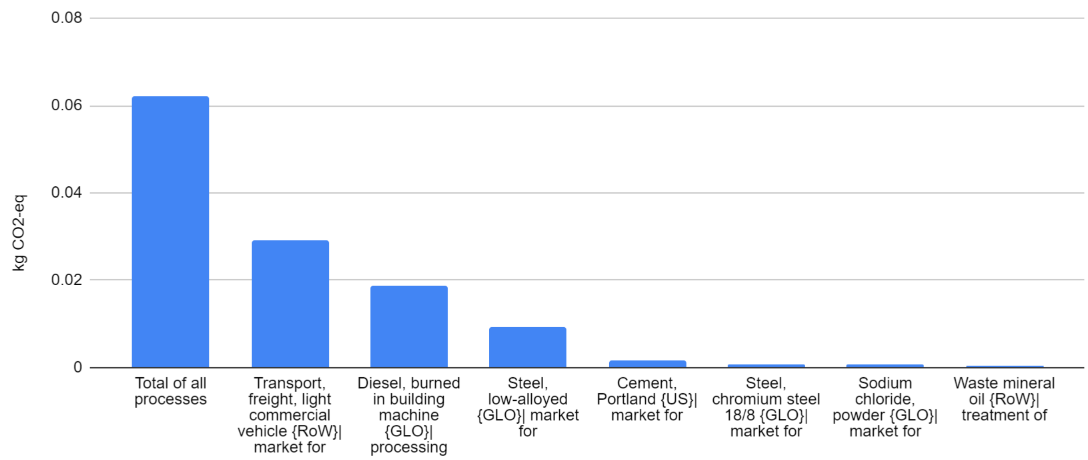

Figure 4.1: IMPACT 2002+ characterization, electricity production only. The lesser contributors do not show up on this scale.

the resulting impact. These same trends appear in the EGS co-production case, but impacts are reduced due to the system expansion credit.

As shown in Figures 4.2 and 4.7, the EGS system that is credited with heat production has lower impacts in every midpoint and endpoint category.

However, these differences are only significant in the midpoint categories: global warming, non-renewable energy, carcinogens, and ozone layer depletion, roughly 55-90%. Both EGS scenarios are comparable in the remaining categories, with perhaps a slight improvement in non-carcinogens and respiratory organics. For endpoint categories, the EGS system with heat has significantly reduced impacts for climate change and resources by roughly 75-92%. The endpoint impacts for ecosystem quality and human health are still lower, but only by about 7-11%.

4.2.2 All Cases Comparison

The scenarios for electricity-only EGS and co-producing EGS were compared with electricity production from photovoltaics, a combined-cycle natural gas plant, and a conventional geothermal system. For the competitors, ready-made ecoinvent equivalences, detailed in Appendix B, were employed. The greatest relative impacts from the EGS categories occur in human health category; climate change and resource use are comparable and of lower impact, and ecosystem quality sees the least damage.

Because this LCA uses system expansion, the EGS system is being "credited" with heat that would otherwise be produced using natural gas. Thus subtract the impacts from natural gas heat production can be subtracted according to the amount the amount of heat produced, which for the reference case, is -1.11

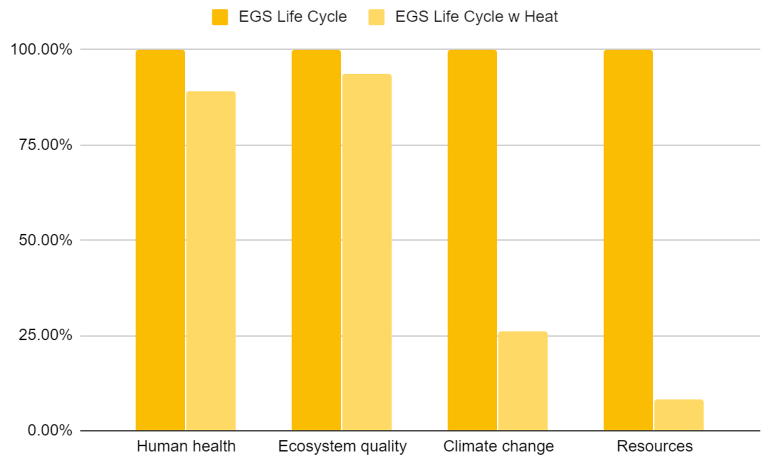

Figure 4.2: Comparison between the two EGS scenarios. While the co-producing scenario improves on all categories, the results are only significant for climate change and resource categories.

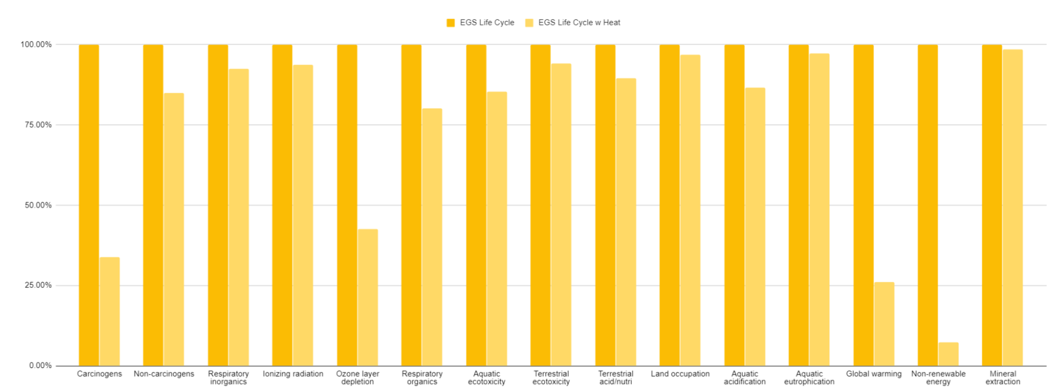

Figure 4.3: Midpoint comparison between the two EGS scenarios.

MJ.

Among all the scenarios in this LCA, EGS is not significantly different in the human heath endpoint category; in fact, all scenarios are similar here. However, EGS is at least comparable to the lowest impacting energy sources for all other categories, even the other renewable energy category, photovoltaics.

Both EGS scenarios outperform the nonrenewable energy source, natural gas, in both the climate change and resources endpoint categories. Also, these scenarios are significantly better than conventional geothermal processes and photovoltaics in the ecosystem quality category. The co-producing EGS scenario further improves on this, being significantly better than all competitors in the climate change and resources categories. The only scenario in which EGS is significantly not favorable is ecosystem quality in relation to natural gas. As a result, EGS is a viable alternative to fossil fuels, and a valid competitor for other renewables.

The most likely improvements in the EGS scenarios could be made in more efficient machinery, more efficient transportation, or judicious site-selection that minimizes the need for longer transport. Also, site selection could result in a greater geothermal gradient, and lessen the need for low-alloy steel to build deep enough wells. However, finding site suitability or selecting different site scenarios was outside the scope of this LCA.

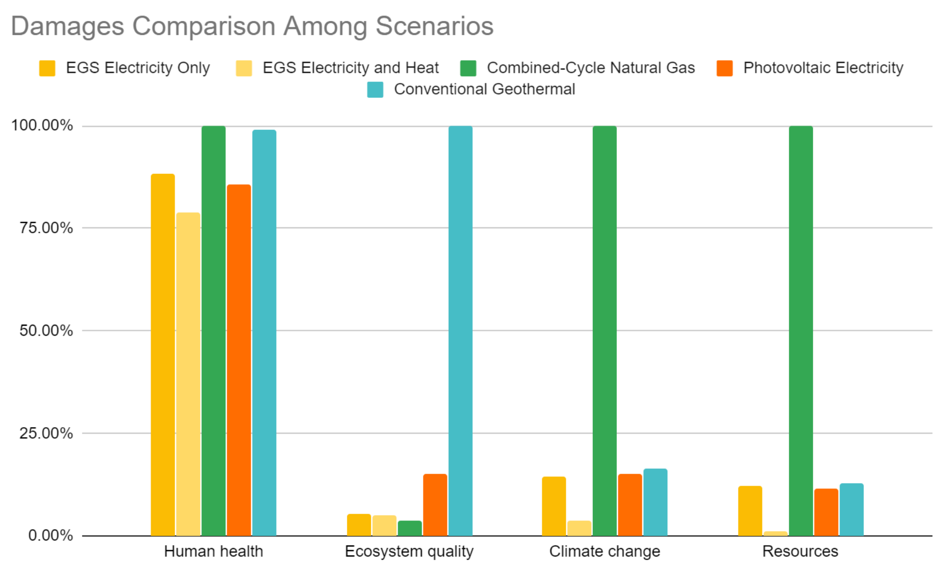

Figure 4.4: IMPACT 2002+ results showing endpoint categories for all scenarios. The “worst offender” in all categories is shown at 100% and all others are shown for how much they improve on that impact.

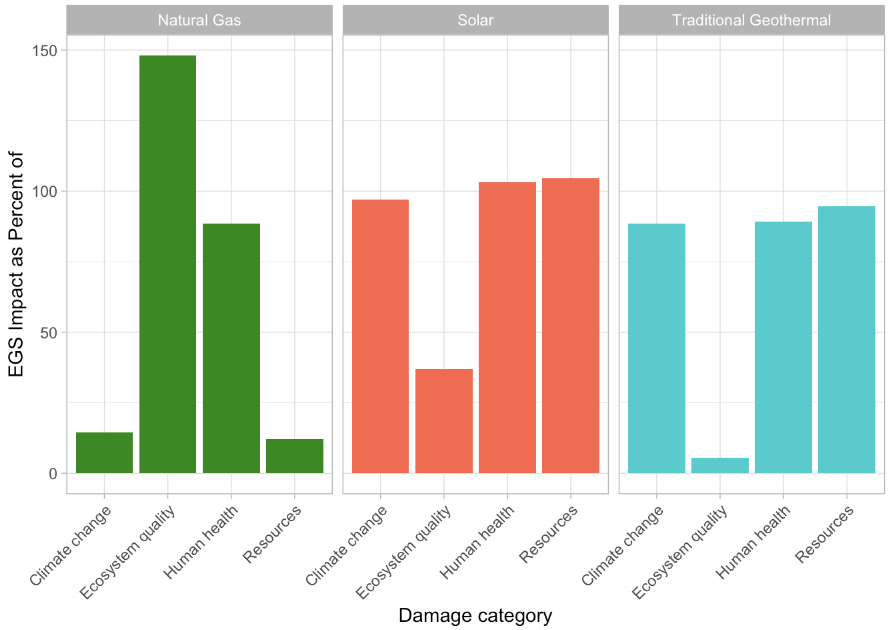

Figure 4.5: IMPACT 2002+ results comparing EGS results directly against the other scenarios.

4.3 Interpretation

4.3.1 Uncertainty Analysis

The assumptions made throughout this project are outlined above in the Life Cycle Inventory, as well as in Appendix A. Each of these assumptions affects the final certainty of the LCA. Specifically, in determining the reference flows, the midpoint between an upper and lower bound was used for our reference case, electricity-only EGS. And in the waste scenario of this project, we grouped multiple waste products–scaling and displaced materials–into a nonspecific hazardous waste equivalence because a more specific case did not exist.

In the Impact Assessment, uncertainty arises from the models selected to interpret the results. Models attempt to simplify the data in order to make predictions, so a certain amount of this uncertainty is unavoidable. These uncertainties are minimized by using both Impact 2002+ and TRACI. Selected comparisons between these models are shown in Appendix B.

The database used for this LCA, EcoInvent, is a European database, though this project is focused in the United States. The equivalences used were as specific as possible to the United States, but it was often necessary to use equivalences for the rest of the world or even globally; these are noted in Appendix A. To reduce this type of uncertainty as much as possible, a site specific LCA would need to be completed.

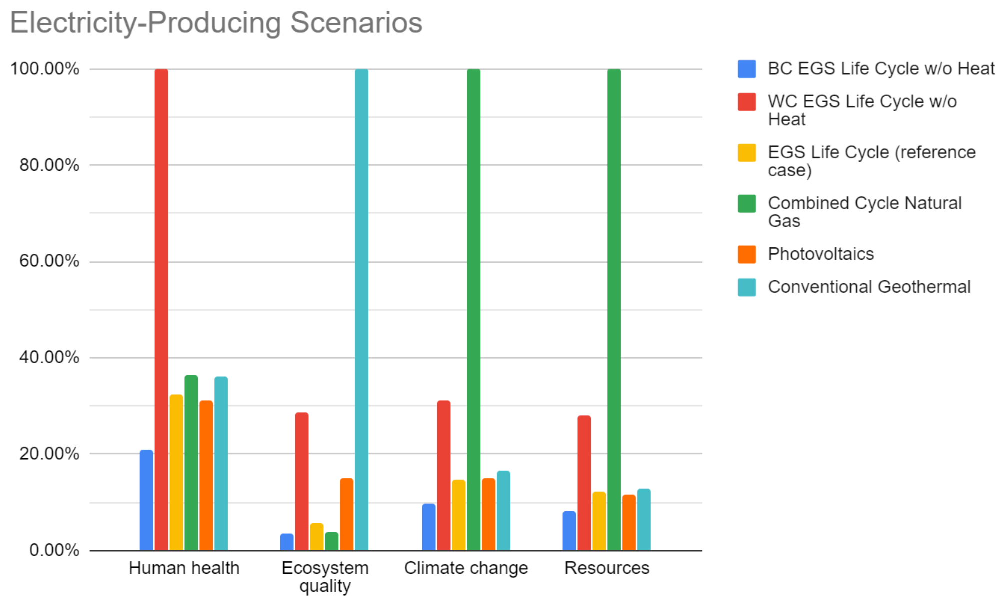

Figure 4.6: All scenarios compared to electricity-only EGS, and best- and worst-case scenarios for electricity-only EGS

4.3.2 Sensitivity Analysis

Categories considered sensitive to variation in key parameters should show a discrepancy of greater than 10-20% between best and worst case scenarios in the climate change and resources categories, and greater than 50% difference in the human health and ecosystem quality categories. The human health category is determined to be sensitive to key parameter changes due to the impact difference between the best case and the worst case scenario for the electricity only EGS (79.2%) as well as the electricity with heat EGS (82.3%). So, where it initially appeared EGS was roughly comparable to the other scenarios, it may actually be worse for human health. For ecosystem quality, where there is much uncertainty about the impacts, both the best-case and worst-case EGS scenarios have an impact difference of under 50% (25.4% and 25.1% respectively); serious sensitivity to parameter variation is not apparent for this impact category. Thus, they can be generally confirmed to be better than conventional geothermal and roughly comparable to our other scenarios. For both the electricity only EGS and the electricity with heat EGS scenarios, the percent difference in climate impact between the best case and worst case scenarios are 21.62% and 23.57%. This signifies climate change as an impact category that is sensitive to variation of key parameters, despite being marginally over the threshold of sensitivity to variation. The results show that resources is the only endpoint category that is not sensitive to variability in key parameters for specifically the electricity only case (19.82%). The electricity with heat EGS scenario demonstrates sensitivity to key parameters due to

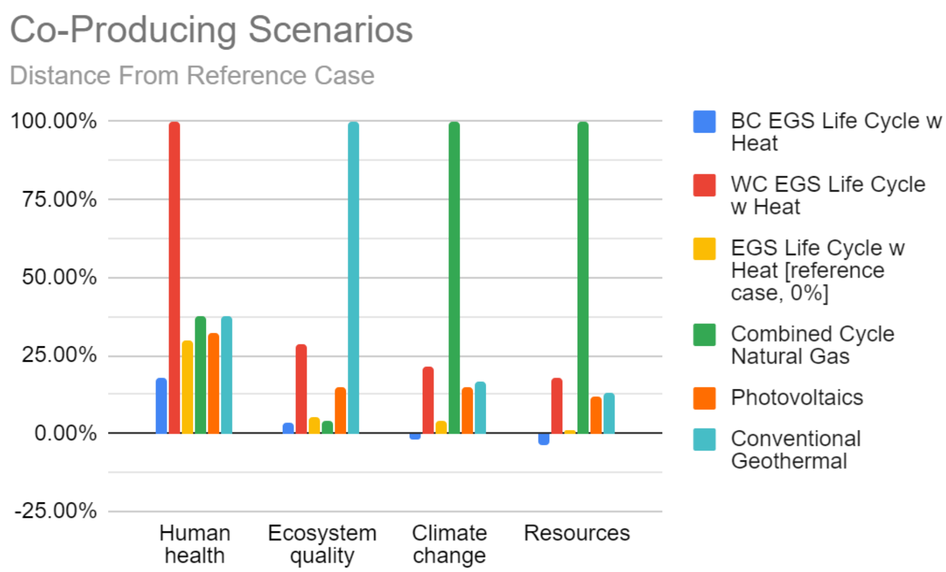

Figure 4.7: All scenarios compared to co-producing EGS, and best- and worst-case scenarios for co-producing EGS

the resources impact difference between the best case and worst case being 21.83%.

4.4 Conclusion

EGS is a relatively new technology. It is possible that in this project, there are some unknown impacts because it is a relatively new process for electricity production. However, this LCA begins to show that, while a given EGS installation could have a wide range of possible impacts, there are certainly cases where EGS can compete with existing technologies, renewable and non-renewable.

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Appendix A

Reference Case - EGS Electricity Production

Well Construction	Reference Flow	Units	Equivalence Used	Geo.	Assumptions
Diesel	86400000	MJ/FU	Diesel, burned in building machine — processing — Cut-off, S	GLO	36 MJ/L
Water	23760	m3/FU	Water, completely softened, from decarbonised water, at user — market for — Cut-off, S	RoW	Sourced from a utility company and will not be transported to the site; decarbonized because tap water has minerals
Bentonite	190080	kg/FU	Bentonite — market for — Cut-off, S	GLO	
Salt	1090800	kg/FU	Sodium chloride, powder — market for — Cut-off, S	GLO	
Silica sand	32400	kg/FU	Silica sand — market for — Cut-off, S	GLO	
Caustic soda	60480	kg/FU	Sodium hydroxide, without water, in 50% solution state — market for — Cut-off, S	GLO	
Soda ash	12960	kg/FU	Soda ash, dense — market for — Cut-off, S	GLO	

Lubricant oil	32400	kg/FU	Lubricating oil — market for lubricating oil — Cut-off, S	RoW	
Uniden. Inorganic Chemicals	60480	kg/FU	Chemical, inorganic — market for — Cut-off, S	GLO	
Displaced Materials	6480	MT/FU	Hazardous waste, for underground deposit — market for — Cut-off, S	GLO	
Portland Cement	879120	kg/FU	Cement, Portland — market for — Cut-off, S	US	
Blast Furnace Cement	105840	kg/FU	Cement, blast furnace slag 25 -75%, US only — market for — Cut-off, S	US	25-70% blast furnace slag because we do not consider freezing to be a risk
Steel	2397600	kg/FU	Steel, low-alloyed — market for — Cut-off, S	GLO	Low-alloy steels used most often for construction
Transportation	3.02	kg km /FU	Transport, freight, light commercial vehicle — market for transport, freight, light commercial vehicle — Cut-off, S	RoW	100km average distance
Well Stimulation	**Reference Flow**	**Units**	**Equivalence Used**	**Geo.**	**Assumptions**
Water	78000	m3/FU	Water, completely softened, from decarbonised water, at user — market for — Cut-off, S	GLO	
Hydrochloric acid	4.2	MT/FU	Hydrochloric acid, without water, in 30% solution state— market for— Cut-off, S	RoW	
Diesel	4800	GJ/FU	Diesel, burned in building machine — processing — Cut-off, S	GLO	

Transportation	2.65E-02	kg km /FU	Transport, freight, light commercial vehicle — market for transport, freight, light commercial vehicle — Cut-off, S	RoW	100km average distance

Power Plant Construction	Reference Flow	Units	Equivalence Used	Geo.	Assumptions
Generic steel	5.06E+03	MT/FU	Steel, low-alloyed — market for — Cut-off, S	GLO	Low-alloy steels used most often for construction
Stainless steel	1.77E+03	MT/FU	Steel, chromium steel 18/8 — market for — Cut-off, S	GLO	Most common stainless steel grade
Copper	5.57E+02	MT/FU	Copper GLO market for — cut-off, S		
Lubricant oil	1.11E+06	L/FU	Lubricating oil — market for lubricating oil — Cutt-off, S	RoW	0.875 kg/L
Organic fluid (butane)	1.92E+03	m3/FU	Butane — market for — Cut-off, S	RoW	Butane
Diesel for machinery	2700000	MJ/FU	Diesel, burned in building machine — processing — Cut-off, S	GLO	
Land	5.64E-06	m^2/FU	Land use for 1m^2 for EGS construction, occupation		Under processes, we chose equivalencies for “inputs from nature”. Chose the transformation of land from “unspecified, natural (non-use)” to “industrial area.” Also have to include occupation of the industrial area, so input “Occupation, industrial area” in m2/year. Multiplied by 25 to account for 25 year plant lifetime, so occupation is in 25m2/year.

Transportation	9.83E-02	kg km /FU	Transport, freight, light commercial vehicle — market for transport, freight, light commercial vehicle — Cut-off, S	RoW	100km average distance
Operation	Reference Flow	Units	Equivalence Used	Geo.	Assumptions
Scaling to be disposed	5.32E+07	kg/FU	Calcium carbonate, precipitated — market for calcium carbonate, precipitated — Cut-off, S	RoW	
Water lost	1.33E+06	m3/FU	Water, completely softened, from decarbonised water, at user — market for — Cut-off, S	GLO	
Transportation	1.20E+01	kg km /FU	Transport, freight, light commercial vehicle — market for transport, freight, light commercial vehicle — Cut-off, S	RoW	100km average distance
Decommissioning	Reference Flow	Units	Equivalence Used	Geo.	Assumptions
Gravel for filling	1.08E+06	kg/FU	Gravel, crushed — market for gravel, crushed— Cut-off, S	RoW	
Transportation	4.67E-01	kg km /FU	Transport, freight, light commercial vehicle — market for transport, freight, light commercial vehicle — Cut-off, S	RoW	100km average distance; incinerator is not on site
Waste Scenario	Reference Flow	Units	Equivalence Used	Geo.	Assumptions
Copper recycled	1.56E+01	MT/FU			70% of copper recycled.
Steel recycled	1.91E+02	MT/FU			70% of steel recycled
Steel landfilled	8.20E+01	MT/FU	Scrap steel treatment of, indt material	RoW	30% of steel landfilled
Copper landfilled	6.68E+00	MT/FU			30% of copper landfilled

Lubricant oil incinerated	4.46E+04	L/FU	Waste mineral oil — treatment of, hazardous waste incineration — Cut-off, S	RoW	Same equivalency for lubricant oil and inorganic fluid
Organic fluid incinerated	7.70E+01	m3/FU	Hazardous waste, for underground deposit	RoW	Same equivalency for lubricant oil and inorganic fluid GLO

Table A.1: Reference Case. These are the reference flows used to produce the LCA for EGS only producing electricity.

Appendix B

Alternative Scenarios

B.1 EGS Heat and Electricity Production

Equivalence Used	Geo.	Assumptions
Heat, district or industrial, natural gas — market group for — Cut-off, S	GLO	

Table B.1: Co-production case. The equivalence used as a credit for heat that could otherwise have been produced by natural gas.

B.2 Photovoltaic Electricity Production

Equivalence Used	Geo.	Assumptions
Electricity, low voltage — electricity production, photovoltaic, 570kWp open ground installation, multi-Si — Cut-off ,S	SERC	Using the largest solar plant equivalence (570kW) available; used SERC since this is our region

Table B.2: An example renewable electricity production service.

B.3 Conventional Geothermal Electricity Production

Equivalence Used	Geo.	Assumptions

Electricity, high voltage — electricity production, deep geothermal — Cut-off, S	WECC, US only	Using WECC bc western US is only place where they do deep geothermal

Table B.3: An example non-renewable electricity production service.

B.4 Combined Cycle Natural Gas Electricity Production

Equivalence Used	Geo.	Assumptions
Electricity, high voltage — electricity production, natural gas, combined cycle power plant — Cut-off, S	SERC	Used combined cycle power plant because this is the newest technology for natural gas–if we were to build a new nat gas plant it would be this kind. Used SERC for our region.

Table B.4: An example non-renewable electricity production service.

Appendix C

TRACI Method Results

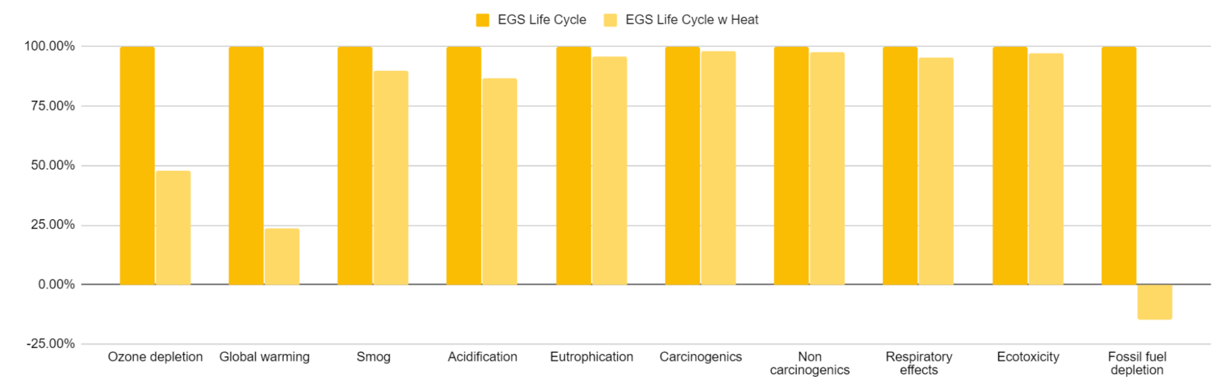

Figure C.1: All of the midpoint categories as calculated by the TRACI method. The major difference between this method and IMPACT 2002+ is that the co-producing scenario actually gets credited for improving on impacts in some categories as an alternative source.

The TRACI method does not share the same endpoint categories as the IMPACT 2002+ method, or does not have any endpoint categories.

Appendix D

Selected Process Contributions

Here, we some more of the process contributions to the global warming potential category, as calculated by the TRACI and IMPACT 2002+ methods. They are largely similar, but with some variation among the lesser contributors

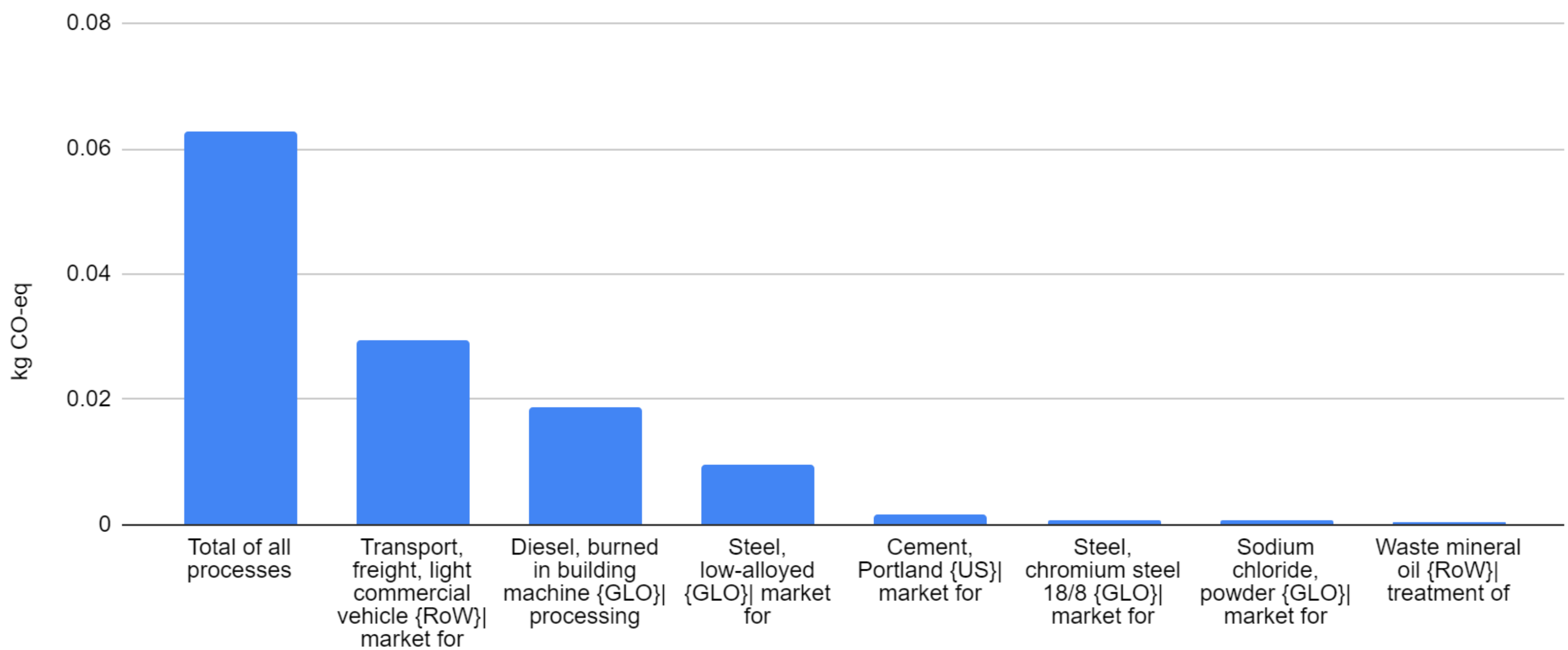

Figure D.1: TRACI Method results for major process contributions to the global warming midpoint category. These results are almost indistinguishable from the IMPACT 2002+ results.

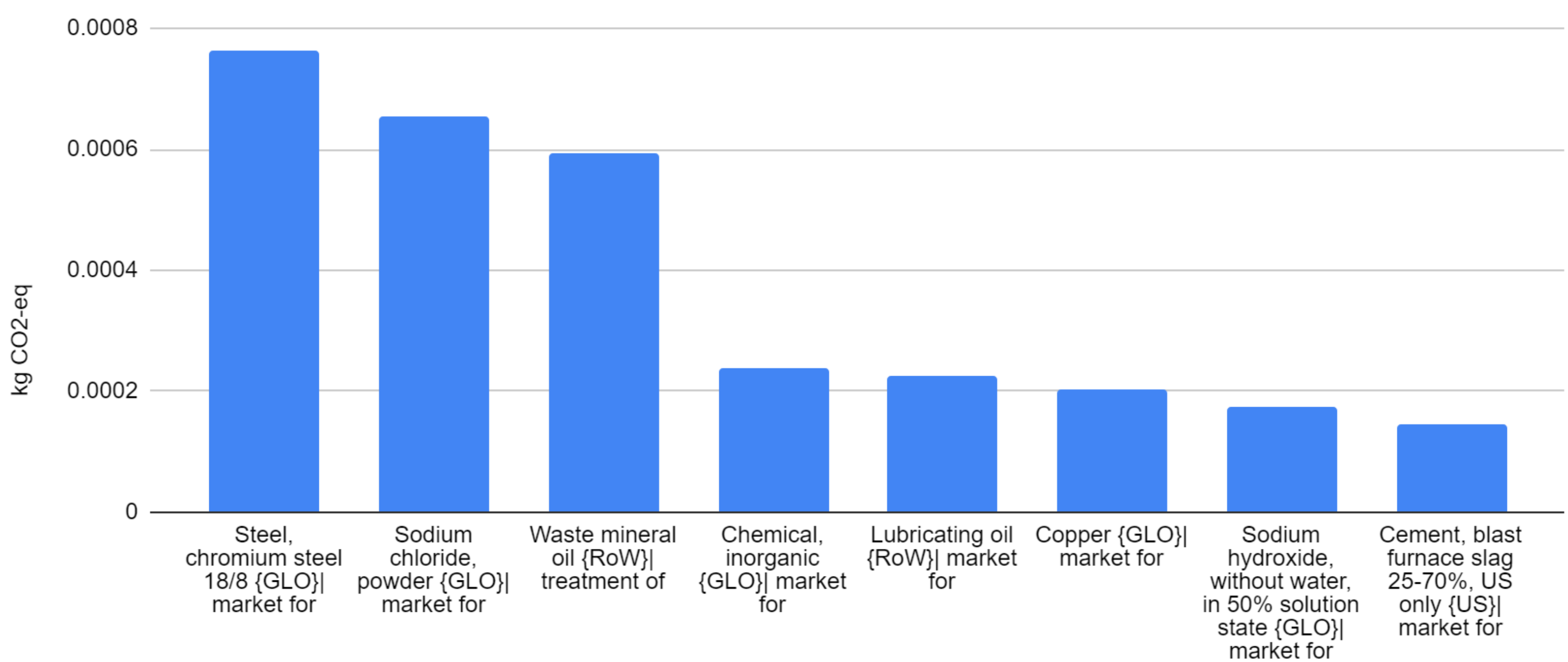

Figure D.2: IMPACT 2002+ Method results for minor process contributions to the global warming midpoint category.

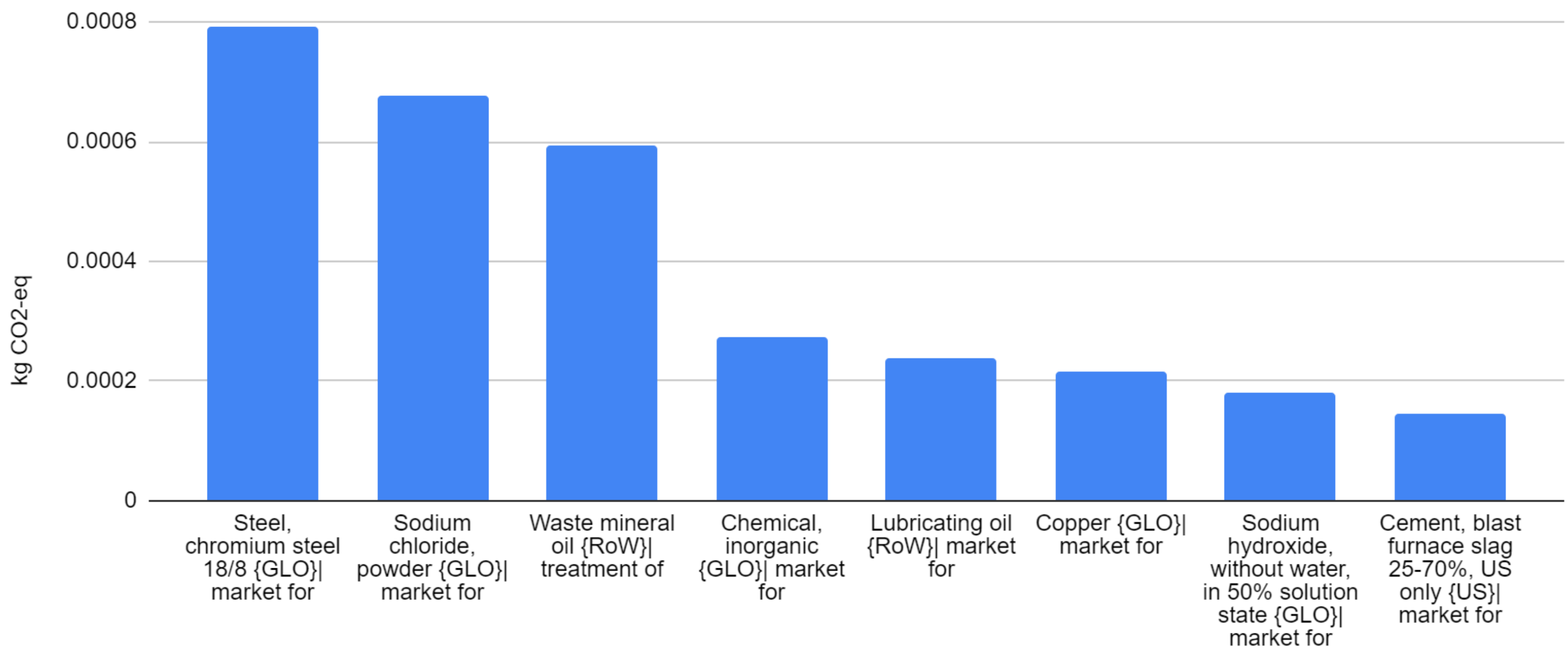

Figure D.3: TRACI Method results for minor process contributions to the global warming midpoint category. There are slightly higher contributions from stainless steel and copper using this method, but it is orders of magnitude lower than the most major contributors.