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Life Cycle Assessment of High Temperature Geothermal Energy Systems

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ABSTRACT

European and French regulations state that 50% of the energy mix in the French Caribbean should be sourced from renewable energies by 2020. Because of the volcanic conditions of the French Caribbean islands, geothermal energy would seem to be a very favorable solution to reach this ambitious objective, as, unlike other renewable sources, it is continuous and weather independent. According to the Intergovernmental Panel on Climate Change (IPCC), geothermal energy source is recognized as a competitive energy source (with a carbon footprint around 50 gCO_{2eq}/kWh over its lifetime) compared to conventional energies such as coal or oil (with a carbon footprint around 800 g $CO_{2\ eq}$/kWh). The IPCC make their overall environmental assessments of energy pathways using Life Cycle Assessment (LCA). LCA assesses the environmental and human health impacts throughout the life cycle stages of a product by providing a “cradle-to-grave” environmental profile. A LCA of an existing high temperature geothermal system is reported here with two objectives: quantifying the environmental impacts of a geothermal plant installed in the French Caribbean islands, and comparing and identifying technological alternatives which potentially reduce its environmental impacts. The geothermal power plant assessed in this study is Bouillante geothermal power plant located in the Guadeloupe island. Built in the 80s, Bouillante is a high temperature geothermal system (the reservoir temperature is around 250°C) which is representative, in terms of size, spatial and technological constraints, of future power plants to be developed in French overseas territories. Its medium size (15.75 MW) enables it to supply 6 to 7% of Guadeloupe’s annual electricity needs. It has two production units: UB1, a double flash technology (4.75 MW), and UB2, a simple flash technology (11 MW). The data inventory is mainly based on site-specific data, extracted from drilling reports: annual environmental and exploitation reports, and technical sheets completed with personal communication with experts. This power plant however presents some unusual design configurations related to the age of its construction: use of a sea water cooling system and absence of geothermal fluid reinjection. To model a configuration that fits better with current practices, two new scenarios based on alternative technologies are considered: a cooling tower or air dry cooling condensers. Three scenarios are assessed via a multicriteria approach using a selection of life cycle environmental indicators: climate change, water consumption, eutrophication, land use, ecotoxicity, primary energy demand, abiotic depletion, acidification and human toxicity. These environmental indicators are assessed at all phases of the plant life cycle: drilling, construction and installation of the surface equipment, operation, and end of life (decommissioning).

First results show that greenhouse gases (GHG) are mostly generated at the operation step (around 90% of total GHG) and are mainly due to leakage of CO_2 and CH_4 emissions (a geothermal stream is composed of non-condensable gases fraction such as CO_2, and CH_4 which are emitted due to the decrease in pressure). Results range from 38 to 47 gCO_{2eq}/kWh over the 3 scenarios. Primary energy demand is mainly due to the construction and installation phase (around 70% of total energy consumption) from background processes such as steel or copper production processes. The primary energy demand and GHG for the reference scenario and the cooling tower system alternatives are found to be lower than those for the aerocondenser cooling system scenario (for the same energy production). As an outcome of the study, we establish the development of a general parameterized LCA model developed for conventional geothermal systems with a temperature reservoir ranging from 230°C to 300°C. Results obtained from this model enable high temperature geothermal systems to be positioned from an environmental perspective in comparison with other energy systems, and also highlight the main drivers leading to the reduction of environmental impacts of future geothermal systems.

1. INTRODUCTION

Strong incentives and regulations are found at European and National levels to promote and include renewable energies in the energy mix by 2020 [European Parliament and Council 2009]. For the French overseas territories, French regulations, referred to as *Grenelle* Laws [Loi n°2009-967 2009] [Loi n°2010-788 2010] are particularly ambitious aiming to ensure that 50% of energy production comes from renewable energies by 2020, and achieving energy self-sufficiency by 2030. Despite their high natural potential of renewable energies, the current electricity production of these territories is, however, essentially based on imported fossil energies (70 to 90% of the electricity production). In 2006, for example, the energy dependence rate in the French West Indies was over 90% [INSEE Antilles-Guyane and DRIRE Antilles-Guyane 2010]. To reach the 2020 and 2030 targets, there is a need for a strong development of combined renewable energies, including geothermal energy. Considering the specific volcanic context of these French overseas territories (hot spot of La Reunion and subduction area of the Lesser Antilles), geothermal energy appears today as one of the very favorable solutions for supplying a high proportion of the local energy needs [Sanjuan et al. 2011]. A power plant is already running in Guadeloupe (Bouillante) and supplies 7% of the local energy needs and a strong increase of this renewable energy is possible and expected.

To favor good conditions for renewable energy deployment, the assessment of its environmental impacts is needed. LCA is a relevant tool to assess the environmental and human health impacts throughout the life cycle stages of a product by providing a “cradle-to-grave” environmental profile [ISO 14040 2006]. It has been applied successfully to renewable energies [Ness et al. 2007] accounting for their specificities: environmental performances of renewable energy systems highly depend on their geo-localization and are driven by external factors influencing electricity production over the lifetime of an installation [Blanc et al. 2008]. In the geothermal context, these geo-dependent factors are the reservoir characteristics (well depth, water availability,…) [Clark et al. 2009], the reservoir temperature [Frick et al. 2010], [Sullivan et al. 2010], or the geothermal fluid flow rate [Sullivan, Clarck, Yuan, Han and Wang 2010].

Currently, there are few publications related to the environmental assessment of geothermal systems [Bayer et al. 2013]. These LCA geothermal references can be classified according to technical particularities: the type of energy produced (electricity or combined district heat and electricity), the type of reservoir (conventional or unconventional) and the type of conversion technology. The classification of these LCA geothermal references is reported in Table 1.

Table 1: The classification of published LCAs of geothermal energy production according to the type of energy produced, reservoir and conversion technology

Classification of references		Publications
Type of energy produced	Electricity	[Hondo 2005], [Pehnt 2006], [Bauer et al. 2008], [Rule et al. 2009], [Fthenakis and Kim 2010], [Sullivan, Clarck, Yuan, Han and Wang 2010], [Lacirignola and Blanc 2013]
	Combined-production of district heat and electricity	[Clark, Wang, Vyas and Gasper 2009], [Frick, Kaltschmitt and Schröder 2010], [Karlsdottir et al. 2010], [Matuszewska 2011], [Gerber and Maréchal 2012]
Type of reservoir	Conventional or hydrothermal reservoir	[Hondo 2005], [Rule, Worth and Boyle 2009], [Karlsdottir, Palsson and Palsson 2010], [Sullivan, Clarck, Yuan, Han and Wang 2010], [Matuszewska 2011]
	Unconventional reservoir or Hot Dry Rock (HDR) or Enhanced Geothermal System (EGS)	[Pehnt 2006], [Bauer, Dones, Heck and S. 2008], [Clark, Wang, Vyas and Gasper 2009], [Frick, Kaltschmitt and Schröder 2010], [Sullivan, Clarck, Yuan, Han and Wang 2010], [Matuszewska 2011], [Gerber and Maréchal 2012], [Lacirignola and Blanc 2013]
Type of conversion technology	Flash systems (single or double)	[Hondo 2005], [Karlsdottir, Palsson and Palsson 2010], [Sullivan, Clarck, Yuan, Han and Wang 2010], [Matuszewska 2011], [Gerber and Maréchal 2012]
	Organic Rankine Cycle (used a binary fluid)	[Clark, Wang, Vyas and Gasper 2009], [Rule, Worth and Boyle 2009], [Frick, Kaltschmitt and Schröder 2010], [Sullivan, Clarck, Yuan, Han and Wang 2010], [Matuszewska 2011], [Gerber and Maréchal 2012], [Lacirignola and Blanc 2013]

In this literature panel, only two LCA publications provide environmental impacts of a geothermal plant producing electricity from deep aquifer (hydrothermal reservoir) and flash systems conversion technology corresponding to the Bouillante configuration: [Hondo 2005] and [Sullivan, Clarck, Yuan, Han and Wang 2010]. Results from these studies are focused on greenhouse gases (GHG) emissions.

Considering the lack of available LCAs fitting the geothermal system to be studied, we design our study to perform the LCA of the existing high temperature geothermal system situated in Guadeloupe in Bouillante. The objective is to compare technological alternatives to the present situation with a view to investigating potential reduction of the environmental impacts. Bouillante power plant presents some unusual design configurations related to the age of its construction: use of a sea water cooling system and absence of geothermal fluid reinjection. In order to better represent current practices, two new cooling strategies based on alternative technologies are modelled.

A life cycle inventory is elaborated to enable the modelling of several technical scenarios in a modular way. This inventory is based on the in situ material and energy data collection from Bouillante plant (scenario 1). We then perform the environmental assessment with characterization methods as recommended by ILCD [European Commission et al. 2011]. These results are interpreted to compare three scenarios. Results are positioned according to existing literature on the LCA of geothermal energy and to other energy production pathways. From these specific geothermal system LCA results, we also initiate the building of a general LCA model for conventional geothermal systems with a temperature reservoir ranging from 230°C to 300°C.

2. THE LCA MODEL FOR BOUILLANTE HIGH TEMPERATURE GEOTHERMAL SYSTEM

Our LCA study is defined according to the ISO standard and follows the ILCD recommendations [European Commission, Joint Research Centre and Institute for Environment and Sustainability 2011]. As a first step it is necessary to define the system function and the functional unit. These elements are essential to characterize the studied systems. The functional unit corresponds to the comparison basis and must be common to all assessed alternatives [Clift et al. 2000], [ISO 14040 2006].

2.1 System function and functional unit

High temperature geothermal systems are used in French Caribbean territories to produce electricity only. In this context, the production of electricity is chosen as the function of the system. The functional unit is set in this study to the kWh of net energy produced (injected on the electricity network) by a geothermal plant over a fixed operating period of 30 years. The system boundaries include energy and material flows of the plant, including the cooling system, the surface and sub-surface equipment related to the geothermal fluid loop connected to construction and installation, the operation and the end of life phases.

2.2 Presentation of the scenarios

Bouillante geothermal plant presents some unusual design configurations related to its relatively old construction: use of a sea water cooling system and absence of geothermal fluid reinjection. To model an installation better fitting current and future technical configurations, two new scenarios based on alternative technologies are investigated.

2.2.1 The base scenario (Bouillante case)

The base scenario represents the current Bouillante power plant. In the 70s, the first drillings allowed the determination of the geothermal potential of the Guadeloupe Island. Between 1970 and 2005, different steps of well construction and administrative change owner occurred. The base scenario is based on the operation of Bouillante plant since 2005. Currently, Bouillante power plant has two production units: UB1 with a power of 4.75 MW and UB2 with a power of 11MW. The reference year for the electric production is 2007 which corresponds to an annual production of 95 GWh (with a load factor[1] of 0.83).

The geothermal fluid is extracted from the reservoir thanks to production wells and is sent into a high pressure separator (HP) which separates steam from water. Then, steam is dried in the HP dryer and sent to the turbine unit B2 and turbine unit B1. Part of the separated water passes into the low pressure separator (LP) that generates a second steam flow for the second-stage of turbine unit B1 (the power unit B2 does not have low pressure stage). The steam activates the turbines, which then drive the generator and produce electricity. The transformer adjusts the voltage before injection of the electricity into the network. At the turbine, the non-condensable gases contained in the geothermal steam are isolated and released to the atmosphere by the vacuum group. Barometric condensers, supplied by sea water, condensate the steam from the turbine by direct-contact. The condensed steam and cooling seawater are then collected by two mixing basins before going to the atmospheric condenser (which also received the water separated from the separator). The whole mixture is cooled by seawater pumped and direct contact with the atmosphere before being discharged into the sea through outfall structures. Each unit has its own pumping station to supply it with the necessary seawater for the cooling system.

Recognizing the initial research purpose of Bouillante, its technical configuration is very specific. These features cover the use of sea water by direct contact to cool the geothermal fluid, the release of geothermal fluid in the sea via a rejection canal, the absence of geothermal fluid reinjection as well as the absence of gaseous treatment. These technical characteristics were taken into account in the environmental assessment of the base scenario, while recognizing that these specific features would not be reproduced in the future geothermal power plants in the Caribbean context.

2.2.2 Scenario 2a and 2b

The definition of prospective scenarios enables a comparison of different technologies expected to be implemented in future geothermal power plants, such as a different cooling system or the reinjection of geothermal fluid. The definition of two alternative scenarios focuses on technical practices to be implemented in the future but not on technical options like the conversion technology.

We have considered two solutions:

- scenario 2a : a cooling system by evaporation on wet tower and geothermal fluid reinjection;
- scenario 2b : a cooling system by aerocondenser (closed circuit) and geothermal fluid reinjection.

The choice of alternative solutions for the cooling system like Bouillante power plant is complex as the cooling system has to integrate local conditions such as water availability or resource scarcity. Both solutions have advantages and drawbacks: the wet tower cooling system requires water consumption but has a reduced noise level (important parameter to consider in urban area) while the performances of an aerocondenser cooling system could be somehow reduced because of the Caribbean territories climate which has a high humidity saturation level.

2.3 Life cycle inventory

Two types of activities are distinguished in the inventory, namely foreground and background activities. Foreground activities correspond to activities directly related to the studied system (the Bouillante geothermal plant) and for which specific data are used. The latter are mainly collected from reports and interviews with experts of CFG Services (the Bouillante operating company) and of Geothermie Bouillante (GB, the owner of the geothermal power plant). Background activities correspond to activities supporting the system function (i.e. materials and fuels extraction and transformation, transports and end-of-life of equipment) and for which the level for initiatives is more limited. In our study, these background activities are essentially modelled using generic data, considering the ecoinvent v2.2 database.

The characteristics of the Bouillante geothermal reservoir configuration are the following:

- based on a fractured volcanic reservoir containing ground water about 250°C;
- with a main high permeability area located at more than 500m depth;
- covered by a low permeability area allowing the thermal confinement of the system;
- fed by marine and meteoric waters.

A specific drilling scheme based on four sections of homogeneous diameter (18"5/8; 13"3/8; 9"5/8 and 7") has been considered.

[1] Load factor: annual functioning rate of the plant.

2.3.1 Data collection procedure

The Life Cycle Inventory (LCI) calculation is based on the compilation of all inputs (materials, resources and energy consumption) and outputs (emissions and waste) involved in the various stages of the life cycle of the geothermal plant. The LCI is built distinguishing 5 life cycle stages, as detailed below. All data are reported per kWh of geothermal electricity (the functional unit), considering 2850 GWh of overall production over the assumed 30-year lifetime of the plant. The data used for the inventory of scenario 1 are now described. A final paragraph is dedicated to the specificities of the inventories related to scenarios 2a and 2b.

The phases of drilling exploration and production wells are both accounted for distinctly, but are gathered in the inventory due to the predominance of drilling operations in these two phases. Depending on geology, resource enthalpy and well-depths, the drilling of wells may be unsuccessful. We consider an average success rate of 74%, and a constant 5.4 MW electric power per production well [International Finance Corporation 2013]. To get 15.75 MW we therefore have to consider four production wells.

The quantities of materials and fuels required for drilling operations, cementation and casing are compiled from the daily and final drilling reports related to one Bouillante well in the years 2001-2002. Prior to the drilling of production wells, deep exploration wells are required to provide the confirmation of the existence of an important reservoir. In this study, the phase of exploration drilling wells encompasses site preparation (including roads construction) in addition to drilling operations with a drilling rig. Three deep exploratory wells are assumed to be necessary on average [DiPippo 2012]. In the absence of any data on the drilling of exploration wells specific to Bouillante power plant, the inventory compiled for production wells is used as a proxy. Scaling factors of 0.5 and 0.3 are assumed regarding respectively cement and steel, to account for the lower diameters of exploration wells (ratio between diameter exploration well and diameter production well).

The phase of construction and installation takes into account the manufacturing, installation and land-use related to subsurface equipment, premises and surface equipment. Their maintenance is also included considering the assumed 30-year plant lifetime. The following equipment is accounted for in the inventory: well head unit, steam inlet unit, separator unit, separator pipeline, turbo-generator unit, condensers and vacuum creation, pumping station and release, electric and control system, lubricating and back up control system. The corresponding data (type of equipment, materials, lifespan and quantities) are compiled from reports on plant operation (2006, 2007 and 2012), from a report on plant environmental impacts [Caraïbes Environnement 2011], from equipment technical sheets and delivery orders from manufacturers, completed with interviews with experts from CFG Services, GB and BRGM (The French Geological Survey).

Three types of emissions occur during the plant operation. Emissions to atmosphere (mainly of CO_2, H_2S and CH_4) originate on the one hand from the condensers, where non-condensable gases are removed by vacuum pumps, and on the other hand from the cooling system related to degassing of liquid effluents. Occasional discharges of brine (purges) are emitted to the ground at the shutdown of operations. The seawater and geothermal fluid effluent is discharged into the sea. These emissions are quantified based on yearly reports on plant operation (2006, 2007 and 2012) and on the study of the plant environmental impacts [Caraïbes Environnement 2011]. Furthermore, during the operation phase, supplementary wells are drilled in order to replace the old wells with a decreasing productivity during the plant lifetime. It is assumed that the productivity decreases by 38% after 30 years of operation [International Finance Corporation 2013], so that 1.1 additional wells are required to be drilled during the operation phase.

Data on the closure of wells is approximated from ecoinvent v3 data related to the closure of a borehole of 6000 m depth for geothermal power generation in an unspecific rock formation. Moreover, in the absence of information on the end-of-life treatments of equipment at Bouillante power plant, generic scenarios are considered. Extrapolating from UNEP report on metal recycling [United Nations Environment Programme and International Resource Panel 2011], 50% recycling and 50% landfilling is assumed regarding copper, and 70% recycling and 30% landfill regarding steel. All other materials (including plastics, concrete, and fiberglass) are assumed to be entirely landfilled. Recycled waste material is assumed to substitute for primary produced material, without considering any correction factor. The landfill and recycling operations are assumed to take place around Bouillante in Guadeloupe.

Scenarios 2a and 2b do not represent the current situation at Bouillante. They are therefore not based on real plant data but rather on data compiled from pre-feasibility reports at Bouillante and Wotten Waven Geothermal fluid (Dominica) [B.P. Power 2003], [Verkis 2008] and from technical sheets, completed with the LCI performed by [Lacirignola and Blanc 2013] and interviews of experts from CFG-Services. Geothermal reinjection involves returning all extracted water from the reservoir back into the geothermal system. The production well over injection well ratio is assumed to be 1:1, while the rate of success for reinjection well drilling is assumed to be 74%, as in the case of production wells. The required additional injection pumps are accounted for by using data on Bouillante surface pumps and control system as a proxy. No supplementary wells are considered to be necessary during the operation of the plant, due to the additional recharge provided by the fluid reinjection. Data on new cooling systems (materials and mass) are compiled by use of technical sheets and by extrapolating from an EGS geothermal plant [Lacirignola and Blanc 2013].

2.3.2 Aggregated data tables

According to the inventory procedure, we generate an aggregated input data table per each of the life cycle phase expressed per kWh (Table 2).

Table 2: Synthesis of inputs and outputs relatively to the production of 1 kWh geothermal electricity, in scenario 1 (Bouillante)

Life Cycle Phase	Element	Quantity	Unit/kWh
Drilling of exploration and production wells	Land use	1.20E-06	m².an
	Road construction	1.41E-06	m²
	Materials for drilling (gravel, concrete, steel mud, cement and sand)	4.98E-03	kg
	Diesel	5.00E-03	MJ
	Road transport	3.16E-04	t.km
	Ship transport	7.77E-03	t.km
	Disposal of mud and mineral waste	2.73E-04	kg
	Total emissions of pollutants to water	8.63E-06	kg
	Land use	1.73E-04	m².an
	Minerals	1.05E-03	kg
Construction and installation	Material for construction and installation (concrete, cement, steel, copper, plastics and electronics components)	6.58E-03	kg
	Road transport	7.38E-04	t.km
	Ship transport	6.46E-03	t.km
	Diesel	1.51E-05	MJ
	Lubricating oil	6.51E-05	kg
Operation	Use of water	6.88E-01	m^3
	Occasional discharges of brine to ground	6.43E-05	kg
	Permanent discharges of Cl^- to the sea	2.94E+01	kg
	Permanent discharges of SO_4^{2-} to the sea	3.95E+00	kg
	Permanent discharges of NH_4^+ to the sea	8.21E-04	kg
	Other permanent discharges to the sea	3.07E+00	kg
	Direct CO_2 emissions to atmosphere	4.16E-02	kg
	Direct H_2S emissions to atmosphere	1.02E-03	kg
	Direct CH_4 emissions to atmosphere	3.26E-06	kg
	Drilling of additional production well	3.86E-10	unit
Decommissioning	Recycling of steel and copper	6.42E-04	kg
	Landfilling of metals	2.77E-04	kg
	Landfilling of minerals	9.19E-03	kg
	Landfilling of plastics	3.14E-06	kg
	Cement for wells closure	2.22E-06	kg
	Gravel for wells closure	2.34E-05	kg

2.4 Construction of the LCA model for high temperature geothermal systems

Based on the specific Bouillante power plant inventory, we can now extrapolate and built a general LCA model for conventional geothermal systems with a temperature reservoir ranging from 230°C to 300°C. This model is represented on Figure 1.

The aggregation of environmental impacts associated to the life cycle steps permits the determination of total impact of geothermal power plant. This impact is brought back to the electricity production (*electricity production* on Figure 1) providing the environmental performances of geothermal power plant according to the kWh produced (functional unit of our system). The electricity production accounts for the lifetime (*lifetime*) of the geothermal power plant and for its load factor (*load factor*).

This model is built accounting for the explicit relations between the input variables and the specific parameters of Bouillante geothermal system.

<u>2.4.1 Exploration and production drilling phases</u>

The drilling length depends on two parameters:

- the depth of the geothermal reservoir (*reservoir depth (sections 1 → 3)* in Figure 1) which correspond to the first three sections of the well;
- the depth which is necessary to drill within the geothermal reservoir to obtain the focus resource (the expected flow rate) (*well depth section 4* related to drilling last section).

In the case of production drilling, the section 1 to 3 lengths are unlikely to vary (they are fixed according to the estimated depth of reservoir (*reservoir depth*)), whereas section 4 has a variable length which depends on the obtained flow rate. The total drilling length is specific to the geothermal site. The reservoir depth is generally correctly estimated and described precisely *via* projected logs. On the other hand, the total length of drilling and more particularly the last section is likely to vary.

The material quantities related to the drilling step are proportional to the number of wells to drill in exploration and production steps (*number of exploration wells*, *production wells* and *reinjection wells*). For our study, the number and the type of drilling related to the functional unit are the following:

- the number of production wells is related to the well potential electric power (*well potential electric power*) (energy produced by each well) to the net power of geothermal power plant (*net power*) and to the success rate (*success rate*) associated to the drilling realization;
- the number of reinjection wells (for the scenarios with reinjection modelling) is related to the number of production wells (*number of production wells*): a ratio 1 to 1 between the reinjection wells and the production well is selected.

The well potential electric power parameter is set to a constant value for our three scenarios but could be variable in a more generalized parameterized geothermal power plant model.

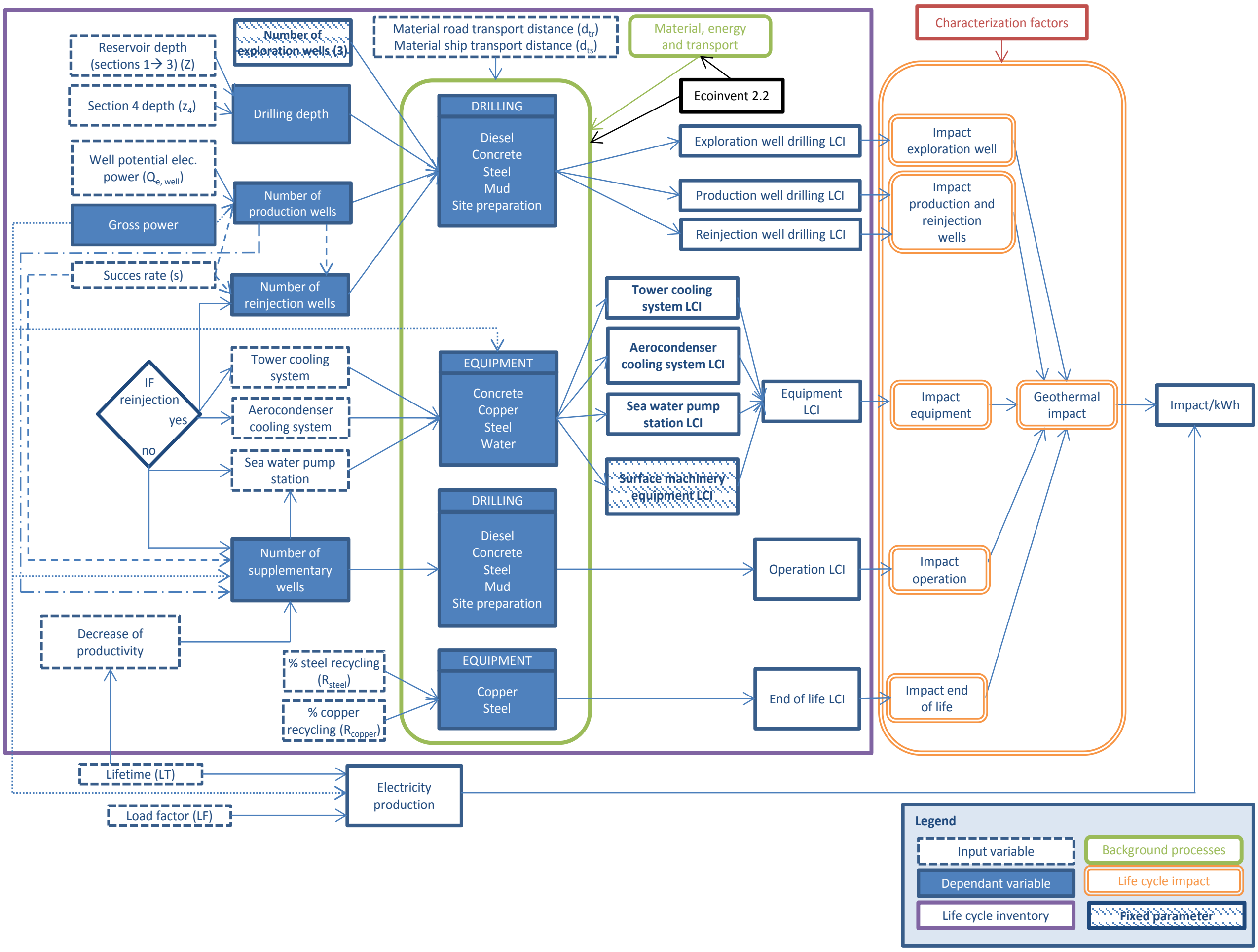

Figure 1: LCA model of conventional geothermal power plant in Caribbean context for a reservoir temperature range = [230°C; 300°C]

2.4.2 Power plant construction and installation phase (equipment)

The construction and installation phase aims to model the construction of surface and cooling system equipment. The reference model considers the following solutions:

- scenario 1: configuration of geothermal power plant without fluid reinjection in the geothermal reservoir (*IF reinjection – No*). In this case, the cooling system is based on seawater use, and includes the pump station construction (*sea water pump station LCI*). In this scenario, the non-reinjection of geothermal fluid leads to supplementary wells (*number of supplementary wells*) offsetting the decrease of productivity (*decrease of productivity*) modelled in the operation step;
- scenarios 2a and 2b: configuration of geothermal power plant with fluid reinjection in reservoir (*IF reinjection – Yes*) leads to drilling reinjection wells (*number of reinjection wells*) (with a ratio 1 for 1 with production wells). In these scenarios, the modelled cooling systems are: tower cooling system (*tower cooling system*) or aerocondenser cooling system (*aerocondenser cooling system*). Next, two inventories related to both cooling systems are built (*tower cooling system LCI* and *aerocondenser cooling system LCI*).

Concerning the surface machinery equipment (*surface machinery equipment LCI*), we suppose it to be similar for the three scenarios and related to the gross power (the reference gross power being the UB2 unit production of Bouillante power plant).

2.4.3 Operation phase

Input variables differ according to the scenario:

- scenario 1: configuration of geothermal power plant without fluid reinjection in reservoir (*IF reinjection – No*).

The absence of reinjection leads to a decrease of reservoir productivity (*decrease of productivity*) which is related to the lifetime of geothermal power plant (*lifetime*). The number of supplementary wells is related to the gross power (*gross power*), the success rate (*success rate*) and the number of production wells (*number of production wells*).

- scenarios 2a and 2b: configuration of geothermal power plant with fluid reinjection in reservoir (*IF reinjection – Yes*).

In our study, when a geothermal fluid reinjection in the reservoir is set, we suppose there is no decrease of productivity nor supplementary wells-drilling. The assumption of no considering productivity decrease is taken at first to simplify the modelling. However this assumption would deserve further analysis.

The main input variables associated to this step are the choice of reinjection or not, the drilling of supplementary wells, the installation lifetime and the number of reinjection wells.

2.4.4 End of life phase

This step aims to model the dismantling of the geothermal power plant and more particularly the surface equipment. The percentages of recycling are variable inputs (*% steel recycling* and *% copper recycling*). For sub-surface equipment, we suppose no dismantling (this assumption has been shared with geothermal experts). The reference model considers a single scenario for the equipment material for all scenarios:

- steel and copper equipment are recycled (70% for steel and 50% for copper);
- plastic equipment are not recycled.

The manufacturing of material such as steel, concrete or copper is issued from ecoinvent v2.2.

3. RESULTS

3.1 Comparison of scenarios

The environmental impacts associated with the life cycle of the three scenarios are assessed according to fourteen impacts categories (Table 3). In particular, in the case of scenario 1 (Bouillante power plant), the environmental impact potentials associated with the delivery of 1 kWh amounts to 47.0 g CO_2eq in terms of climate change and 82.8 kJ in terms of non-renewable energy. The impact in terms of climate change however decreases to 38.5 g CO_2 eq/kWh in the case of scenario 2a and to 73.5 kJ/kWh for non-renewable energy consumption. For scenario 2b, the result for change climate is 39.4 g CO_2 eq/kWh and 92.7 kJ/kWh for non-renewable energy.

Table 3: Impact Assessment results for the scenarios 1, 2a and 2b, considering 14 impact categories

Impact categories	Units (/kWh)	S1	S2a	S2b
IPCC GWP 100a	kg $CO_{2\ eq}$	4.70E-02	3.85E-02	3.94E-02
Ecological scarcity2006 water consumption	UBP	1.05E-02	8.17E-03	1.24E-02
ReCiPe, freshwater eutrophication	kg P_{eq}	1.68E-06	1.44E-06	2.01E-06
ReCiPe, marine eutrophication	kg N_{eq}	6.42E-04	1.33E-06	1.83E-06
CML2, terrestrial eutrophication	kg $PO4^{---}_{eq}$	2.80E-04	8.04E-06	1.03E-05
ReCiPe, natural land transformation	m²	3.56E-06	4.24E-06	4.70E-06
USEtox, ecotoxicity	CTUe	2.80E-02	2.12E-02	2.70E-02
CML2, abiotic depletion	kg Sb_{eq}	3.71E-05	3.36E-05	3.96E-05
CED Non-renewable	MJ	8.28E-02	7.35E-02	9.27E-02
CED Renewable	MJ	9.19E-04	8.17E-04	1.20E-03
ReCiPe agricultural and urban occupation	m²a	3.74E-04	3.91E-04	5.22E-04
USEtox Human toxicity (cancer)	CTUh	2.23E-13	1.67E-13	3.04E-13
USEtox Human toxicity (no cancer)	CTUh	1.16E-12	1.13E-12	1.43E-12
CML2, acidification	kg SO_2 eq	1.95E-3	1.61E-3	1.61E-3

Compared to scenarios 2a and 2b, scenario 1 contributes significantly more to climate change, acidification, terrestrial and marine eutrophication categories (Table 3 and Figure 2). For the agricultural and urban occupation as well as for natural land transformation categories, scenarios 2a and 2b contribute significantly more than scenario 1. For all other impact categories (water consumption, fresh water eutrophication, abiotic depletion, cumulative energy demand (renewable and non-renewable) and human toxicity (carcinogenic and non-carcinogenic), scenario 1 is intermediate between scenario 2a and 2b. Compared to scenario 1, both scenarios 2a and 2b generate the lowest local environmental impact (marine and terrestrial eutrophication).

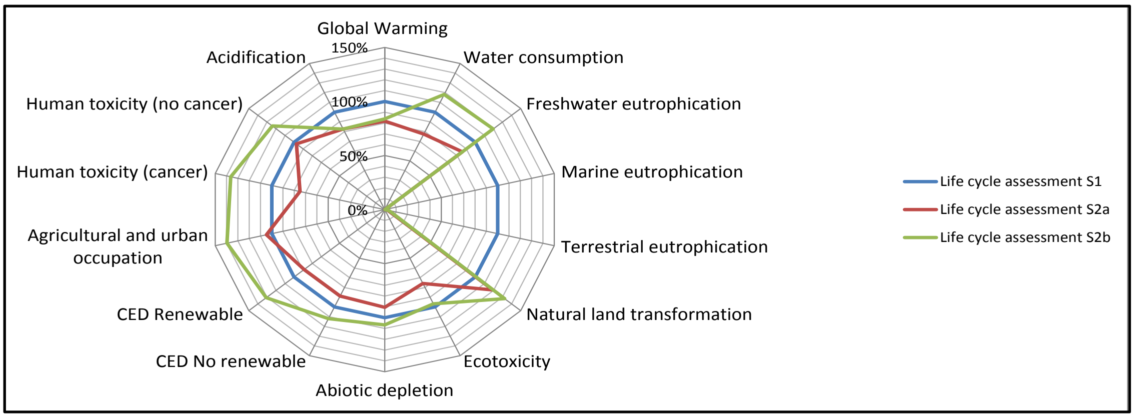

Figure 2: Environmental impact potentials of the three scenarios, considering scenario 1 as the reference (100%) for each impact category

3.2 Identification of key processes and parameters

The processes mostly contributing to the different impact categories assessed ("key processes") can be identified thanks to Table 4. The contribution of each life cycle phase to each impact category may be identified:

- the drilling phase contributes most to natural land transformation;
- the construction and installation phase shows the larger contribution to impacts on water consumption, fresh water eutrophication, ecotoxicity, abiotic depletion, cumulative energy demand (renewable and non-renewable), agricultural and urban occupation and human toxicity (with carcinogenic and non-carcinogenic effects). These impacts are related to background process (steel production);
- the operation phase contributes most to climate change, due to the direct release of CO_2 and CH_4 emissions to atmosphere, acidification (H_2S emissions), marine and terrestrial eutrophication (NH_{4+} emissions) impact categories;
- the end of life phase does not significantly contribute to any impact category.

Table 4: Environmental impact analysis according to the most polluting processes

Impact categories	Life cycle step	Relative contribution of each life cycle step			Key processes identified
		S1	S2a	S2b	
Climate change	Operation	89%	90%	87%	Release of non-condensable gases to atmosphere (CO_2 and CH_4)
Water consumption	Construction and installation	87%	75%	142%*	Resources used for the steel manufacturing
Cumulative Energy Demand – non-renewable	Construction and installation	77%	61%	153%*	Resources used for the steel manufacturing
Cumulative Energy Demand – renewable	Construction and installation	99%	92%	170%*	Resources used for the steel manufacturing
Human toxicity with carcinogenic effects	Construction and installation	84%	86%	139%*	Steel manufacturing process
Human toxicity with non-carcinogenic effects	Construction and installation	207%*	222%*	228%*	Steel manufacturing process
Fresh water eutrophication	Construction and installation	141%*	132%*	258%*	Steel manufacturing process
Marine eutrophication	Operation for S1 and construction and installation for S2a and S2b	100%	61%	133%*	Permanent releases of effluents to the sea (ammonium)
Terrestrial eutrophication	Operation for S1 and construction and installation for S2a and S2b	97%	89%	199%*	Permanent releases of effluents to the sea (ammonium)
Natural land transformation	Drilling	75%	79%	71%	Preparation and transformation of drilling site for production wells

Impact categories	Life cycle step	Relative contribution of each life cycle step			Key processes identified
Agricultural and urban occupation	Construction and installation	102%*	99%	144%*	Excavation, transformation and sols occupation for power plant
Ecotoxicity	Construction and installation	47%	48%	169%*	Steel manufacturing process
Abiotic depletion	Construction and installation	84%	67%	176%*	Steel manufacturing process
Acidification	Operation	99%	99%	99%	Release of non-condensable gases to atmosphere (H_2S)

*The indicated percentages correspond to proportions of generated and avoided impacts (for the end of life step), which explains the fact that some percentages are superior to 100 %.

According to this environmental result analysis, it is possible to identify the four discriminating physical parameters driving the differences observed among the scenarios:

- the steel quantity used, related to equipment;
- the quantity of non-condensable gases emitted;
- the quantity of effluents (geothermal fluid + seawater) released to the sea;
- the total number of wells (exploration, production and reinjection).

Considering the life cycle as a whole, the power plant construction and installation phase has the greatest impact of all the impact categories assessed. The analysis of scale of impacts shows that a majority of environmental impacts are related to background activities and more particularly to the steel manufacturing process. For these background activities, the decision maker has no direct action. Foreground activities contribute to climate change, acidification, marine and terrestrial eutrophication impact categories and more particularly in the case of scenario 1.

The comparison of the three scenarios allows the identification of the environmental benefits of the reinjection scheme, despite the drilling of supplementary wells for reinjection wells. To limit the emissions of non-condensable gases, it could be profitable to set up a gaseous system treatment. This would significantly reduce emissions to air and more particularly CO_2 and CH_4 emissions as well as H_2S emissions to reduce the installation odor impact (impact not assessed in this study).

3.3 Comparison with the literature

Concerning the geothermal pathway and its related impacts on climate change, it is possible to compare our results with the literature (Figure 3). The Life Cycle GHG respectively range from 22 $gCO_{2\,eq}$/kWh to 80 $gCO_{2\,eq}$/kWh for EGS and from 5 $gCO_{2\,eq}$/kWh to 100 $gCO_{2\,eq}$/kWh for flash technology whereas few grams of $CO_{2\,eq}$/kWh are estimated for binary technology. The results related to the three scenarios 1, 2a and 2b presented above therefore lie within the range of values found in the literature.

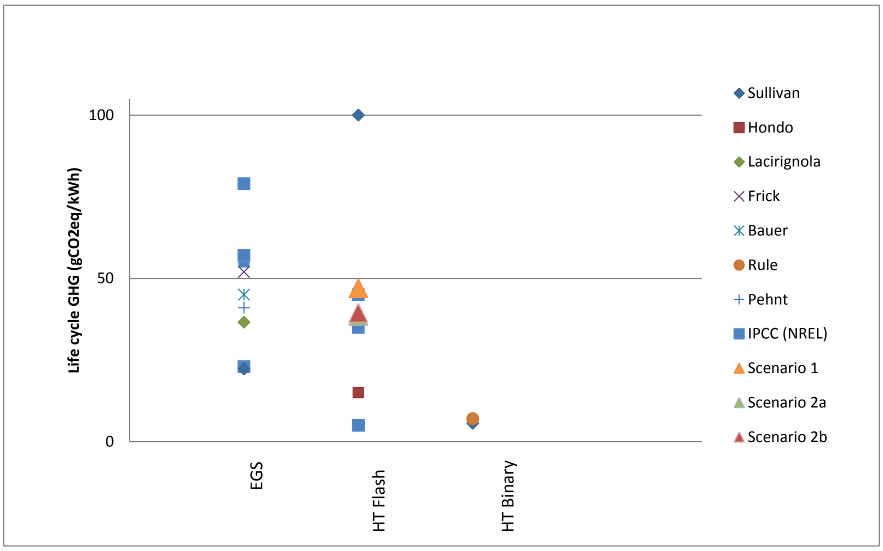

Figure 3: Comparison of Life cycle GHG associated with geothermal electricity production (in CO_{2eq}/kWh), based on a literature survey and considering different technologies

These values may be put in perspective with GHG performances for other electricity production systems. According to the IPCC study reporting LCA literature reviews for energy pathways, the median value of GHG for geothermal energy is 45 $gCO_{2\,eq}$/kWh, is 46 $gCO_{2\,eq}$/kWh for photovoltaic energy, 12 $gCO_{2\,eq}$/kWh for wind technology, 16 $gCO_{2\,eq}$/kWh for nuclear technology, around 470 $gCO_{2\,eq}$/kWh for natural gas technology, 840 $gCO_{2\,eq}$/kWh for oil technology and more than1000 $gCO_{2\,eq}$/kWh for coal technology [IPCC 2011].

4 CONCLUSION

LCA is applied to determine the environmental impacts of the existing Bouillante power plant by comparing technological alternatives such as different cooling systems or the modelling of geothermal fluid reinjection. The study is based on site-specific data extracted from Bouillante documentation such as technical reports, equipment plans, purchase orders, completed by discussion with geothermal experts from CFG Services and Géothermie Bouillante SA.

The main conclusions of the environmental assessment are:

1. considering climate change, GHG values range from 38.5 to 47 $gCO_{2\ eq}$/kWh, in line with results found in the literature [Hondo 2005], [Sullivan, Clarck, Yuan, Han and Wang 2010], [IPCC 2011].
2. prospective scenarios 2a and 2b generate the lowest local environmental impact, in particular for global warming, acidification, marine and terrestrial eutrophication;
3. prospective scenario 2b generates the largest environmental impact related to background process and more precisely related to steel production. Optimizing the equipment size is a key element in minimizing the environmental impacts of such installation.
4. the assessment illustrates the environmental benefits of geothermal fluid reinjection and more particularly for marine and terrestrial eutrophication impact categories. Indeed, the geothermal fluid effluent mixed with the cooling seawater contains ammonium elements. The geothermal fluid reinjection allows these releases into environment to be avoided.

Based on the specific Bouillante power plant inventory, we built a general LCA model for conventional geothermal systems with a temperature reservoir ranging from 230°C to 300°C. Further scaling modelling could be applied to get a parameterized generic model for high temperature geothermal system accounting for variable reservoir depth, success rate, etc. The definition of this type of model is an iterative process which requires improvements and collection of more detailed and systematic data from other installations. Considering scaling modelling, it will be necessary in particular to collect more technical information relating the installation power and the surface equipment material and to extend to other types of conversion technology (binary systems). The generalization of this type of renewable energy technology is also very sensitive to local conditions like the in situ geologic characteristics of the geothermal field. The interest of such reference LCA model is to be representative of the energy pathway [Greenpeace and EREC 2008] and deserves further study.

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