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Life Cycle Assessment and Economic Impacts of the Rittershoffen EGS Geothermal Plant, Upper Rhine Graben, France

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ABSTRACT

The Rittershoffen geothermal plant is a deep Enhanced Geothermal System (EGS) project initiated in 2011 and located in Northern Alsace, French Upper Rhine Graben. This geothermal plant, in operation since 2016, supplies 25% of the industrial heat demand of "Roquette Frères" bio-refinery at Beinheim, 10 km east of Rittershoffen. This study assesses the sustainability of this plant with a dual perspective over the complete life cycle covering the exploration and drilling phase, the construction of the geothermal plant, its operation over 25 years and its end of life: i) the economic aspects and ii) the environmental performance. With regard to the economic aspect, the complete life cycle costs were estimated, by accounting for the capital, operational and dismantlement costs. Capital expenditure of this project includes the phases of exploration, drilling and construction of the heat geothermal plant. 25 years of operational costs were considered, and estimation of the power plant dismantlement was also integrated in the study. Life Cycle Assessment (LCA) is widely recognized at the international level as a relevant framework for assessing environmental impacts of energy pathways. The LCA methodology has been applied to assess the environmental performance of Rittershoffen heat plant by generating a comprehensive life cycle inventory necessary to quantify the environmental impacts related to the categories of climate change, human toxicity, particulates matter (PM 2.5) and ionizing radiation. The results of this case-specific study present a comparison of environmental and economic aspects that are rarely analyzed hand in hand in geothermal projects. The development of reliable quantitative assessments of EGS projects may contribute to support the decision-making process, thanks to the identification of the main environmental and economic contributors, and to improve the public acceptance, thanks to a more efficient communication and more transparent information.

1. INTRODUCTION

1.1 Context

Public acceptability of geothermal energy is an important topic for decision makers (Chavot et al., 2018). Access and dissemination of key economic figures as well as environmental performance indicators for geothermal installations are at stake when considering such public acceptability. Environmental assessments have been performed over the last years for a quite large selection of geothermal installations (Eberle et al., 2017; Tomasini-Montenegro et al., 2017) based on Life Cycle Assessment (LCA), mainly focusing on climate change concerns. LCA is a relevant approach for the estimation of a wide range of environmental indicators. Furthermore, it allows identifying, over the total life cycle, the contribution of any phase of the life cycle considered (i.e: the construction, the operation, the end of life) as well any sub-system (i.e: material, electricity consumption, chemical substances). Thanks to the current progress of methodologies based on a life cycle perspective, economic assessments are also currently undertaken following an equivalent approach (Schwab et al., 2009), (Ristimaki et al., 2013). Combining environmental assessment and economic evaluation has not yet been initiated for geothermal installations and such life cycle integrated assessment is proposed in this study.

1.2 The methodology

In this study, we developed an integrated assessment and applied it to the Rittershoffen Enhanced Geothermal System (EGS) located in France in Alsace. We considered four life phases for the Rittershoffen geothermal plant: exploration and drilling phase, geothermal plant construction, operation phase over 25 years and end of life. The contribution of each phase over the life cycle has been investigated, both in the economic assessment and the environmental assessment. Life cycle costs (LCC) reported in this study cover the investment, operational and end of life costs of Rittershoffen power plant. The geographical distribution of the costs has been explored to understand the direct economic benefit for the region of Rittershoffen. Direct employment has also been investigated to highlight its geographical characterization depending on the life cycle phase. The LCA methodology, following the ISO standards (ISO-14040, 2006), (ISO-14044, 2006), has been applied to assess the environmental performance of Rittershoffen heat plant by generating a comprehensive life cycle inventory, necessary to quantify the environmental impacts related to the categories of climate change, human toxicity, particulates matter (PM 2.5) and ionizing radiation. The choice of these indicators is directly linked to the specificity of the geothermal plant. Several scenarios have been studied to investigate the influence of the mix for the feeding electricity on the environmental impacts. As a final step, we developed an integrated life cycle comparison combining both the economics and environmental analysis of the geothermal plant to understand their respective contribution to each phase of the life cycle.

1.3 The Rittershoffen geothermal plant

The Rittershoffen heat plant has been developed to supply geothermal heat to Roquette Frères Company, a bio-refinery, for its industrial processes. This industrial user, located in Beinheim, France, has a total thermal demand of 100 MW_{th}. The geothermal heat plant, with an installed capacity of 27 MW_{th}, provides its entire heat production to this company via an isolated heating transport loop with a 15-km length (Ravier et al., 2017). The geothermal brine is produced at a temperature of 170°C from a production well, GRT-2 at 2700-m depth, penetrating Triassic sedimentary layers and the top crystalline fractured basement interface (Baujard et al., 2015, Baujard et al., 2017). The geothermal brine flows through a system of twelve consecutive tubular heat exchangers (Ravier et al., 2016) and is fully reinjected without injection pump at an average temperature of 80°C into one injection well, GRT-1, with a depth of 2500 m (Figure 1). This reinjection temperature varies depending on the return temperature of the transport loop. The brine flow rate is adjusted to 75-80 kg/s using a downhole production Line Shaft Pump. The geothermal plant has been successfully producing heat under commercial conditions since June 2016.

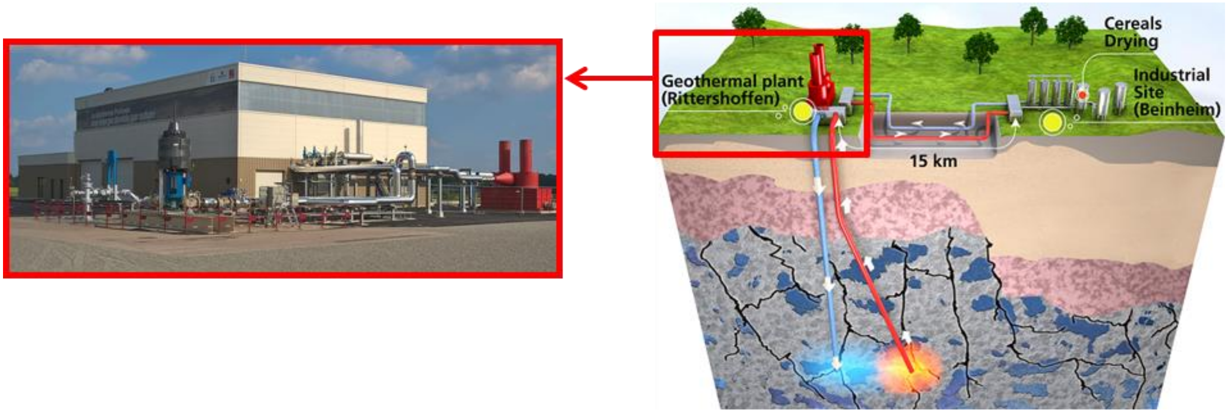

Figure 1: Sketch of the Rittershoffen geothermal project.

2. LIFE CYCLE COSTS AND EMPLOYMENT

2.1 Life cycle costs of the geothermal plant at Rittershoffen

Life cycle costs (LCC) reported in this study cover the investment costs, the operational costs as well as the end of life costs of Rittershoffen power plant. The transport loop and the heat distribution at the bio refinery are excluded in the analysis in accordance with the scope of the study.

The exploration and the drilling costs include the costs of seismic survey, land acquisition, drilling platform, doublet's drilling, and wells testing. Total costs of exploration and drilling were established from the geothermal plant owner's accounting and amount to 21.4 M€. About 84% of the order volume was allocated to French companies. The most important expenses outside of France were related to special service companies for directional drilling, casing cementing, well stimulation and drilling tools.

Geothermal plant construction costs include all the costs such as engineering, leveling works, civil works, building erection, electrics and piping works, as well as specific equipment (pumps, filters, heat exchangers…). These costs were also determined by the geothermal plant owner's accounting and add up to about 9.5 M€. About 83% of these expenses concerned the companies based in France. The downhole production pump, supplied by an American company, was the largest expense outside of France.

Operational costs are related to maintenance and operation of the geothermal plant, on-call team, electricity consumption, consumables (water, chemicals…) and equipment renewal. Rittershoffen geothermal plant has been in operation for nearly three years, since 2016. Thus, plant owner and operator accounting were analyzed to estimate the operation costs. Based on the expenses in 2018, which is a representative operational year because of steady-state operation conditions, operation costs of the geothermal plant at Rittershoffen were estimated to 34.8 M€ over 25 years. More than 90% of operation expenses are related to companies based in France.

The end-of-life costs include wells logging and cementing, pipes cleaning and disassembling, plant dismantling, leveling works, transport required for disposing the used equipment at the waste treatment center and Naturally Occurring Radioactive Material (NORM) disposal. This final step of the plant life cycle is the most uncertain one due to the lack of experience. However, the costs for workover rig rental, as well as logging and cementing could be easily estimated from known drilling costs. Pipes cleaning and disassembling, as well as NORM disposal, were assessed from the experience during operation. Plant dismantling and leveling works were estimated from costs of the plant construction, including materials recycling. A list of possible companies to be involved during the end-of-life phase was established and the cost was estimated to be about 2.5 M€. It was predicted that nearly 88% of the works could be allocated to French companies.

Life cycle cost were investigated both at a local scale (for the department of Bas-Rhin) and at a national scale (France). The life cycle costs of the Rittershoffen geothermal plant were detailed per location and per life cycle steps (Figure 2).

The construction, operation and end-of-life phases have stronger relative impacts on the local economy: respectively 48%, 60% and 57% of the total costs compared to exploration and drilling, which only contributes with 19 % of the total costs. Indeed, drilling and services companies are mostly the oil and gas upstream industry, which is located outside the department of Bas-Rhin or even outside of France. The region around Rittershoffen had an oil production history that ended in the late 1970s so no companies are located there anymore. The company involved in Rittershoffen's drilling was French, but based in Paris area. During drilling, local companies were involved in drilling site preparation and mud disposal. Nevertheless, several orders for electrical, piping, civil works were done by companies located in the area of the Rittershoffen. These companies were involved in the construction of the geothermal plant and were assumed to potentially participate in the end-of-life. During operation, local operators involved in the daily maintenance and exploitation of the geothermal plant are needed.

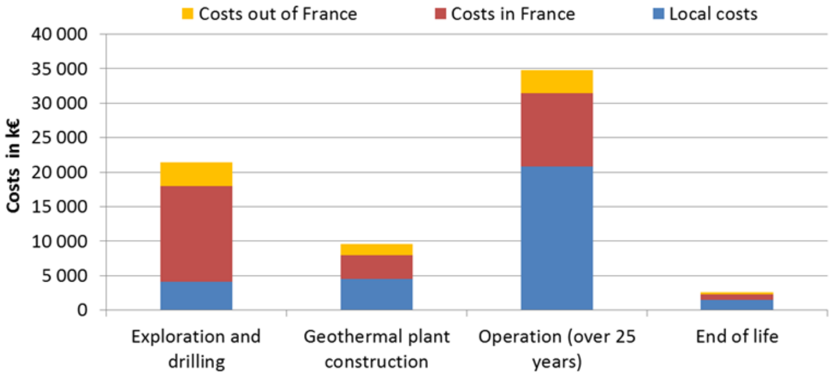

Figure 2: Life cycle costs of the Rittershoffen geothermal plant.

2.2 Direct employment during the life cycle of the geothermal plant at Rittershoffen

We defined *direct employment* as workers who are employed by companies involved in the different steps of the life cycle of a project or activity (here the Rittershoffen plant), and *indirect employment* as the job creation in local economy as a result of the demand created by the project and its direct employees. This study focuses on direct employment within the boundaries of France. Interim jobs are not in the scope of this study. The unit related to this employment assessment study is full-time job equivalents (1 607 h/year).

First, a data collection on all suppliers involved in the Rittershoffen plant from exploration to the end-of-life was performed. Collected data was of juridical type, such as business identification and activity codes, but also of economical type if published, such as turnover, added value and average number of permanent staff. These data were enriched with national economic statistics, extracted from the National Institute of Statistics and Economic Studies, which collects analyses and disseminates information on the French economy and society (INSEE, 2018): output and gross value added by industry in volume at linked prices (2014), prices index (2014) and total domestic employment in full-time equivalents. Currently, 2014 is used by this institute as a reference for inflation correction.

For each company and year of expenses, two ratios were calculated: value-added productivity per turnover and value-added per employee. The first ratio expresses the value created by a company for each unit of sales, while the second expresses the value per employee. These ratios were calculated at inflation-corrected prices from companies' data collected in the first step. In case of unavailable economic data for a company, activity statistics from the National Institute of Statistics and Economic Studies were used to calculate these ratios.

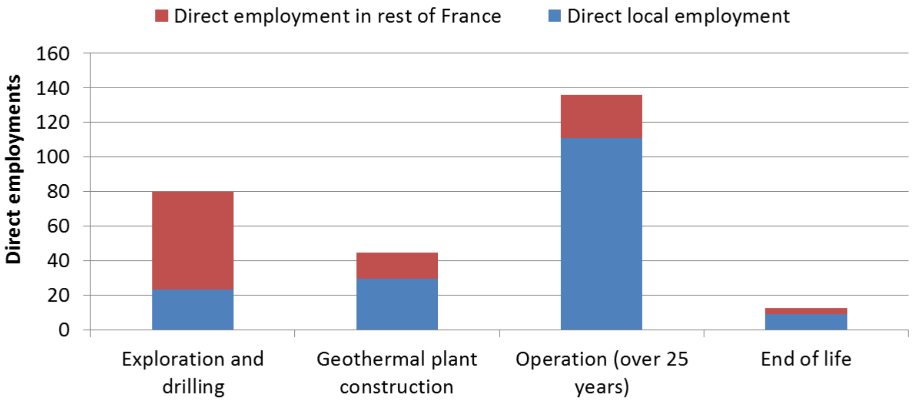

Figure 3: Direct employment in France during the life-cycle of the geothermal plant at Rittershoffen.

Finally, all costs, from exploration up to the end of life stage, were converted into inflation-corrected prices and the value-added was determined using the ratios of value-added productivity to companies' turnover. Once the value-added is known, the second ratio was applied to estimate the direct employment impact of each expense.

Associating costs to the location of the companies involved in the life cycle cost of Rittershoffen geothermal plant has made it possible to distinguish the location of the direct employment: either at a local level in the French department of Bas-Rhin or at a national level (Figure 3).

As expected, the geographical distribution of the direct employment within France during the life cycle is similar to that of the life cycle costs. Direct employment is more important at a local level than at a national level during the operation and construction phases. On the contrary, the direct employment is stronger at a national level during the exploration and the drilling phases. Direct employment is balanced between the exploration and construction phases on the one hand and operation phase in the other hand.

Exploration, drilling and plant construction, from early 2012 to mid-2016, occupied about 124 full-time job equivalents. Annually, maintenance and operation of the geothermal plant has involved about 4 local full-time job equivalent and 1 in the rest of France, which amounts to about 136 full-time job equivalents over 25 years of operation. End-of-life job estimation is about 12 full-time job equivalents during 4 to 6 months for wells cementing and plant dismantling.

According to the 2017 report of the Observ'ER, 1 MW ground mounted solar PV installed in France involves about 4 employees (Courtel et al, 2018). For Rittershoffen, the number of workers involved from the exploration to the plant construction in Rittershoffen was 124 employees. Considering 27 MW_{th} installed power, this gives about 4.6 full-time job equivalents per MW_{th} installed at Rittershoffen plant. The two figures could not be directly compared as the first considers electricity production and the latter considers heat production. However, one could already observe an example where geothermal energy project proved to be relatively competitive regarding employment creation, and especially, local employment.

3. LIFE CYCLE ASSESSMENT

LCA has been applied to the Rittershoffen plant for several scenarios. The complete definition of the Baseline scenario for the Rittershoffen plant is to be found in Pratiwi et al. (2018) under the description of S1, except that the heat transport loop to the starch plant (the *heat user*) transporting hot softened water at 160 °C is excluded. Only the exploration and drilling, the geothermal plant construction, the operation phase and the end of life have been considered in this study. Such definition of the scope of the LCA is meant to be as general as possible so the results could be extrapolated to others EGS plants with different links to heat end users. The scenarios differ by the nature of energy for the drilling of the wells and the source of electricity mix for the operation phase. The choice of these scenarios is directly linked to the identification of hot spots (Pratiwi et al., 2018) mainly related to the operation phase with a high energy demand as detailed later in the analysis of the results (Figure 5). Table 1 describes the scenarios while the elements defining the electricity mix are given in Figure 4.

Table 1: Description of the scenarios

Scenario	Energy for Drilling	Electricity for Operation phase
(1) Baseline scenario	Diesel	Regional Electricity mix (Alsace)
(2) French electricity mix	France Electricity mix	France Electricity mix
(3) Regional electricity mix (Alsace)	Regional Electricity mix (Alsace)	Regional Electricity mix (Alsace)
(4) European electricity mix	Europe Electricity mix	Europe Electricity mix

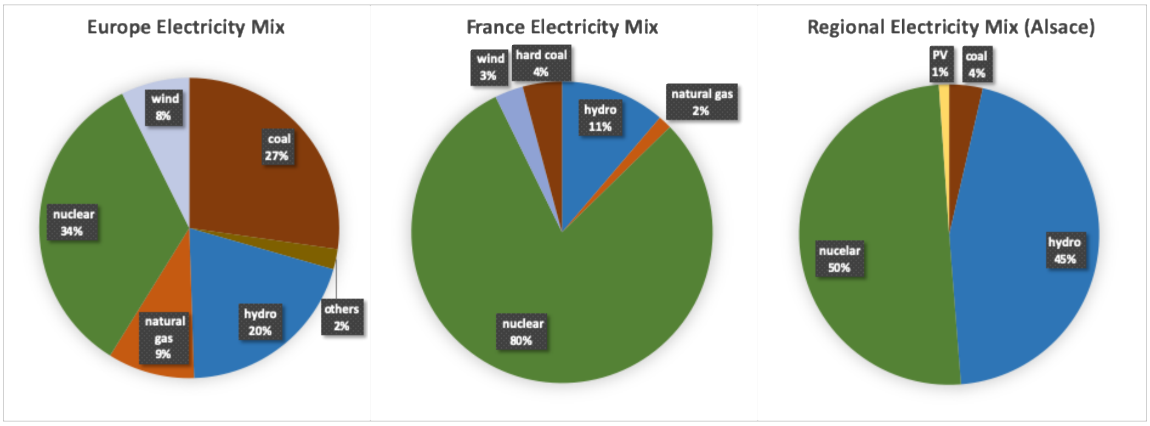

Figure 4 : Electricity mix distributions

Four impact indicators have been selected: Climate change, Human toxicity effects, Particulate matter (PM 2.5) and Ionizing radiation. These four categories, defined after the European ILCD method midpoint (JRC, European Commission, 2011), are representative of general trends of all other impacts and are in accordance with the recommendations of the Environmental Footprint version 3.0 (Fazio et al., 2018). They were also choosen to reflect possible differences between the scenarios investigating different alternatives for energy mix. The impact results of the 4 scenarios are proposed on Figure 5.

Local and national-based scenarios have very similar results for Climate change (Figure 5a), Human toxicity (cancer effects) (Figure 5b) and Particulate matter (Figure 5c), while scenario (4) "European electricity mix" exhibits 2 to 3 times more impact related to the operation phase. Such difference is explained by the high share of fossil fuels contributing to the EU electricity mix, while the other 3 scenarios rely on a mix either based on nuclear energy or hydro energy (See Figure 4). This result highlights the importance of the background electricity mix in the environmental performance of geothermal heat plants. With a low carbon background electricity (as for the 3 first scenarios), Rittershofen plant has a very low carbon footprint: around 5 gCO_{2eq}/kWh_{th}. Such value corresponds to the range assessed for Rittershoffen plant by Pratiwi et al. in scenario 1 without transport pipe: 4.69 – 7.14 gCO_{2eq}/kWh_{th} (Pratiwi et al, 2018). This carbon footprint is comparable to the figure reported by Karlsdóttir et al. (2014). The scope of the analyzed system in this latter study is a district heating system that supplies heat from two wells situated 4 km and 5 km away. The geothermal water is extracted at 85°C and injected at 47°C. The calculated greenhouses gases amount to 5.8 $kgCO_{2eq}/MWh_{th}$, including the contribution of the transport pipelines. It is worth underlining that these figures are notably low compared to an assessment for other EGS installations but producing electricity such as the one in Soultz-sous-forêts: 16.9–49.8 gCO_{2eq}/kWh_{elec} (Lacirignola, Blanc, 2013). It is important to note that the functional unit is different as we are considering heat in Rittershoffen case study, while the latter case study is considering power generation. The Organic Ranking Cycle ORC unit in Soultz-sous-forêts converts the primary geothermal energy into electricity with a thermodynamic efficiency of approximately 12.5%. Impacts on climate change of exploration and drilling and power plant construction of a ORC geothermal plant are 8 times higher compare to a geothermal heat plant.

Operation phase is a dominant one for climate change category, while the geothermal plant construction explains most of the impacts related to Human toxicity (cancer effects) and Particulate Matter. These impacts are mostly attributed to metal equipment (heat exchangers made of high-alloyed steel, carbon steel for the building and piping construction, transformer, etc.). The manufacturing processes and raw material extraction are the activities responsible for these environmental impacts.

Drilling with diesel (baseline scenario) increases the Particulate Matter indicator contribution by 100% compared to the electricity drilling (all other scenarios) (Figure 5c). Among the electricity-based drilling scenarios, the Alsacian scenario (3) is the lowest for Particulate Matter indicator as the Alsacian mix is based on a high propostion of hydro electricity and nuclear electricity.

Ionizing radiation results only depend on the operation phase, and the French electricity mix has the highest impact in this regard due to the highest proportion of nuclear electricity (Figure 5d).

The end-of-life phase has very litte impact on these 4 indicators, regardless of the considered scenario. In this phase, we considered the activities for installing cement plugs in the wells, dismantling the building and the transport required for disposing the used equipment at the waste treatment center.

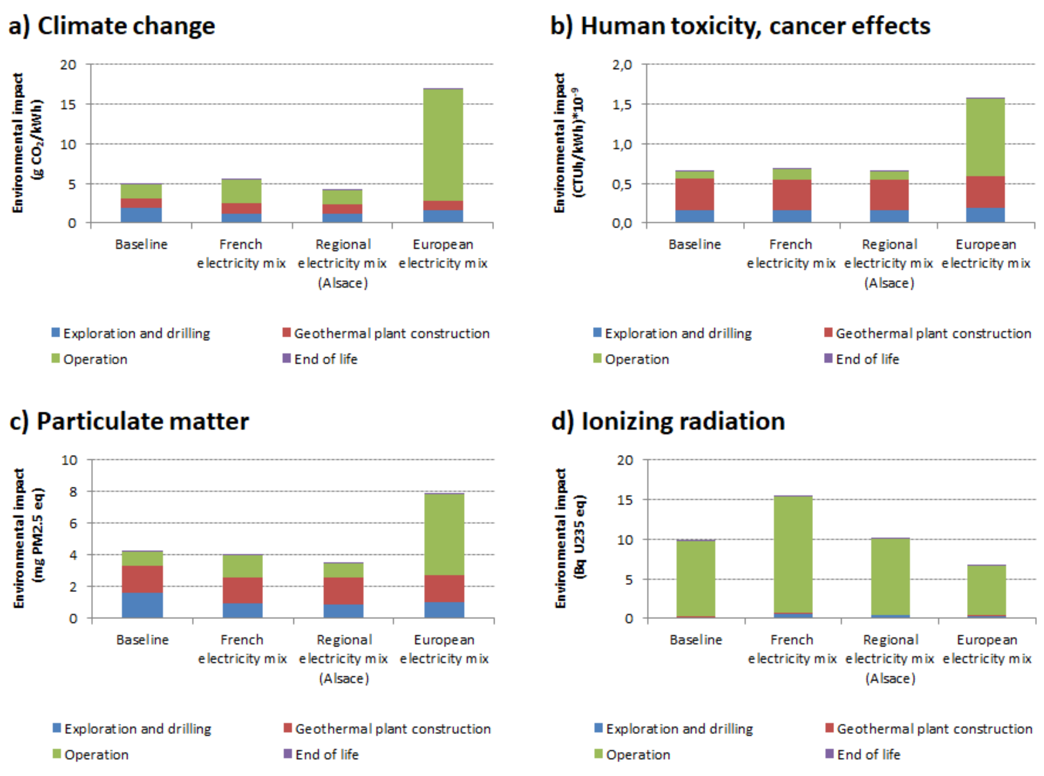

Figure 5: Impact results for the 4 scenarios for the Rittershoffen geothermal plant

4. COMBINING LIFE CYCLE ASSESSMENT AND LIFE CYCLE COST

We have developed an integrated life cycle approach combining both the economic and environmental analysis of the geothermal plant to understand their respective contribution in each phase of the life cycle. The outcomes of coupling the life cycle impact indicators to the life cycle costs are illustrated in Figure 6 for all scenarios. The cumulative impact associated to each of the environmental indicators (Figure 5) was coupled to the same cumulated costs calculated as the total costs over the life cycle from Figure 2. We assumed that the total costs are nearly the same for all scenarios, except for the diesel cost that is different for the Regional electricity mix scenario (Alsace). Costs and impacts are disaggregated along the life cycle phases.

The regional electricity mix scenario has the lowest environmental footprint except for the Ionizing radiation indicator, where the European electricity mix scenario has a better performance by nearly 50%.

The representation of climate change versus total costs shows that the Baseline scenario and the Regional electricity mix scenario follow the same trend (Figure 6a): the exploration and drilling phase carbon footprint (around 25% out of the total climate change figure) is relatively low compared to their costs which contribute at a higher level of the total costs (around 33%). For the European electricity mix scenario, the carbon footprint for this phase contributes to a much lower part (15 % out of the total) keeping the same level of costs (around 33%). Exploration and drilling phase is a costly phase for heat geothermal plant with a relative lower carbon footprint. This analysis is even amplified when looking at the operation phase which represents 50% of the total costs while only 25% for the carbon footprint of both the Baseline and Regional electricity mix scenarios. For the European mix scenario the trend is the opposite, with the operation phase representing a high relative carbon footprint (80%) for the same level (50%) for the total costs.

Considering the Particulate Matter indicator (Figure 6b), for all scenarios (except for the European electricity mix scenario) the exploration and drilling phase contributes to the same relative level (30%) compared to their associated costs (30% out of the total). It is worth underlining that the baseline scenario shows a higher level of PM 2.5 for the drilling phase compared to the same level of costs as it relies on diesel drilling.

The trend of the impacts related to those of the costs is intensified when considering the Ionizing radiation impact category (Figure 6d). For all scenarios, the operation phase contributes to a very high level (between 85 to 90% out of the total) while their associated costs still represent 55% out of the total. The French electricity mix scenario shows the most extreme results (95%), associated with the highest rate of nuclear energy.

These results highlight the discrepancy between the distribution of economic value of the different life cycle phases and their related impact. Exploration and drilling and operation are the two most important phases in terms of costs while their environmental footprint (represented here by three key impacts: climate change, Human toxicity and Particulate Matter 2.5) contributes at a lower level on the overall life cycle. Trends are the opposite for the operation phase for the European electricity mix scenario with a relative higher contribution for the environmental footprint for a lower contribution to total costs.

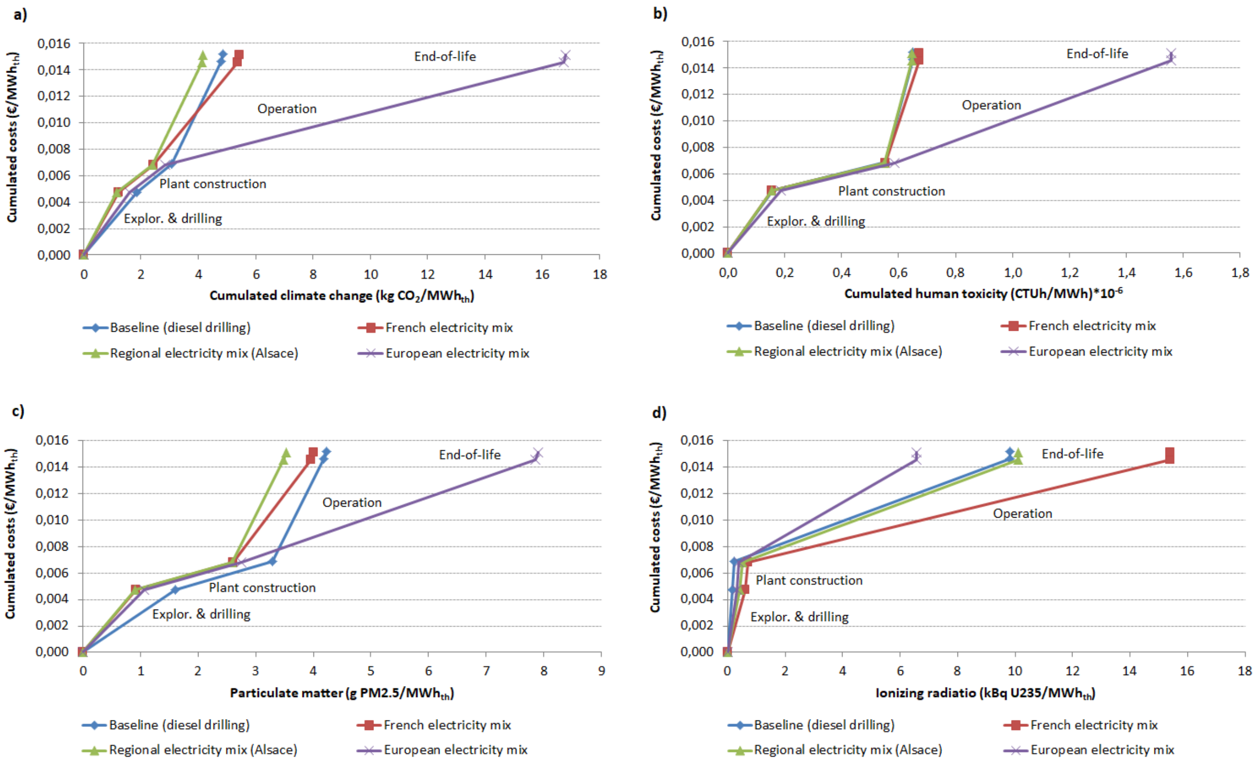

Figure 6: Coupling Life cycle impact indicators and life cycle costs for the 4 scenarios

CONCLUSION

This work is a first attempt to provide a combined economic and environmental assessment for EGS heat geothermal plants. Based on the results obtained for Rittershoffen, the environmental footprint of geothermal heat is fairly low compared to other energy pathways in particular if located in a region enabling to take advantage of renewable electricity such as hydro-electricity. Such electricity mix is very beneficial for the drilling and operating phases for a geothermal plant. Considering the economic aspect of the installation over its overall life cycle, direct employment and costs are allocated for a majority at the regional scale. Such figures are worth to feed the debate when considering sustainability assessment and public acceptability. Nevertheless additional indicators would be necessary to add to get an enhanced comprehensive panorama for the environmental footprint with notably a better collection of air emissions (Parisi et al., 2019), noise and induced seismicity (Lacirignola, Blanc, 2013).

Coupling an environmental assessment to an economic assessment with the same life cycle approach has been explored in this study. It is clearly an asset when aiming at a comprehensive integrated assessment not only to support decision-makers but also when aiming at a reliable communication to ease public acceptability. Findings on the relative importance of the environmental footprint along the life cycle phases are somehow different than the one for the costs and direct employment figures in particular for scenarios integrating electricity mix based on fossil fuels. Exploration, drilling and operation phases are costly phases for heat geothermal plants but have a relatively lower contribution to carbon footprint especially when the energy is based both on low carbon electricity and renewable energies such as the Alsace region where the Rittershoffen plant is located.

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