Report on perception of environmental concerns and strategies/recommendations to deal with biased perception

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GEOENVI

Table of content

Table of figures

Table of tables

Executive summary

To contribute to the strategy to better deal with environmental concerns related to deep geothermal, this work reports how these concerns rank compared to environmental concerns of other RES (Renewable Energy Sources). This overview also shows how RES project and the related environmental concerns are perceived.

Work package 2 of GEOENVI project is dedicated to collecting information on environmental concerns. This specific deliverable aims at putting into perspective the information collected in WP2 with concerns existing in other field of energy production, specifically electricity production.

The task number 2 is about stepping back the environmental concerns about deep geothermal by considering other kinds of geothermal applications, renewable energy sources and beyond. In order to better understand and weight environmental concerns on deep geothermal energy, to better target efforts for environmental impacts and risks reduction, and to develop more efficient strategies to deal with societal perception of environmental concerns (when this perception is exacerbated compared to the reality), GEOENVI proposes to broaden the state of the art to other RES that may generate a similar kind of impact.

This report is organised into four chapters making a panorama that deals with different point of view of a project:

- Environmental aspects: this chapter deals with topics that are assessed with LCA (Life Cycle Assessment);
- Economical aspects: this chapter deals with the varied cost of producing energy with different technologies. Energy Return on Investment (EROI) is compared for different energy pathways;
- Technical aspects: this chapter deals with the practicality of a project and its integration;
- Social aspects: this chapter deals with the social perception of RES but also with perception of some environmental concerns.

For each chapter, different aspects are treated with a synopsis and a table giving figures to be able to have a quantified point of view. The exception is the social perception chapter that covers the topic overview.

Some conclusions can be drawn from this panorama:

- Looking at figures, deep geothermal energy production is comparable in a lot of ways to other RES and has no crippling figures. The pros and the cons of each technology are highlighted. However, in order to get robust and comparable results, LCA

guidelines are needed and this is one of the objectives of WP3 with the setting of D3.2 “LCA guidelines for geothermal installations”.

- The comparison on Energy Return on Investment (EROI) for different energy pathways has revealed that room for improvement is the greatest for geothermal power plants.
- Environmental concerns exist and are real but new technology improvement is currently aiming at limiting furthermore the environmental effect of RES as we have highlighted material consumption reduction for geothermal construction and operation
- Public perception is made of varied aspects and each project within a specific RES can have different perception. However, we can highlight that negative perception of some environmental concern is related to some specific accidents and also to other fields of underground exploitation.

Introduction

In order to reach the 2050 climate objectives, a free-carbon European economy, it is crucial to develop the renewable energy sources (RES). We need also to better understand and weight environmental concerns on RES such as deep geothermal energy. It is interesting to compare the environmental effects of this specific energy source with other renewable energies. The conventional fossil fuels technologies are not assessed in this report as they are not compatible with the climate agenda. Moreover, this report covers only the RES electricity sources.

The following report aims to provide insights on the relative position occupied by deep geothermal energy in the field of renewable energy sources. This study covers essentially the environmental issues, but also the economic, technical and social aspects of the problem through several meaningful parameters and enlightens the particularities of each technology.

The second objective of this report is to benefit from other technologies feedback on environmental aspects management, as well as public perception. Various documents have been reviewed to produce this report, among them publications, reports, database... The documents looking at different RES are used first as they are better suited to energy pathways comparison. One drawback to this approach is that some of these publications are not recent (up to 10 years old) and so the numbers may be outdated.

The environmental aspects cover the greenhouse gas emissions, materials and water consumption, followed by a synthesis of specific environmental concern of each energy source, especially the life cycle assessment impact categories, such as the acidification and eutrophication potentials, as well as the human health impacts.

The economical parameters affecting the deployment of renewable energies are firstly the capital cost of installation and the full cost of energy for the society. Secondly, it involves the project financing structure and the risk profile.

One major technical aspect regarding renewable energy sources is the energy return on investment (EROI), which is the ratio between the energy produced by an energy source and the energy consumed by its manufacturing, operation and decommissioning. Indeed, to raise the interest of stakeholders, a renewable energy source needs to demonstrate its competitiveness from the start of a project, as well as low overall cost of the produced energy. Lower figures due to different technological specificity and maturation need to be addressed or compensated by other advantages such as greater availability of energy (high capacity factors, cogeneration, degree of flexible generation, ancillary services) meeting the energy needs and more environmental friendliness, etc. Furthermore, deploying a low EROI technology, which ends up consuming an important part of the energy it can produce, has a negative economic impact.

The other technical aspects considered in this report are mainly power grid connection and hold on the ground that can be a major drawback for some renewable energy sources. In this section, geothermal energy is expected to present good performance compared to wind energy, utility scale solar energy, or even biomass power plant.

Another point to consider is the availability of the energy source that can be different for geothermal operations compared to wind energy and photovoltaics (PV) for example.

Finally, the social aspects of renewable energy sources cover the evaluation of the consequences implied by a major incident occurring in a facility, particularly in term of public or personnel fatalities, as well as the overall perception of the different energy sources by the public, in term of disturbances and safety.

It is important to highlight that the positive impact of RES especially in terms of social and environmental aspects (fighting climate change, global warming, local air pollution, health issues …) are not in the scope of this report which aims at discussing concerns about RES with associated figures.

RES are defined by the European Renewable Energy Directive [1] in its article 2 as: energy from renewable sources' or 'renewable energy' means energy from renewable non-fossil sources, namely wind, solar (solar thermal and solar photovoltaic) and geothermal energy, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas.

It is quite difficult to compare the different renewable energy sources through specific parameters in a meaningful way. The different technologies use different manufacturing technics, consume different kind of materials, need different kinds of energy for manufacturing, transportation, installation, operation and/or decommissioning. A life cycle analysis approach is imperative to account for the overall impacts of each energy system (Laurent, Espinosa, et Hauschild 2018). Even then, the use of different LCA methodologies and different boundaries and operation parameters (e.g. the capacity factor, which is the ratio of average output power to peak power when dealing with wind energy for example), can lead to biased comparison. A results harmonization is necessary to reduce the data variability, aligning methodological inconsistencies in published LCAs, such as different system boundaries, the use of outdated data, variations on similar energy process chains, and even simple differences in reporting of results (Asdrubali et al. 2015). Deliverable D3.1 of this project is focusing on this point by making a panorama of the different LCA available for geothermal energy and Deliverable 3.2 is providing common LCA guidelines for geothermal installations.

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[1] DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)

In order to improve the relevance of the proposed comparison, following the paper of Asdrubali et al (2015), the present report focuses on the renewable energy sources producing electricity and combined heat & power at a utility scale. These energy sources are the following:

- Wind onshore
- Wind offshore
- Hydropower (dams and run-of-river)
- Solar PV (utility scale, not rooftop)
- Concentrated Solar Power (CSP)
- Deep Geothermal Energy
- Biomass Power Plant

Environmental aspects

LIFE-CYCLE GREENHOUSE GAS EMISSIONS

Table 1 presents a synthesis of the results of published life cycle assessment (LCA) of greenhouse gas (GHG) emission by different renewable energies. The two recent LCA reviews by Kis, Pandya, et Koppelaar (2018) and Amponsah *et al.* (2014) are coherent with the global review published by the IPCC in 2011 (Edenhofer et al. 2012). Figure 1 displays the same IPCC results and the more recent results of Kis, Pandya, et Koppelaar (2018).

Table 1: Life-cycle greenhouse gas emissions in grams of equivalent CO_2 per produced electrical kWh.

gCO_2eq / kWh	Wind onshore	Wind offshore	Hydro power	Solar PV	Solar CSP	Geothermal	Biomass
IPCC (Edenhofer et al. 2012)	8 – 20	8 – 20	4 - 14	30 – 80	14 – 32	4–45 (flash) 20–80 (EGS)	16 – 74
(Kis, Pandya, et Koppelaar 2018)	27.5	18.7	29.5 – 53	27	30.2	55.1 (EGS)	93.6
(Amponsah et al. 2014)	16 – 34.2	13	20	91 (c-Si) 31 (a-Si)	36 – 43	40 - 60	56 – 199

GHG from geothermal energy is globally similar to the one from other renewable energies with emissions equivalent to those of Solar PV or Biomass power plants. However, there is an important GHG variability among the different geothermal technologies, particularly with direct GHG such as CO_2 emission. But, with some geothermal technology it is not easy to assess the direct CO_2 emission due to the plant. Indeed, in some geological contexts the soil naturally emits some CO_2 (Ármannsson, Fridriksson, et Kristjánsson 2005). This is the case in natural geothermal areas. The CO_2 emitted by the plant can be negligible compared to these natural emissions. Moreover, over time the amount of CO_2 the soil emits can decrease probably due to the reinjection of fluid depleted in CO_2 into the reservoir that will absorb the free CO_2 (Akin et al. 2016). Similarly, the bulk of the GHG emissions by Solar PV, which are of the same order of magnitude than geothermal energy, are produced in the manufacturing process, not in the electricity production phase.

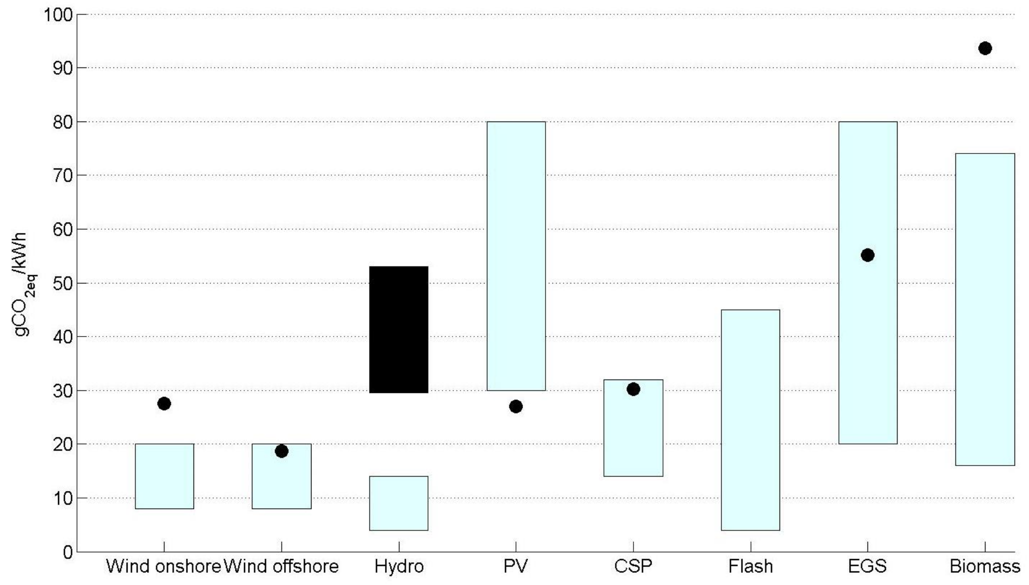

Figure 1: Lifecycle GHG emission of different energy sources. Bars in light blue show the 25th to 75th percentile of the data gathered by IPCC (Edenhofer et al. 2012). Points and black bars shows the newer data of (Kis, Pandya, et Koppelaar 2018).

MATERIALS CONSUMPTION

Kis, Pandya, et Koppelaar (2018) produced a very complete life cycle analysis of the most common energy production means. They give precise insight on the materials consumption of these technologies, which is presented in Table 2.

Depending on the technology used to produce geothermal energy, the consumptions of concrete and steel are quite different. If geothermal use of steel is of the same order than biomass and hydropower, these two energies also consume enormous amount of concrete. Solar PV is a great consumer of aluminium, Silicon (about 5.4 mt per MW) and other rare materials. Wind onshore uses lots of concrete, and wind offshore lots of steel. Wind energy is also a consumer of rare earth material (Dodd 2018; Pavel et al. 2016). Wind farms use permanent magnet synchronous generators that are employed in some turbines. Rare-earth such as neodymium, dysprosium and praseodymium are needed to build these types of magnet. Up to now, no substitute has been found but other rare-earth free turbines exist that have only a moderate performance loss.

The above-mentioned figures for concrete consumption are mostly consistent with the founding of the Argonne report in 2011 (Sullivan et al. 2010). Still, this report found 2000 to 5000 metric tons per MW aluminium consumption for onshore wind energy sources, based on a lifecycle assessment from the wind turbine manufacturer Vestas in 2006. However, keep in mind that this report is 13 years old and the number provided may need to be updated. A newer study of LCA by Vestas (2017) shows an aluminium consumption of 32 mg/kWh for a lifetime of 20 years. This translates to a consumption of 5.3 mt/MW which is closer to what is estimated by Kis, Pandya, et Koppelaar (2018) for a lifetime of 25 years.

Table 2: Life-cycle consumption of concrete, steel and aluminium in metric tons per MW (Kis, Pandya, et Koppelaar 2018).

mt / MW	Wind onshore	Wind offshore	Hydro power	Solar PV	Solar CSP	Geothermal	Biomass
Concrete / cement	380	7.8	6 900 / 8 600	47	340	121 - 425	714 / 2300
Steel	92	246	82 – 184	52	171	204 – 1 223	110 - 325
Aluminium	0.77	0.41	0.69	27	2.6	3.8	3.5

Lowering material consumption is one of the key point of the development of RES. Concerning geothermal energy, solutions are explored to lower the material consumption. Geothermal development can also be a solution for a more secure supply of some material.

Materials Roadmap Enabling Low Carbon Energy Technologies

On 13 December 2011, the European Commission published its Staff Working Paper investigating Materials Roadmap Enabling Low Carbon Energy Technologies. The document is intended to complement and expand the technology roadmaps developed in the framework of the SET Plan. It puts forward key materials research activities to advance energy technologies in the next ten years.

The Materials Roadmap for Geothermal recognizes geothermal as being a “promising renewable energy source able to provide naturally a continuous base load power”. In order to further develop engineered geothermal systems (EGS) and to make it economically viable, the Roadmap highlights that “innovative materials solutions and an improved understanding of the long-term interaction between the materials and their harsh environment is of key importance”. An excerpt of the main R&D priorities identified are detailed below.

Focus is on innovative developments for accessing geothermal reservoir (including spallation drilling) that should work towards an increase of economic depth. An important contribution would come from researching lightweight materials for drill bits to extend their lifetime in highly abrasive and corrosive environments at high temperatures and developing site specific materials for proppants in conjunction with stimulation techniques. Improved monitoring of the downhole requires materials developments to make fiber optic cables and power electronics withstand the hostile environment they should operate in. When assessing the heat reservoir and the subsequent production phase, the accumulated deposition of material inside the pipes (scaling) and the extreme corrosion and temperature problems need to be tackled from a materials' perspective. This involves the development of corrosion resistant materials for the pipes, equipped with protective outer coatings and insulation, and inner liners. Novel polymeric, ceramic or metallic membranes to separate and re-inject gases would make the operation of a zero-emission plant possible. During the operation, continuous monitoring of the system should allow for early intervention thus reducing the risk of a fatal breakdown of a well too early in its exploitation life. Also, the downtime due to replacement or maintenance of instrumentation such as downhole pumps could be reduced by selecting specific metal alloys[2]. The establishment of research wells, one at supercritical conditions, one in over-pressured reservoirs, and one to improve EGS technology and stimulation materials are proposed as technology pilots. Another important aspect pointed out in the document is that several materials and research areas designed to address the specific needs of geothermal, e.g. corrosion-resistant material, separation membranes and coatings and coating techniques, are common to other technologies. Leveraging these commonalities and synergies is of critical importance. Economies of scale and scope can be realized and cross-technology knowledge can be pooled together at European level to accelerate the development and integration of innovative materials.

Table 3. Key materials for the geothermal sector.

(Source: US DOE Geovision, European Commission list of critical raw materials).

Material	Supply vulnerability status
Iron	Non-critical
Carbon (coking coal)	Check (63% import dependency)
Chromium	Mixed status[2]
Nickel	Non-critical
Molybdenum	Non-critical
Titanium	Non-critical
Aluminium	Non-critical
Epoxy/Plastics	Non-critical

[2] Identified as non-critical in the 2018 European Commission list, it is nonetheless considered as potentially critical by some studies (e.g. Franhaufer 2014)

The complete roadmap for geothermal is available on the EC Staff Working Paper.

Below is a list of key raw materials for the deep geothermal industry, in comparison of the European Union list of critical raw materials. The Table 3 underlines the relative independence of the deep geothermal sector value chain to these materials, as most of the key materials for deep geothermal is listed as non-critical by the EU.

Deep geothermal projects indeed rely primarily, in terms of volume for raw materials, on steel and concrete. The only key material of the geothermal value chain identified as “critical” by the EU is coking coal, which is used in the steel industry to transform iron into steel. This resource is considered critical notably because of its high economic importance overall, a limited concentration of suppliers, and especially a large dependency on exporters that do not contribute to the EITI[3]. However, the 2017 list also considers this material as critical on a cautionary basis.

The specificities of the operating environmental of deep geothermal installations introduces some specific requirement for materials in terms of strength and corrosion resistance that may expose the deep geothermal sector to some degree of vulnerability. For instance, chromium, as key component of stainless steel is by some measures considered a critical raw material (although not in the EU 2018 list). For concrete, although there seem to not be major vulnerability of supply thus far, emerging tension in the availability of sand may be a source of vulnerability in the long term[4].

Geothermal energy is however much less dependent on the extraction of some strategic raw material, in particular so-called rare earths, that other energy generation technologies. The extraction of rare earth is often carried out with an important impact on environment and human rights[5]. The strategic raw materials identified by the European Commission include:

- Eight metals classified as ‘critical’. These include six REEs (dysprosium (Dy), europium (Eu), terbium (Tb), yttrium (Y), praseodymium (Pr) and neodymium (Nd)), as well as gallium (Ga) and tellurium (Te).
- Six materials classified as ‘near critical’ (graphite, rhenium (Re), hafnium (Hf), germanium (Ge), platinum (Pt) and indium (In)) implying that their market conditions should be monitored closely.

The European Commission is notably considering these elements from the perspective of supply vulnerability for the European economy. These studies also consider the risk linked to

[3] Extractive Industries Transparency Initiative, an initiative launched in 2002 to promote revenue transparency and accountability in the extractive industries sector. It notably has a focus on good governance of the extractive industries supply chain for citizens of resource rich countries and ensuring security of trade.

[4] https://science.sciencemag.org/content/357/6355/970

[5] Materials Roadmap Enabling Low Carbon Energy Technologies

the supply of lithium, an essential component for many energy technologies, in particular batteries. For lithium and other materials, geothermal energy can be a solution for a more secure supply, that has simultaneously dramatically lower environmental and human rights impacts.

Lithium extraction from geothermal Brine

Meanwhile, geothermal energy can also be an opportunity for increasing the security of supply of critical raw materials in the European Union. Rapidly emerging from amidst the debates surrounding the supply chain for Information and Communication Technologies, as well as for some renewable energy technologies and batteries, the issue of securing the supply of certain strategic raw materials is becoming increasingly acute for Europe, as illustrated by the European Commission's 2017 launch of the European Battery Alliance and the Clean Energy Industrial Forum. Geothermal energy is now coming up with solutions to this challenge in the form of several research projects around the topic of brine mining, i.e. extracting minerals from the geothermal brine. In particular, prospects for lithium extraction are especially promising in terms of the amount of resources extracted.

The Soultz-sous-Forêts geothermal power plant, which was already a trailblazer in fostering EGS technology, is the site of a project aiming to demonstrate new technologies for the extraction of lithium from geothermal brines. This project, EuGeLi (European Geothermal Lithium brines) gathers Eramet, Vito, BRGM, IFPen, VUB, ES Géothermie, BASF, Chimie ParisTech, and EIfER.

The prospects raised by combined heat and power and raw material extraction may lead the European geothermal industry to be major supplier of rare material in the medium term. The H2020 funded CHPM2030 projects for instance "aims to develop a novel and potentially disruptive technology solution that can help satisfy the European needs for energy and strategic metals in a single interlinked process".

Brine mining represents an opportunity for the geothermal sector to develop new income channels, and therefore further secure investments. Following the demonstration of the technology, a sound regulatory and policy framework will be a key requirement for allowing investments in geothermal brine mining. Indeed, in many cases, permitting and authorizations do not allow minerals to be extracted from the same concessions as those subject to geothermal energy extraction. A sound framework would allow for synergies, exploiting the valuable renewable geothermal energy for electricity and heat production as well as the strategic minerals contained in the brine to foster the digital and energy transitions.

Beyond lithium, other critical materials can be extracted from geothermal brine in the future, for instance rare earth elements, which are present in many parts of Europe where geothermal is also suitable.

Circular economy

For detailed information see ETIP-DG SRIA & Roadmap

The circular economy is a core topic for geothermal development. This means developing a system of production and trade in which durability and recyclability are built into products and components from the design stage onwards so that they can be reused or made into new raw materials, thus reducing waste volume and energy consumption while preserving natural resources. The integration of geothermal into the circular economy would involve components, products and systems which are optimized, used and re-used, repaired, redistributed, refurbished, and/or remanufactured. Another aim is to develop a quality label for the geothermal products, components and systems, becoming greener and eco-friendlier.

In 2016, the European Commission published a Circular Economy Package for a more sustainable economy. This package sets out a plan and targets for EU waste that should be achieved by 2030 in order to make the transition to a resource-efficient economy. Many manufacturers, designers and developers in the geothermal sector have endorsed this initiative and are working on producing greener products, but the sector is not yet organized such that it can be fully integrated into the concept of the circular economy with all its components.

The next steps should be:

- Adopting geothermal standardization procedures and quality branding focused around the circular economy in order to improve the confidence of consumers and legal authorities regarding sustainable geothermal products and promote mutual understanding in the geothermal sector through agreed terminology, sharing vocabulary and definitions in order to have an agreed and consistent approach
- Improving the applicability and use of recycled/secondary materials/waste in geothermal plants
- Monitoring the use of raw materials in geothermal, especially the critical materials in terms of availability. Identifying, classifying and quantifying the data regarding raw materials, promoting interoperability and comparability with other materials
- Developing new business models with eco-friendly geothermal actors
- Performing research and innovation to develop new technologies for waste and water management

- Develop innovative greener and eco-friendly geothermal products, components and systems, transitioning to the use of sustainable materials
- Monitoring the entire process using digital applications.

WATER CONSUMPTION

Water use can be a major concern in some region, raising environmental issues and water allocation requirements. Wind energy does not consume an important volume of water, and hydropower, while taking energy from water gives it back for further use. However, the creation of retention basins for dam hydropower may induce very significant amount of evaporation of water, and reduces the global hydrology (destruction of wetland areas) and may impact water quality for other uses (reduced availability of stilts for irrigating crops for instance)[6]. Depending on the chosen cooling option, CSP can consume between 0.4 and 4.7 l/kWh, while Geothermal and Solar PV consume generally below 1 l/kWh (Asdrubali et al. 2015).

Crops used for **biomass** production compete with food production and consume the same amount of resources, like water and fertilizers. The conversion from heat to electrical energy also enhances these figures. Gerbens-Leenes, Hoekstra, et Van der Meer (2009) published an evaluation of the water footprint of first generation biomass power plant. They found an average water footprint of 86 l/kWh for European countries, and up to 515 l/kWh in Africa (Zimbabwe). Second generation biomass power plants are found to consume between 18 and 241 l/kWh (Mathioudakis et al. 2017).

ACIDIFICATION AND EUTROPHICATION POTENTIAL

Figure 2 present the acidification and eutrophication potentials of some renewable energies collected and harmonized over a complete lifecycle by Asdrubali et al. (2015). Geothermal and Solar PV have generally two to ten times higher acidification and eutrophication potentials than CSP, wind and hydropower. This comes mainly from the fabrication process of the solar panels for solar PV, and the drilling of the production wells for geothermal energy.

[6] Pearce, 2018.

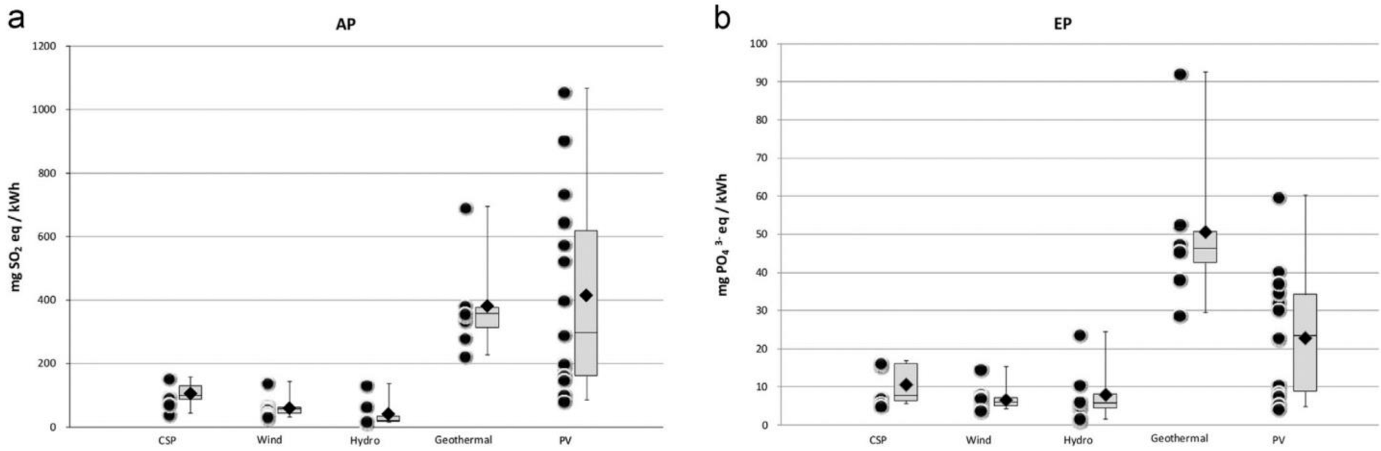

Figure 2: Harmonized data from Adrusbali et al. (2015). a. Acidification Potential. b. Eutrophication Potential.

SPECIFIC LOCAL ENVIRONMENTAL IMPACTS

Each renewable energy source can have specific local environmental impacts linked with the technology and materials they use. Geothermal impacts include water spilling, induced seismicity, etc. These particular aspects are addressed in the D2.1 deliverable of the GEOENVI project on environmental concerns.

Risks commonly associated with geothermal energy are induced seismicity and chemical spilling. Hydropower can also induce seismicity, when large water bodies exert important shear and/or normal stress on a nearby fault plane. Grigoli *et al.* (2017) reported 47 seismic events (magnitude >1.5) caused by dams until 2016 and only 21 for geothermal power plants. The biggest events for geothermal are generally associated with the reservoir engineering technic used in the USA, which is prohibited in Europe. Ship collision with offshore wind turbine can become a non-negligible risk if the expansion of offshore wind farms continues (IPCC, 2011, p. 747). Dai *et al* (2015) published an extensive review of “environmental issues associated with wind energy”.

Hydropower can have important consequences on the natural flow regime of rivers, and the associated equilibrium of the nature and wildlife (Poff et al. 1997; Petts 2009; Waples et al. 2008).

Wind farms impact on bird mortality is difficult to assess, leading to disparate results, between 0.03 and 35 bird fatalities per turbine and per year (Dai et al. 2015). The rotor diameter is expected to have an impact on these numbers, but it is generally believed that the bird fatality rate of a turbine is comparable to the one of buildings of similar size.

Utility scale solar energy reduces the vegetal cover and consequently reduces the CO_2 capture by the vegetation, thus degrading the GHG reduction performance of solar energy (De Marco et al. 2014). This is linked to the land use problem, which is assessed in the following of this report.

HUMAN HEALTH IMPACT

A global assessment of the impact of several electricity generating technologies following several life cycle impact assessment methods have been undertaken by Treyer, Bauer, et Simons (2014), and the results are summarized in Table 4. ReCiPe LCIE method can be applied to different time scales, depending on the assessment approach. A short timescale will assess mainly air pollutant and GHG emissions, whereas a long timescale will assess mainly mining and long-term groundwater emissions. The results are measured in ''Disability Adjusted Life-Years'' (DALY), taking into account the years of life lost due to premature mortality and the life-years spent with permanent disability.

The results of this study show that hydropower has always less health impacts than geothermal and CSP, but while offshore wind has low health impact in a short-term assessment, its long-term impact is very important, mainly due to the mining of several metallic and rare earth materials used for the construction of the electricity generator. It would have been interesting to assess wind onshore and solar PV energies as well, as these are on the same trend than wind offshore.

Table 4: Human health impact for short and long-term life cycle assessment.

(DALY / kWh)	Wind onshore	Wind offshore	Hydro power	Solar PV	Solar CSP	Geothermal	Biomass
(Treyer, Bauer, et Simons 2014) Short-term		10	4		14	26	
(Treyer, Bauer, et Simons 2014) Long-term		824	23		179	208	

Economical aspects

CAPITAL COST

Initial investment in geothermal energy can be high on a when considering only the electricity capacity to be installed, compared to onshore wind, hydropower and solar PV energies, due to the cost of drilling at great depth and the capital costs associated with the geothermal resource risk. However, these investment costs are similar to biomass power plants, concentrated solar energy and offshore wind energy. Bilgili, Yasar, et Simsek (2011) obtained a 1300 $ / kW of investment cost for onshore wind, and 2000 to 3000 $ / kW for offshore. Moreover, comparing capital cost for a unit of capacity is not a metric that reflect the actual cost of using energy from geothermal compared to other source, as the availability of geothermal capacity is much greater than that of the other technologies compared below (i.e. a kW of geothermal capacity will generate more electricity than a kW of another energy technology) in Table 5. Besides, this metric does not include the possible associated thermal capacity from cogeneration.

Table 5: Initial investment per installed kW.

($ / kW)	Wind onshore	Wind offshore	Hydro power	Solar PV	Solar CSP	Geothermal	Biomass
(IRENA 2019) for Europe	1 900	4 350	1 900	1 210	5 200	3 975	4 500

LEVELIZED COST OF ENERGY, SYSTEM COSTS AND EXTERNALITIES

The high capacity factor of geothermal energy can compensate for its high capital cost, and explains its low LCOE. Geothermal power plants produce annually energy corresponding to 84 % of availability of its rated capacity, against 34 % for onshore wind and 18 % for solar PV (IRENA 2019). At similar rated power, geothermal will produce 2.5 times more annual electricity (not including possible cogeneration of heat) than onshore wind and 4.7 times more than solar PV. Figure 3 is an excerpt from the ETP-DG (2018), and shows the good economic performance of the geothermal energy when compared with other renewable energies, and even with non-renewable energies. Other studies have found similar results, displayed in Table 6.

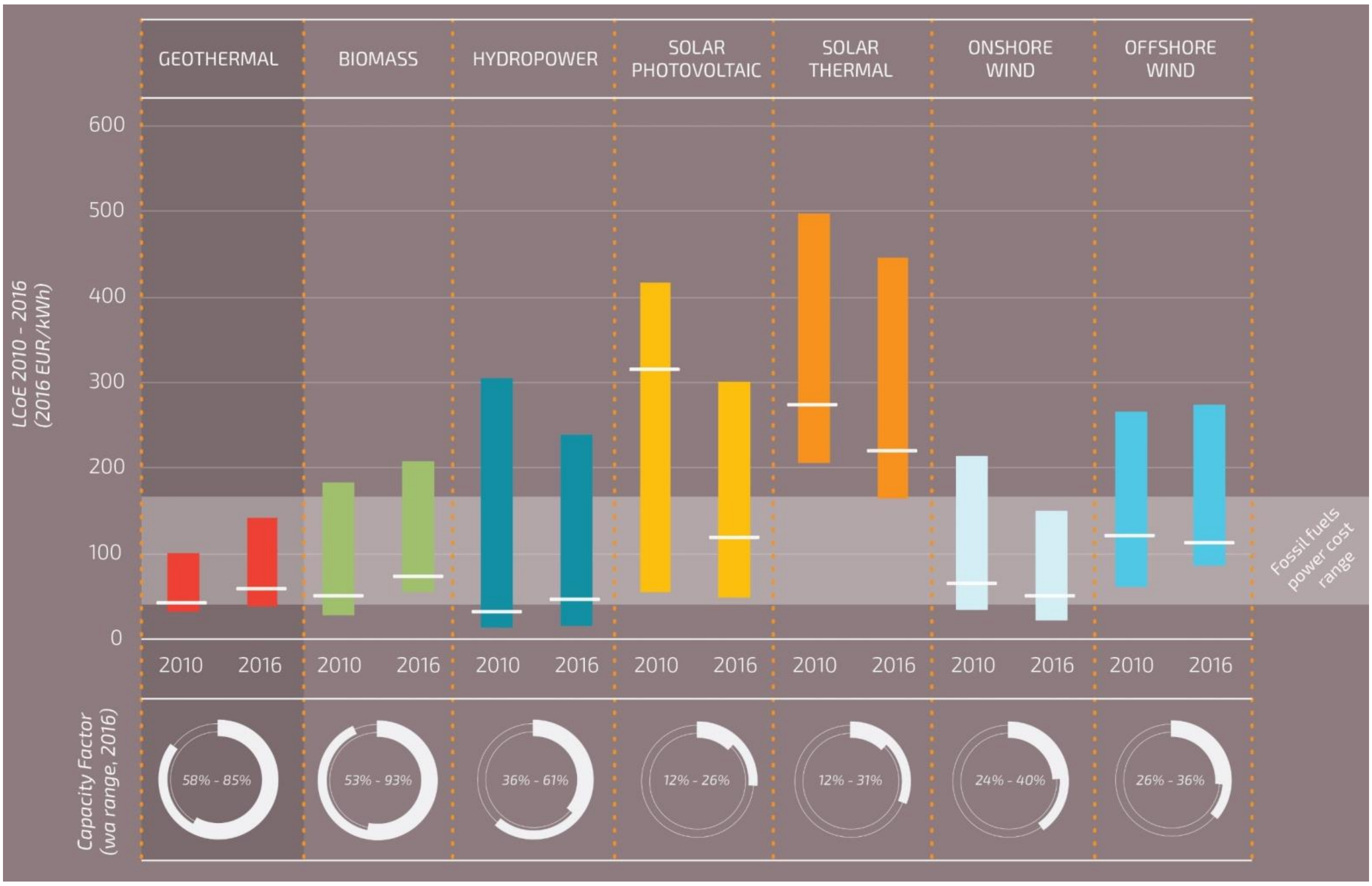

Figure 3: Levelized Cost of Energy and availability for different electricity sources from ETIP-DG (2018).

Table 6: Levelized Cost of Electricity (LCOE) per produced MWh.

($ / MWh)	Wind onshore	Wind offshore	Hydro power	Solar PV	Solar CSP	Geothermal	Biomass
IPCC (Edenhofer et al. 2012)	80	140	50	250	190	70	50 – 200
(IRENA 2019) for Europe	70	134	125	100	185	72	80
(Kost et al. 2018)	40 – 82	78 – 138		40 – 70			100 – 150

Technical aspects

ENERGY RETURN ON INVESTMENT

The EROI number is the ratio between the total energy produced by an energy source and the energy invested to manufacture, install and operate this same energy source. Local economy, raw material extraction capacity and many other parameters can affect this ratio. Thus, it needs to be evaluated on the global life cycle of the utility to allow accurate comparison between extremely different technologies. Table 7 displays results from recent and global studies.

Kis, Pandya, et Koppelaar (2018) calculated an actual global EROI number around 11.3. A decrease of the global EROI number due to mismanagement of renewable energy would mean that more energy has to be spent towards the production of energy, impeding as much the other production sectors and potentially reducing overall wealth. Thus it is essential to implement in the global power grid energy sources with EROI numbers sufficiently high (typically superior to 9) to produce a sufficient amount of energy in order to sustain the global economy.

In this perspective, wind energy has a good mean EROI value. It is however important to pay attention to the capacity factor associated with the geographical implantation of this technology, that can reduce its EROI number to 6.9 and 8.1 for offshore and onshore wind energy respectively. Similarly, the capacity factor of solar PV has an important influence on its EROI number. Furthermore, EROI is not calculated accounting for the intermittency of these technologies, thus do not include the energy cost of back-ups and storage.

Hydrothermal geothermal energy has a very good EROI number, but EGS needs technological progress to achieve sufficient production efficiency.

Table 7: Energy Return On Investment for different energy sources.

(-)	Wind onshore	Wind offshore	Hydro power	Solar PV	Solar CSP	Geothermal	Biomass
(Kis, Pandya, et Koppelaar 2018)	12.6	13.5	9 – 24.7	4.7 – 13.6	9.8	5.9 (EGS) 34.8 (hydro)	2.9
(Hall, Lambert, et Balogh 2014)	18	18		6 – 12		9	

Atlason *et al.* (2014) gave the definition of an “ideal” EROI number, based on the potential energy produced by a particular technology. The difference between the ideal and standard EROI numbers gives an evaluation of the potential progress on the overall lifecycle of the energy producing systems. The authors showed that the room for improvement is the greatest for the geothermal power plant.

ENVIRONMENTAL PERFORMANCE OF ENERGY SOURCES FOR THE FINANCIAL SECTOR

In the financial sector, establishing clear criteria for the environmental performance of different energy technologies is crucial step to develop financial products that are focused on sustainable investments. At the European level, the proposed Sustainable Finance Regulation aims to do just that, by proposing a taxonomy that set criteria for energy technologies to be eligible. The regulation goals are to:

- Establish clear criteria for what investments are sustainable and therefore eligible for "sustainable finance" such as green bond, green private equity funds, etc. The regulation proposes a taxonomy that sets criteria for eligibility as a sustainable investment. These criteria will be used by actors of the financial sector to direct their investments to projects that allow their financial products to be considered sustainable finance;
- Increase trust in the impact of sustainable finance to increase the amount of capital flowing towards such products, by this mean alleviating the risk of greenwashing;
- Increase transparency, and possibly tradability of sustainable finance assets, again with the objective of facilitating private investment in sustainable projects.

The criteria set in the Sustainable Finance Regulation taxonomy[7] include notably life-cycle emission thresholds and so-called do-no harm criteria.

Energy technology	Eligibility criteria	Key do no harm criteria for each technology (i.e. main environmental impact)
Geothermal electricity	Life Cycle Emissions (LCE): 100 g CO_{2eq}/kWh, decreasing to net 0 gCO_{2eq}/kWh in 2050.	Compliance with environmental regulations, notably Water Framework Directive and Air Emission regulations (NGC, water

7 https://ec.europa.eu/info/sites/info/files/business_economy_euro/banking_and_finance/documents/190618-sustainable-finance-teg-report-taxonomy_en.pdf

		emissions to surface or groundwaters)
Geothermal heat	LCE: 30 g CO_{2eq}/kWh, decreasing to net 0 g CO_{2eq} /kWh in 2050.	Compliance with environmental regulations, notably Water Framework Directive and Air Emission regulations.
Heat pumps (including shallow geothermal)	Seasonal Performance Factor 3.33 Refrigerants with a Global Warming Potential < 10	
Concentrated Solar Power	Exempt from performing a LCE (100 g CO_2/kWh decreasing to net 0 gCO_2/kWh in 2050 if LCE becomes applied)	Comply with Environmental regulations, notably EU Habitats and Bird Directives.
Wind Power	Exempt from performing a LCE (100 g CO_2/kWh decreasing to net 0 g CO_2/kWh in 2050 if LCE becomes applied)	Ecosystem impacts (underwater noise, bird collisions…), management of composite wastes
Ocean Energy	Exempt from performing a LCE (100gCO_2/kWh decreasing to net 0 gCO_2/kWh in 2050 if LCE becomes applied)	Impact on marine ecosystems, local pollution.
Hydropower	LCE: 100 g CO_{2eq} /kWh, decreasing to net 0 g CO_{2eq} /kWh in 2050.	Water pollution (need to comply with WFD), impacts on biodiversity/ecosystems.
Gas combustion	LCE: 100 g CO_{2eq} /kWh, decreasing to net 0 g CO_{2eq} /kWh in 2050.	Local water impact, air emissions (NOx)
Bioenergy	Facilities operating at less than 85% of GHG (approx. 100 g CO_{2eq} /kWh) emissions	Impact on local water, waste and recycling, air emissions, impacts on ecosystems…

	in relation to the relative fossil fuel comparator set out in RED II increasing to 100% by 2050, are eligible	
Solar Photovoltaic	Exempt from performing a LCE (100 g CO_2/kWh decreasing to net 0 g CO_2/kWh in 2050 if LCE becomes applied)	Production and management of end of life, impact on ecosystems during installations

ELECTRICITY MARKET

The inherent intermittency of wind and solar energies, and their decoupling with load demand on the power system is a major drawback to the large expansion of these renewable energies, compared to other sources such as geothermal energy, hydropower or biomass. Nowadays, the additional flexibility needed in case of sudden load demand increase in a power system integrating high intermittent electricity generation (PV, wind) is provided by gas-fired power plant capable of rapid power build-up. Geothermal power plants also have a rapid power build-up and could provide this additional power reserve. This power system management reduces significantly the environmental performances of wind and solar power, especially in terms of CO_2 reductions.

Mitigations solutions exist and have been reviewed by Ren *et al.* (2017). It includes better power demand management through smart grid technologies, and energy storage in order to smooth the energy production (Lund 2005). However, most of the storage technologies are not yet fully mature and can have high economic and environmental impact during production and manufacturing. In case of important wind power installation, the storage needs to mitigate the intermittency effects over a 14 days period can reach 14 % of the average power load per day (Saarinen, Dahlbäck, et Lundin 2015).

LAND USE AND ELIGIBILITY

The proper evaluation of land use by an energy production facility in order to compare it with other production means is very difficult. A complete lifecycle analysis should take into consideration the land impact of the extraction and treatment of the necessary materials, particularly when it is open mining.

Table 8 gives the land use factor derived by Arent et al. (2014) under specific assumptions, in their study on high renewable energy scenario in the US. This study shows a low land use (high energy rate by squared kilometre) for geothermal energy. Wind energy has a very low score, but this number uses a mean distance between turbines. Much of the land in between can be used for other purposes, although this alternate use of land is difficult in large wind farm. A specific study of Poggi, Firmino, et Amado (2018) on wind farms and solar utilities in the county of Loures in Portugal, assuming a 100 meters square of land use by each turbine including the service roads, give a 57 MW / km^2 land use factor, still much lower than the geothermal energy performance.

This study is in agreement with the review from Asdrubali et al (2015) that shows that land use for geothermal energy is low compared to other ENR (Figure 4). This point is tempered by the low number of study available for geothermal operations and the high variability of the results for hydropower and PV. However, geothermal energy does not need a lot of land during operation due to directional drilling techniques and once the drilling is done the land above can be used for other land use such as livestock grazing[8].

The best land use performance is the run-of-river hydropower plants, producing 1000 MW par km^2, but dams exhibit a much lower factor due to flooded area (not evaluated).

Utility scale solar energy land use factor is dependent on its location (more specifically on the incident solar radiation), and on its load factor and conversion coefficient. The figures published by Poggi, Firmino, et Amado (2018) show a 12.2 MW / km^2 land use factor for the studied Portuguese solar energy utilities.

Table 8: Land use factor of different renewable energy sources in rated energy by kilometre square.

(MW / km^2)	Wind onshore	Wind offshore	Hydro power	Solar PV	Solar CSP	Geothermal	Biomass

8 https://www.energy.gov/eere/geothermal/geothermal-power-plants-minimizing-land-use-and-impact

(Arent et al. 2014)	5		1000 (run-of-river)	50	31	500	

Furthermore, studies like De Marco et al. (2014), Capellán-Pérez, de Castro, et Arto (2017) and Ryberg, Robinius, et Stolten (2018) showed that a number of constraints affect the eligibility of land to sustain efficient renewable energy sources. These constraints can be physical (slope, woodlands, dam construction ...), technical (wind speed, radiation incidence, availability of geothermal resources …) environmental (protected areas) or social (distance from urban settlements, etc.). They affect all energy sources, but especially wind and solar power, which are specifically and strongly dependent to outer physical parameters.

We do not have exact number for biomass however we can give an estimate. If we take a wood production of 5.6 m^3/ha/year in France[9] and a consumption of 113 000 t/year of wood for a 10MW power plant[10] considering the density of fire we can estimate an upper bond of 0.1MW/km^3. We do not have exact value because there is some uncertainty on wood density and this estimation do not consider the part of wood used in this plant for heat.

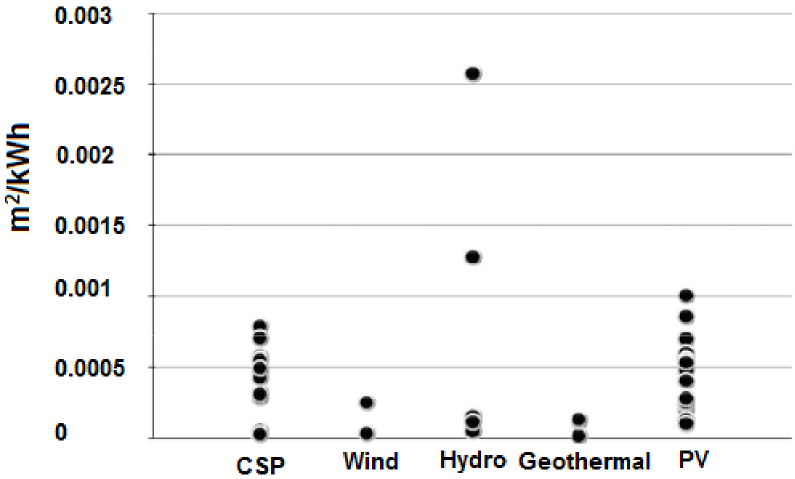

Figure 4: Land use from different reviewed study by Asdrubali et al (2015). Pay attention to the unit that is different from what is reported in table 6.

[9] https://inventaire-forestier.ign.fr/IMG/pdf/memento_2012.pdf

[10] http://alsace.edf.com/wp-content/uploads/2016/12/20161124-centrale-biomasse-strasbourg-fiche-technique.pdf

Social aspects

FATALITY RATE / MAX CONSEQUENCES

The fatality rate presented below (Table 9) does not exactly represent the intrinsic danger of a particular technology, rather the potential consequences in the (rare) event of a failure. Failure of a large power dam can have much more consequences than a wind turbine. The fatality rate of solar PV includes the risks of selected hazardous substances. Theoretical model of large dam failure in Switzerland indicates a 7000 to 11000 possible fatalities, reduced to less than 30 with a two hour warning (See Annex II of IPCC 2011, Moomaw et al. 2011)).

Table 9: Number of fatalities per TWh of produced electricity and per year, for different energy sources.

(TWh^{-1} . yr^{-1})	Wind onshore	Wind offshore	Hydro power	Solar PV	Solar CSP	Geothermal	Biomass
(IPCC, 2011)	1.9	6.4	85.3 (Europe)	0.25		1.7 (EGS)	14.9

Fatalities are not the only potential consequences of accidents involving renewable energy.

PUBLIC PERCEPTION OF RES

Studies on social acceptance in energy are generally related to one RES and one country or even community (e.g. Tabi et Wüstenhagen 2017; Kortsch, Hildebrand, et Schweizer-Ries 2015) making the comparison between different RES at an aggregated level quite difficult. Several surveys show that in general population support the development of renewable energies (Kortsch, Hildebrand, et Schweizer-Ries 2015 and ref inside; Wüstenhagen, Wolsink, et Bürer 2007). However, at regional/local level resistance to specific projects appear (Wüstenhagen, Wolsink, et Bürer 2007; Roddis et al. 2018). Some authors argue that resistance is related to a phenomenon called NIMBY (Not In My Back Yard), while other put forward that the NIMBY phenomenon is an over-simplification of the social resistance expressed toward energy-related projects (Wüstenhagen, Wolsink, et Bürer 2007).
Nevertheless, Roddis et al (2018) study the role of community acceptance in the development of solar farms and onshore wind. They focus on the outcome of planning application in Great Britain between 1990 and 2017. They find that surface disturbance such as visual impact affects largely the outcome of public consultation. However, this aesthetic criterion depends on how the addition of a solar farm and more importantly of onshore wind modifies the visual of an area. If some other installations are already present in the area it is more likely a new

project will be accepted. Concerning solar farms, they are more likely to be accepted if the land as a lower grade of agricultural land. This shows that conflicts are arising between land uses.

Liebe and Dobers (2019) compare solar energy, wind energy and biomass energy acceptance and use natural gas as a reference case. Using an on-line survey between September and October of 2013 they measure the acceptance and protest intention toward the construction of power plant using RES in Germany. They find that several factors are in competition to explain the attitude of people. Solar and wind energy are better accepted than biomass and natural gases. Solar and wind energy are perceived as more environmental-friendly and slightly more expensive than biomass energy and natural gas.

Looking at specific RES, Tabi and Wüstenhagen (2017) show that acceptance of hydropower in Switzerland is dependent on its ecological impact and the local ownership of the plant. Acceptance is also dependent on procedural and distributional justice.

Chavot et al (2018) analyze several EGS Alsace projects (France) and their acceptance. Some public inquiry reveals concern about the risk of explosion and others about induced seismicity for example. For one project the concern were focused on the additions of risk upon risks and for other it was about the lack of concertation between the metropole and local municipalities. These variations from project to project a few kilometers apart reveal that other factors are needed to explain the population's positions. The reasons to oppose a project can't only be reduced to fear regarding induced risks or NIMBY mindset. They are also related to the project holder's link with the community. The more anchored projects - with information given upstream and participation process - are more likely to be accepted. The projects that are seen as disconnected from the territory are less likely to be accepted. They also note that concern vary from project to project whereas these projects use the same technology and are only a few kilometers apart.

Social acceptance may be an issue for all RES but the issues leading to acceptance or opposition may be specific to:

- a technology, its role in the energetic transition, its maturity and the way it is perceived by the stakeholders,
- the project holder and its relations with the project stakeholders,
- the territory, its socio-economical fabric and the way the project fits in it.

Some trends can be identified, as in the articles mentioned above, but each project is a specific socio-technical assemblage.

PUBLIC PERCEPTION OF ENVIRONMENTAL CONCERNS

Seismicity

Induced seismicity, also known as manmade or induced earthquake, is associated with rather negative perceptions. Even when the probability of seismic events is considered low, the high perceived consequences may constitute a major concern (Knoblauch, Stauffacher, et Trutnevyte 2018; Benighaus et Bleicher 2019; Stauffacher et al. 2015; Manzella et al. 2018). Various main factors are known to influence perceptions of seismicity. Uncertainty about long term consequences of geological disturbance can create the perception that geological disturbance must be avoided as a principle (Knoblauch, Trutnevyte, et Stauffacher 2019). Also, unclarity about the use of technologies such as fracking have a major influence on perceived seismic risks (Benighaus et Bleicher 2019; Carr-Cornish et Romanach 2014). Furthermore, the siting of deep geothermal is key, the public preferring the implementation of deep geothermal in remote rather than urban areas to avoid the consequence of seismicity on buildings (Knoblauch, Trutnevyte, et Stauffacher 2019).

The perception of induced seismicity is further impacted by contextual elements and social dynamics. Accidents caused by induced seismicity like the one in Basel, Switzerland in 2006, greatly impacted public opinion fed by the negative discourse in media reports (Stauffacher et al. 2015; Kunze et Hertel 2017), which eventually led to the emergence of an environmental protest movement in Germany, and to the withdrawal of deep geothermal projects. National and local context may also alter the perception of induced seismicity. The environmental protest movement in Germany, for example, emerged in a context of overall protestation against nuclear power, carbon capture, shale gas and wind parks (Kunze et Hertel 2017).

Groundwater pollution

Several studies on public acceptance of deep geothermal carried out in Europe such as France, Italy, Greece, Germany, Switzerland, and outside of Europe such as in Australia and Chile continuously highlight that groundwater pollution is perceived as a dominant environmental concern by the citizens (Manzella et al. 2018). For example, in Québec, a survey showed that out of 1353 respondents, 58% of them put groundwater pollution as first environmental concern (Carr-Cornish et Romanach 2014). The literature is not always clear in what it is exactly meant by ‘groundwater pollution’, but it usually refers to the risks associated to water quality or the fear of poisoned water such as arsenic contamination (Vargas Payera 2018; Carr-Cornish et Romanach 2014; Chavot et al. 2018). Some of those concerns are triggered by a lack of knowledge or information on deep geothermal operation processes (Manzella et al. 2018; Carr-Cornish et Romanach 2014). They are also linked to past events such as in Switzerland, or by the collective memory of particular events concerning water, such as the contamination of water due to uranium mining activities conducted until the 1980s in Schneeberg/Bad Schlema, in Germany, which still impacts the lives of its citizens (Carr-Cornish et Romanach 2014; Benighaus et Bleicher 2019). A mismatch between local risks and global benefits can also be observed. For example, water usage concerns raised during the drilling phase remain mostly local concerns, compared to global benefits such as low emissions on the environment (Carr-Cornish et Romanach 2014). Overall, while demanding complete avoidance of human impact on the environment, some express the need for more research (Benighaus et Bleicher 2019).

Air emissions

The topic of air emissions shows more contrasted results in the perception of deep geothermal energy. They trigger the question of whether deep geothermal energy is a renewable energy or not. In Germany, in 65 arguments related to the most concerning environmental preoccupations, only 4 arguments questioned the environmental friendliness of deep geothermal in terms of CO2 emissions, and some participants even proposed some solutions, calling for more research or the responsibility to decrease CO2 emissions (Benighaus et Bleicher 2019). In contrast, there is a strong negative perception of air emissions when controversial cases associated to deep geothermal developments are made publicly known. For example, the case of the Milos pilot plant in Greece, and the case of the Mount Amiata in Italy. In Greece, fierce opponents to deep geothermal developments rose because of errors in the construction of the plant on the Milos Island, which lead to extensive air pollution (Karytsas, Polyzou, et Karytsas 2019). In Italy, a real organization of civil society emerged, and established itself as a social movement called the Amiata, advocating against the development of deep geothermal. This social movement is supported by the Italian 5 Star party, even supported by a few decision makers among European Institutions. The topic of deep geothermal development turned into a controversial situation concerning the emissions of Monte Amiata power plants, and the Amiata movement pledge their case before the court of Tuscany in 2018 (Pellizzone, Allansdottir, et Manzella 2019). They argue in their SOS Geotermia Manifesto that “each geothermal plant emit to the atmosphere, on top of steam, CO2, mercury, arsenic, sulfuric acid, ammoniac and other polluting steam causing severe damages to the environment and the health of its inhabitants (Mobertos 2015)”.

Surface disturbance: noise, vibration, dust, smell, land occupation, visual.

Disturbance can occur throughout the development of a deep geothermal plant. It includes noise, vibration, the land occupation, dust, smell, or the visual pollution. As noise occurs during the drilling and production processes, noise pollution is usually poorly perceived (Benighaus et Bleicher 2019). A survey carried out in 2012 in Soultz-sous-Forêts, France, highlights that it is not so much the presence of the plant that preoccupies but well the noise by 56.7% of the respondents (Chavot et al. 2019). In Switzerland, the noise pollution and the impact on landscape became such a public mater for the inhabitants of the Haute-Sorne that the case was introduced before the Court (Ejderyan, Ruef, et Stauffacher 2019). Concerning the vibration felt by the local residents, an empirical study in France concluded the absolute necessity to avoid vibration felt by the population in order for deep geothermal operations to gain more acceptance.

Disturbance in the literature can also be linked to the location of the deep geothermal project. Several authors (Majer et al. 2012; Richard, Maurer, et Lehujeur 2016; Knoblauch, Trutnevyte, et Stauffacher 2019; Chavot et al. 2019) highlight that the location of the Enhanced Geothermal System technology " in populated areas could be regarded by some as an intrusion on the peace and tranquility of populated areas due to its potential 'annoyance factor' (Majer et al. 2012)". Some interviewees comment: "After reading all the information I think I would be ok if they were to start a project in my area, I am not sure how far they should be, far away enough that there is a minimal noise, traffic congestion, and an eyesore to the environment?" (Carr-Cornish et Romanach 2014). Disturbance due to the location and occupation of the land can also trigger lots of concerns and fierce opposition if there is disturbance to protected natural environment such as natural parks (Chavot et al. 2019).

Ground elevation

The perception of ground elevation is rather slim in the literature. Concerns were raised during one controversial event in Germany, in the city of Stauffen, where it was reported that the ground had lifted from 12 centimeters, caused by the drilling operations. It was concluded that the media reports frame and impact "what and how much people learn from the event presented" (Benighaus et Bleicher 2019).

Radioactivity

Very little is known about the perception by the citizens of radioactivity in the development of deep geothermal plant. Nevertheless, during the legal public inquiry performed in France for the Alsace, Haute-Savoie and Reunion Island projects, it turned out that those legal public enquiries became real protest platforms, through which the radioactive upwelling was reported as one of the major environmental concern by the inhabitants (Chavot et al. 2019).

Conclusion

Each renewable electricity generating technology has its pros and cons regarding either the environmental, economics, technical and/or social aspects. In this section, we would like to highlight the pros and cons of the geothermal energy regarding each considered renewable energy on all these aspects.

Generally speaking, there is no specific parameter in which geothermal power exhibits crippling figures. The values observed are comparable to other RES.

One important advantage of geothermal energy over wind or solar power is its high capacity factor, compensating for its high capital cost and giving him a good EROI number, excepting the EGS technology. The intermittent nature of solar and wind energy is the main drawback of these technology, with also their high land use per produced energy, that reduces vegetal covers and animal habitat.

Wind energy and hydropower have the advantage to release less GHG into the atmosphere than geothermal power plants. Geothermal energy also consumes more steel, aluminium and water than wind and hydropower. That is why current research is focusing in lowering this demand. However, wind and solar PV have a non-negligible demand of rare-earth. The drilling and installation process of geothermal plants emit some acidification and eutrophication substances, comparable to what is produced by the manufacturing of PV, leading to more human health impacts, but still of the same order as other RES, in a short-term assessment. However, the use of rare-earth elements in wind turbines and PV leads to important land use and more human health impact over a long-term period.

Dams can cause more seismic activity than geothermal power plants and have an important impact on river ecosystems by disrupting the natural flow regimes. Biomass power plants produce GHG, pollutants, consume a lot of water from crop production and have a low EROI number.

In term of public perception no RES seems to dominate another, some are more well-known but the opposition or support seems not to be directly related to environmental effect.

Two things need to be kept in mind while looking at this review. First, for information coming from a LCA, a results harmonization is necessary to reduce the data variability, aligning methodological inconsistencies in published LCAs, such as different system boundaries, the use of outdated data, variations on similar energy process chains, and even simple differences in reporting of results (Asdrubali et al. 2015). Second to limit the impact of such variability issue, we privileged older documents comparing different RES over more recent study focused on single RES. This means that some of these results need to be updated as technology may have progressed on some points and lead to different figures.

Nevertheless, these results highlight the benefits of each type of RES depending on the characteristics researched. Additionally, this is the current panorama but new improvement in technology is looking at limiting furthermore the environmental effect of RES as we have shown concerning material consumption for geothermal operations to decrease as much as possible the environmental consequences of energy production.

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