LCA Guidelines for Geothermal Installations

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GEOENVI

Executive Summary

These guidelines were developed as one of the outcomes of the European project GEOENVI [Grant agreement n°818242 -- 2018-2020]. These guidelines are a **first** proposal based on expert judgement from GEOENVI partners and represent a consensus among the authors. They are to be shared among the geothermal community to be revised in order to reach a broader consensus.

Life cycle assessment (LCA) is a structured, comprehensive method of quantifying material and energy flows and their associated environmental impacts caused throughout the life cycle of a good and/or service. The Joint Research Centre and the ISO 14040-14044 standards provide a framework for LCA assessments. However, this framework is general and not tailored to energy pathways and more specifically to geothermal systems. It leaves the user with a large range of choices resulting in a large variability in the LCA results that can affect their understanding by decision makers.

The present guidelines are intended to offer methodological indications and assistance on how to perform LCAs of geothermal systems. The scope is to provide a common and accepted basis to evaluate the life cycle environmental impacts of geothermal energy systems to compare results for different geothermal settings and energy conversion technologies. Guidance is given on geothermal-specific parameters used as inputs in LCA, on choices in life cycle inventory (LCI) data collection, and on modeling approaches and methodological assumptions resulting in the life cycle impact assessment (LCIA) and the interpretation and reporting of the study. A consistent system modeling approach accounting for the type of geothermal technology, the functional unit, the system boundaries, and the allocation aspect enhances the credibility of geothermal LCA studies and enables balanced LCA-based comparisons of different energy systems. A thorough description of exergy as a valuable approach for allocation is provided. This document further discusses the choice of environmental impact categories based on the Environmental Footprint method (V3). It also highlights the importance to report inorganic emissions separately, even when not accounted for in the impact categories used. It also provides recommendations for additional comprehensive metrics such as the Primary Energy Saving (PES) and Energy Payback Time (EPBT).

Transparency in reporting is essential to explain the great variability observed in various published studies of geothermal LCAs. These LCA guidelines list all important information that should be documented in the LCA report. Mainly, these include a thorough description of the goal and scope of the study, including all relevant methodological choices and assumptions, databases and LCA software used. The following parameters shall also be reported in captions

of result figures and tables: (1) Geothermal technology (Hydrothermal with or without stimulation); (2) Type of energy conversion technology (e.g. direct or ORC); (3) Expected annual electricity/heat production or load factor (hours/year) and energy output decay; (4) Lifetime of installation (years); (5) Plant size (MW); (6) Number of wells (production and reinjection) and depth of the wells; and (7) Characteristics related to the output products: for steam: the distribution system pressure, feed and return temperature and flow rate, for hot water: the distribution system feed.

Glossary

CF	Characterization Factor
CHP	Combined Heat and Power
EGS	Enhanced Geothermal System
EoL	End of Life
EPBT	Energy Payback Time
ESP	Electro-submersible pump
GHG	Greenhouse gas
FU	Functional Unit
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LSP	Line Shaft Pump
LHF	Load heat fraction
NCGs	Non-condensable gasses
NREPBT	Non-Renewable Energy Payback Time
ORC	Organic Rankine Cycle
PEF	Product Environmental Footprint
PES	Primary Energy Saving

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Introduction

Geothermal energy is among the most promising renewable energy sources for electricity production and heating and cooling production (IRENA, 2018). Geothermal energy has been identified as a key component of the future European energy system which can contribute to a sustainable development and a transition towards a low-carbon economy (SETIS, 2015). However, the advantages of using geothermal natural resources for power production, heating and cooling applications, and combined Heat and Power Production (CHP) are not yet widely known. Making sustainability-related decisions in the energy field requires a science-based approach which accounts for all stages of energy production including generation, distribution, use, and end of life.

Life cycle assessment (LCA) is a structured, comprehensive method of quantifying material and energy flows and their associated environmental impacts caused throughout the life cycle of a good and service. The Joint Research Centre (JRC, 2010) and the ISO 14040-14044 standards provide a framework for LCA assessments (ISO 14040:2006, ISO 14044:2006). However, this framework is general and not tailored to energy pathways and more specifically to geothermal systems. It leaves the user with a large range of choices resulting in a large variability in the LCA results that can affect their understanding by decision makers.

The present guidelines are intended to offer methodological indications and assistance on how to perform LCA of geothermal systems. The scope is to provide a common and accepted basis to evaluate the life cycle environmental impacts of geothermal energy systems allowing for comparison of results for different geothermal settings and energy conversion technologies. Harmonization has been identified as necessary to reduce LCA results variability, align methodological inconsistencies in published LCAs, such as different system boundaries, the use of out-dated data, variations on similar energy process chains, and even simple differences in the reporting of results (Asdrubali et al., 2015), (Guðjónsdóttir et al., 2019, GEOENVI D3.1). These guidelines were developed to offer guidance for consistency, balance, and quality to enhance the credibility of LCA findings on geothermal systems. They cover the most sensitive aspects of each step of an LCA applied to geothermal systems.

Motivation and Objectives

Geothermal energy is an important renewable resource capable of providing a valuable contribution to sustainable development and to lower the emissions connected with the use of fossil fuels (Tomasini-Montenegro et al., 2017).

The term “Deep Geothermal” applies to systems for the conversion or direct utilization of the vertical temperature gradient. Typically, these systems involve vertical and/or deviated wells of at least several hundred meters and can provide a concentrated form of energy which is peculiar to this technology within the family of renewables (typically, characterized by distributed low-intensity resources). This feature is particularly appreciated as it can provide an easy matching to the load and to the requirements of distribution grids.

Deep geothermal energy can address several needs of society: heat and electricity, but also, even if less commonly, cold production or material streams of valuable products (such as minerals or chemicals).

The availability of the resource depends largely on the location: very few sites combine the availability of the hot resource with that of the water/steam resource. Even in these cases, cultivation (rather than exploitation) of the field must be correctly applied to ensure its long-term availability. However, Enhanced Geothermal Systems (EGS) can be applied where the geothermal fluid resource is not naturally suitable for industrial use, thereby extending considerably the applicability of geothermal energy. In this light, the development of technological solutions for medium and low-temperature applications is having a promising market impact.

The objectives of these guidelines are to provide guidance on:

- how to establish the life cycle inventories (LCI) of geothermal systems
- which environmental impacts to address in life cycle impact assessment (LCIA) and which impact category indicators to use
- how and what to document regarding the LCA of geothermal energy (electricity, heat or combined systems)

Methodological Guidelines

The present guidelines can be applied to deep geothermal systems producing electricity and/or heat/cold. They are extended to cases where chemical by-products (streams of matter) are produced in output of the plant.

The use of these guidelines in the field of shallow geothermal systems, with specific reference to those based on the use of heat pumps which do not rely on the vertical temperature gradient but on the seasonal temperature difference between the atmospheric environment and the soil at small depth, is not recommended.

In principle, these guidelines refer to potential environmental impacts under normal plant operation and not to risk events which deserve specific preventive measures both in the geothermal field development, normal operation, and decommissioning. These impacts take place in different lifetime stages (project development, plant operation and end-of-life), and are, in many cases, monitored to preserve human health and the environment or because of law prescriptions (for source emissions or air quality) or local agreements among the stakeholders (utilities, consumers, communities, local government). The generated LCA results applying these guidelines could contribute to a sustainability assessment of geothermal projects and does not pretend to be exhaustive and exclusive in examining all potential environmental issues. To this end, the LCA could be accompanied by environmental assessment criteria, which can consider site-dependent matters (such as micro-seismicity, subsidence, noise...) or whose evaluation involves social or qualitative acceptance (preservation of landscape, cultural heritage, effects on occupation and economics…).

Specific aspects of geothermal energy production

The environmental performances of the geothermal installation over its full lifecycle depend on the geological conditions (e.g. the temperature and composition of the extracted geothermal fluid), on the technology used to convert or utilize geothermal energy, and on potential abatement measures.

This section includes a brief description of the main aspects and parameters influencing environmental impacts. Impacts on the environment result from direct and indirect emissions as well as land use changes. Direct emissions include (1) the gases carried in the geothermal fluid either as free gas or in a dissolved form, (2) fugitive emissions of working fluids in case of Organic Rankine Cycle (ORC) plants generating electricity, and (3) air pollutants related to the diesel combustion necessary to provide energy for the plant construction (including drilling platform lift + rotation, pumping of muds…) and management of its end-of-life (dismantling, well closure…). Indirect emissions are associated with materials manufacturing and energy production required during the whole life cycle of the geothermal plant. Gathering information related to these emissions is considered as a crucial step when performing a life cycle assessment of geothermal plants.

In this section, an initial short description of the parameters necessary to identify the context is given. The LCA analyst should consider the following information when assessing the potential impacts of energy production from geothermal source: the resource type, the production technology and the operation plant parameters.

In a later section, indications on the modelling of life cycle phases are provided together with a suggested list of reference/default values (see Appendix 2), in order to facilitate the modelling of the geothermal system for the practitioner.

Identification of the geothermal resource type

a. **Dominant phase**. The geothermal fluid in the reservoir can be classified according to its dominant phase. Generally low temperature reservoirs are in a single liquid phase whereas high temperature reservoir can be liquid or vapor dominated. The dominant phase has implications on the gas concentrations in the fluid since Non-Condensable Gases (NCGs) tend to be more present and mixed with vapor in the gas phase. Thus, vapor dominated reservoirs have a higher potential of gas emissions.

b. **Gas content and composition**. Non-condensable gasses (NCGs) occur naturally in geothermal fluids at different content and composition. Typical NCGs concentrations vary from 0.2 to 25 % of the steam with CO_2 being generally the most abundant gas. The NCGs content affects several technical solutions (e.g. production technology, cooling system, and fluid reinjection capabilities). Indeed, high gas concentrations can cause degassing phenomena leading to direct emissions of geothermal gas in the atmosphere.

c. **Depth of the system.** The depth of the reservoir has an influence on the pressure and the temperature of the reservoir which, in turn, affect the solubility of minerals in the geothermal liquid resource (and consequently its composition) and the partitioning of gases to the vapor phase. The depth of the reservoir also affects the fuel and material (e.g. cement) requirements to drill and complete the wells with an impact on indirect emissions. Typical depths range from 2,5 to 4 km.

d. **Hydrothermal system with or without stimulation.** Naturally occurring geothermal systems are known as hydrothermal and are characterized by the local availability of a resource fluid. EGSs are geothermal systems where low natural permeability reservoir does not permit industrial use. Thus, EGSs make extensive use of stimulation techniques to develop the suitable porosity/fracture patterns and increase fluid circulation in those cases to reach industrial operating conditions. Stimulation can also be performed in hydrothermal systems to improve permeability or to recover the original well characteristics that may have decreased because of clogging due to mineralization of salts.

Identification of the production technology type

a. **Fluid flow production** (self-flowing, pumped, gas lift). In order to convert the geothermal energy, it is today necessary to bring geothermal fluids to the surface. This can happen spontaneously due to pressure difference between the reservoir and the inlet of the power plant (self-flowing) or can require the use of pumps. In some cases, the use of pumps can be a choice to avoid degassing of NCGs to the atmosphere, keeping the system in pressure.

b. **Energy conversion technology**. In geothermal power plants geothermal fluids produce work using a turbine that generates electricity, applying thermodynamic energy conversion (heat-power-electricity). The fluid sent to the turbine can be the geothermal fluid extracted from the ground (direct systems) or a secondary fluid heated by the geothermal fluid through a heat exchanger (binary systems), obtaining a so-called Organic Rankine Cycle (ORC). ORCs are widely employed also in other fields or for waste heat recovery. In binary solutions, the working fluid is not necessarily of organic origin – even if this is the current advanced market solution. The three major conventional and widely adopted geothermal technologies to provide energy are:

i. Dry steam systems (direct)
ii. Flash systems, single or multiple (direct)
iii. Binary systems (binary)

These technologies can also be combined in order to improve the conversion efficiency from the geothermal energy resource: the most typical applications of this approach are hybrid power plants employing a top flash turbine and a bottom ORC, to exploit the residual heat of the geothermal fluid. As for all systems applying thermodynamic conversion, the final efficiency is highly dependent on the temperature of the resource: multiple-flashes, regenerative and hybrid plants allow a better matching of the resource under the constraint of limited heat capacity imposed by the well productivity curve (pressure vs. flow rate at well head or separator). All these technologies, except for the binary and zero emission plants, which are based on geothermal fluid full reinjection, emit NCGs from geothermal fluid to the atmosphere.

The selection of energy conversion process for a geothermal project depends on several parameters, such as resource temperature, pressure, flow rate, and chemical composition.

c. **Cooling system**. Cooling systems are usually divided into two main groups: air coolers or wet cooling towers. Water condenser via heat exchangers is another possibility although not very common for geothermal plants. A wet cooling tower is based on the capacity of the water to subtract heat from a system through evaporation and saturation of an environmental air stream, which is a very efficient and compact way of transferring heat through mass exchange. In fact, the latent heat of vaporization is about 2,4 MJ/kg of evaporated water in reference conditions which means that evaporation of a stream of 1 kg/s of water removes effectively 2,4 MW of heat. Usually a simple condenser cooling system requires an external source of water (from the sea or a suitably large river resource), but since geothermal plants are often found in places where there is not considerable availability of natural cooling water resources, re-circulated (condensed) geothermal fluid is often used for cooling purposes. This technology is extremely common in direct cycle power plants (dry steam or flash). A drawback is the possible emission-to-air of chemical compounds dissolved in the geo-fluids together with the water vapour resulting from the cooling process, which represents a potential source of pollution. Alternatively, an air cooler uses heat exchangers cooled by ambient air with a fully separate circuit so that the fluid does not encounter the atmosphere and all emissions can be avoided. In this case, the main drawback is the larger land occupation of this heat exchanger since the heat transfer conditions are much less favourable for rejection of heat to air without its humidification. Additionally, some scaling phenomena might occur and, in some cases, a lower plant efficiency in comparison with the case of a wet cooling tower. Air coolers are commonly used in binary power plants to cool down the working fluid but can be also implemented in direct cycle power plants.

d. **Emissions abatement system**: in order to reduce emissions of pollutants abatement systems can be employed in geothermal power plants to reduce emissions of pollutants. Several abatement systems can be applied for hydrogen sulphide and mercury, which are the most common pollutants encountered; an example, specifically developed for geothermal applications, is the AMIS[1]© process, which is very effective in reducing emissions of gaseous mercury and hydrogen sulphide.

e. **Reinjection (liquid, liquid + NCG)**: reinjection is the practice to reinject into the geothermal reservoir the extracted and exploited geothermal fluids. By reinjecting the fluid, it is possible to extend the lifetime of the reservoir and to improve the environmental performance

[1] AMIS © stands for Abbattimento Mercurio ed Idrogeno Solforato. For a description of the process, see Baldacci et Al., 2005

of the system. The lifetime of the reservoir can virtually be extended endlessly, meaning in practice until exhaustion of the local heat source, which is usually a very long lifetime. Feasibility studies are usually based on a 30 years lifetime. For this reason, geothermal energy is considered as a renewable resource. Currently, the liquid phase is partially or totally re-injected in nearly all geothermal projects. NCG reinjection, on the other hand, is a solution under development for flash plant, but quite common to binary or heat plants, needing specific site-dependent approaches and probably not viable for all sites. The environmental benefits of re-injecting both liquid and gaseous fractions, when technically possible, are obvious as there are in practice no emissions to the atmosphere (zero-emission power plants during the operation phase).

Identification of the operational plant parameters

a. Plant power size
b. For steam production, the distribution system pressure, feed and return temperature
c. For hot water production, the distribution system feed and return temperature

Energy output decay: This parameter quantifies the expected drop in energy output per year. It can be expressed as loss of % of the total energy output. It is recommended to use a thermal decay of 2.5% over 30 years. If no energy output decay is accounted for, drilling of additional wells are to be included in the inventories related to the wells over the whole lifetime.

d. Operating lifetimes: several lifetimes must be considered for the geothermal installation over its whole life cycle. More details on this is provided in the "Goal and Scope definition" section.

The following sections cover all the main steps of an LCA analysis, namely the goal and scope definition, life cycle inventory analysis, impact assessment and result discussion and interpretation.

Goal and scope definition

Items to be defined in the goal and scope definition phase include the functional unit, system boundaries, level of specificity of data through the definition of foreground and background data, exclusion of life cycle stages or inputs, and the selection of impact indicators and characterization factors (Curran, 2017).

Goal of the study

The modelling approach employed to assess an energy system depends on the goal of the study. Generally, we can distinguish among attributional and consequential approaches (JRC, 2010). Most of the LCA studies on geothermal systems currently available in the literature follow an attributional approach (Paulillo et al., 2019, Tomasini-Montenegro et al., 2017, Parisi et al., 2019).

Three major goals can be identified for a geothermal LCA application, which imply relatively different approaches:

1. Assessing the environmental impacts of energy production from an existing geothermal plant supplying a utility's network, comparison of different geothermal systems or technologies. (retrospective attributional LCA).
2. Comparison of future geothermal systems and/ or electricity generation technologies from a geothermal resource. (Prospective LCA, future attributional LCA to model a static future situation).
3. Assessing the consequences of enlarging the share of electricity from geothermal resource in the electric grid of local, regional and national communities. (Consequential LCA).

Depending on the goal of the study, the most suitable LCA approach should be selected and applied. A distinction between foreground and background processes applies in all cases, despite the goal of the LCA study:

- Foreground processes are directly influenced by the decision maker or plant owner and the data regarding these processes are generally measured directly (primary data).
- Background processes are all the other processes included in the system boundaries. The data referring to this type of process is generally retrieved from specific LCA databases (e.g. Ecoinvent database V3 (Wernet et al., 2016)) (secondary data).

LCA practitioners should clearly define the goal and the intended application of the LCA study, the motivation behind it and the audience to whom the study is dedicated.

Functional units

The functional unit (FU) is a quantitative measurement of the function of a system for use as a reference unit. It allows for consistent comparisons among different geothermal systems and with respect to other electricity/energy-generating technologies that can provide the same function.

In the energy sector (including geothermal applications) two main functions can be distinguished, each with a different recommended functional unit:

1. Power production only: 1 kWh of electricity delivered to the grid or a user (kWh_{el});

2. Heating/cooling production only: 1 kWh of heat delivered to the grid or a user (kWh_{th}).

It is worth to underline that when handling combined heat and power production (CHP) a multi-functional approach based on a proper allocation scheme is to be followed. The recommended allocation procedures are listed in the “Life Cycle Inventory” section and application examples are provided in Appendix 1 and Appendix 4.

System boundaries

This section offers guidance on what should be included in the assessment, and what should be excluded. Following the system description, boundaries should be clearly defined. A graphical support is highly recommended. This could also include a simplified representation of the power plant investigated. The approach proposed in these guidelines is based on the description of the “Life cycle phases of energy systems” as reported within the PCR UN CPC 171 and 173 Electricity, steam and hot/cold water generation and distribution [Product Group Classification, 2007]. The system under investigation should be divided into 3 modules: upstream, core, and downstream (Figure 1).

The **upstream module** includes the production processes for materials and energy consumed by the core module. Generally, these are secondary data which are taken from existing LCA databases (e.g. Ecoinvent, GaBi database and others) and represent average estimates. Furthermore, the dataset associated to the production process can contain aggregated data including infrastructure, transport, decommissioning and end of life stages depending on the type of database employed. Therefore, it is of paramount importance to clearly indicate the type of process selected and from which database. Some indication on secondary data selection or alternative proxies if secondary data is not available is given in the modelling sections.

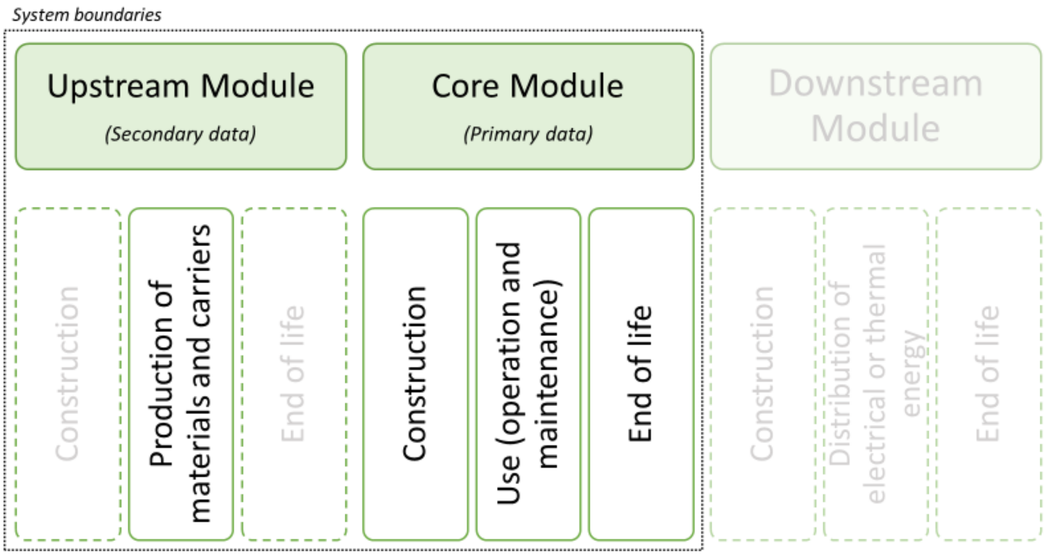

Figure 1 - Graphical representation of system boundaries for geothermal energy systems.

The **core module** is represented by the construction of infrastructure, operation, maintenance, and End of Life (EoL) phases of a geothermal energy conversion plant (system). The core module must be included in an LCA study. Normally, the core module is modelled using primary data that should be directly measured or collected from reports or questionnaires and is representative of the geothermal plant (site and technology specific).

In the specific case of geothermal energy system, the core module is to be split in three different phases (see Figure 2):

1) the phase of construction of the infrastructure, which should include construction works for the wells, wellheads, collection pipelines, power plant building, and all the necessary plant machinery/equipment items

2) the operational and maintenance phase, which should include geothermal fluid exploitation, stimulation, equipment replacement, scaling prevention, drilling of additional wells, and direct emissions to air.

3) the end of life phase, which includes procedures for correct closure of the wells, and the treatment of wastes produced from all previous phases.

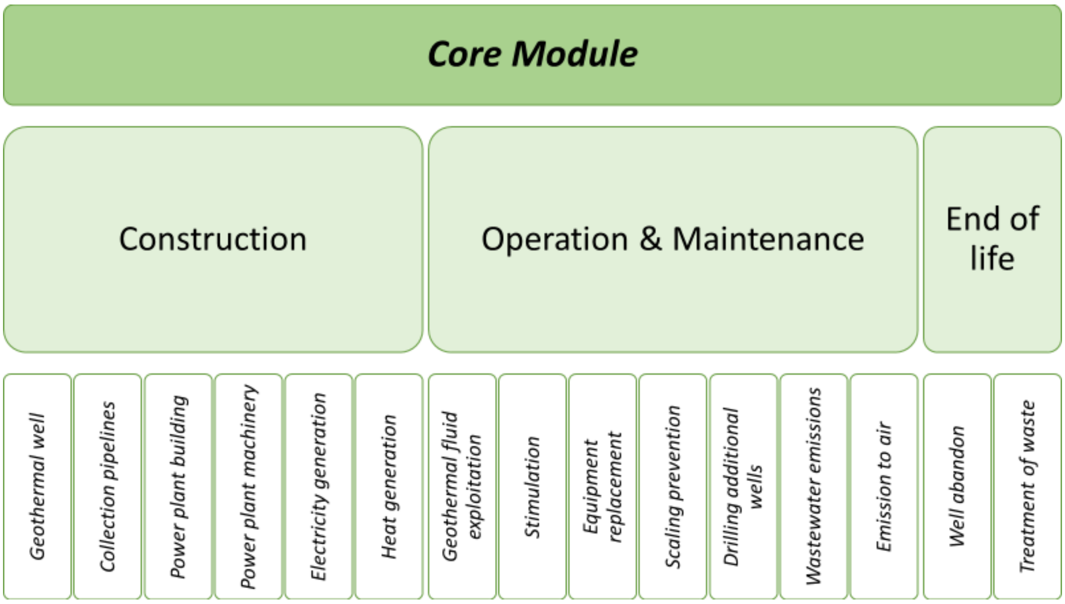

Figure 2 - Phases of the Core module for geothermal energy systems

The **downstream module** consists of the distribution of the electrical or thermal energy produced, from the plant/application to the customer; these guidelines do not cover the distribution part. If the scope of the LCA includes distribution of the energy, it is highly recommended to separate the results for electricity/heat production from those of distribution in order to ensure comparability of results.

It is essential that if any process is excluded from the system boundaries, it should be clearly reported and justified.

Lifetime

Fixed default values are recommended to the LCA practitioner as these parameters highly affect the environmental performance of the geothermal installations.

- Project lifetime is set to 30 years and refers to the duration of the activity of the plant.
- Surface power equipment lifetime is recommended to be set to 30 years (Table 1) and is used to calculate total energy production except for specific equipment such as pumps (Table 2).

Underground resource-exposed equipment lifetime recommended values are given in

- Table 2 – Recommended values for the lifetimes (years) for ESP and LSP according to % mass of NCG. as well as the rate of replacement necessary for maintenance assessment.

- Any other lifetime of common equipment used in geothermal energy production is given in Table 1 – Recommended values for the lifetime of surface equipment.

Table 1 – Recommended values for the lifetime of surface equipment

	Equipment	Lifetime (years)
Surface equipment	ORC	30
	Heat exchanger	15

Table 2 – Recommended values for the lifetimes (years) for ESP and LSP according to % mass of NCG.

ESP (40-120°C)		LSP (80-160°C)	
NCG %mas > 0.5	NCG %mas < 0.5	NCG %mas > 0.5	NCG %mas < 0.5
replacement: pump + motor + 40% of column	replacement: pump + motor + 20% of column	replacement: pump + 40% of column	replacement: pump + 20% of column
3	5	4	7

Comparability

The LCA report should clearly state that comparability of different LCA studies can only be accomplished if the same system boundaries and assumptions are applied in all studies.

Life Cycle Inventory (LCI)

This section covers the technical aspect of modelling a geothermal system to generate a life cycle inventory. This section includes indications on which process design choices are considered, but also how to model the life cycle in term of process selection, types of emissions and receiving compartment, management of wastes and end-of-life processes selection. Furthermore, indications on how to calculate/estimate material consumption and emissions are provided based on the operating parameters of the geothermal system. Whenever possible, it is strongly recommended to use specific data related to the installation, meaning primary data. In case no specific data is available, generic data are provided in Appendix 2 as alternative values to be used in the study (See also the "Goal and scope definition" section).

Databases

These guidelines do not recommend the use of a specific LCI database. However, the choice of an LCI database is of utmost importance and should be driven by considerations of transparency of the documentation and availability of the unit process information and data. The database selected, its version, and an appropriate reference should always be reported.

Data quality

The quality of the used data shall be assessed and described at least qualitatively in the project report. The data quality assessment method as described in the PEFCR Guidance version 3.6 (or later) can be applied. Typical information to be reported relate to the data source, its publication year, and spatial and technological coverage. Potential data gaps should always carefully be reported.

Allocation/multi-functionality hierarchy

LCA often deals with multi-purpose processes, having multiple products. The method chosen to allocate the impacts between different products can be based on different properties, the most common ones being the mass, economic value or energy content of products. The appropriate method for allocation is selected during the definition of the goal and scope of the study and of the functional unit as reported in the section "Goal and scope definition". In the case of geothermal plants, there is a wide variability among the installations:

- Systems producing only electricity;
- Combined heat and power (or even heat, cold and power);

- The production of heat alone for direct utilization;
- The production of other by-products (e.g. natural gas, Lithium, Boron …) is also possible.

Two different allocation schemes can be applied to the wide diversity of geothermal installations and are reported below.

(1) If the share between the co-products > 75% => the system allocation scheme should apply a system expansion with a substitution model for the co-products

For CHP installations, the system allocation scheme should be based on the energy type of output products when the ratio of the net electricity production to the net heat production > 75%. When applying the substitution approach [ISO, 14044], we recommend the EU natural gas process for the heat process and the country-specific electricity mix for the electricity process.

(2) If the share between the co-products < 75% => the system allocation scheme should be based on the exergy content (Appendix 1). For systems producing large amounts of heat, a comparison of the allocation scheme using either exergy or Primary Energy Saving (PES) can be conducted, as illustrated in Appendix 4.

Modelling of the construction phase

Materials and energy requirements to build subsurface, surface infrastructures, and equipment/components as well as drilling of the wells are to be included in the construction phase. Recommendations on the reporting of the type of direct emissions and receiving compartment (e.g. atmospheric emissions, effluents) are provided for each of these sub-systems. The use of primary data in priority is highly recommended. When no primary data is available, a series of average data issued from for different GEOENVI case studies is provided in Appendix 2 and can be used as a first approximation in case no installation-specific data is available.

- **Geothermal wells**
  - **Drilling:** The drilling technique adopted is typically influenced by parameters related to the geothermal reservoir such as temperature, type of host rock, gas concentration in the fluid, and depth of reservoir. In Europe, the common drilling method applied is the well-established rotary drilling method. This method is particularly adopted in situations when drilling into hydrothermal liquid-water and vapour dominated geothermal

reservoirs is required. Rotary drilling can be applied using a diesel or electric-powered rig. Previous LCA studies have demonstrated that diesel consumption of the drilling rig has a significant impact on the LCA results (Lacirignola and Blanc, 2013, Tomasini-Montenegro et al., 2017, Pratiwi et al., 2018). Therefore, emissions to air due to in situ diesel fuel combustion (foreground data) or electricity consumption and the related background emissions data should be accounted for in this process.

Water, lubricant and other chemicals/additives are used during drilling activities. During drilling, effusion of fluids and solid waste materials are produced, such as: i) drilling mud and other drilling fluid additives like cement slurry, diesel and lubricant, cleaning fluid waste and geothermal brine, and ii) cuttings, excavated earth and rocks, industrial waste of different types. Drilling muds are made up of a mixture of water and clay (bentonite) and may also contain additives such as barium sulphate (barite) and synthetic polymers. Anionic polyelectrolytes (e.g. acrylates, polyphosphates, lignin sulphonates), are often used as fluxing agents during drilling to reduce the viscosity of the drilling fluid. The brine extracted during drilling contains both salts and silica in variable amounts and composition, depending on the type of geothermal fluid.

- **Casing and cementing:** Geothermal boreholes are protected by steel and cement casings. Casing is required essentially to prevent holes from collapsing. Steel and cement utilization should, when possible, be derived from the casing design (Default values are given in Table 1.2 in Appendix 2). If not known, the amount of steel and cement might be available directly. The indirect emissions generated from the production of cement and steel should be included in the process.
- **Stimulation:** The techniques currently employed for well stimulation are hydraulic, chemical, thermal and radial jetting stimulations. The most common stimulation technique applied in an EGS context is a hydraulic one often boosted by chemical stimulation. Generally, water is always required in any stimulation and should be included as input in the process. Furthermore, all types of stimulation require electric power which is associated with the pump functioning to maintain an adequate pressure flow. In case of chemical stimulation, the upstream production process of chemicals employed should be accounted for. A list of inputs for the stimulation process is given in Table 3 of Appendix 2 together with reference quantities.

• **Wellhead:** Both production wells and reinjection wells usually share the same wellhead equipment. The wellhead equipment for each well usually includes a well silencer and an aluminium well housing containing a main wellhead valve as well as piping and smaller valves. Material requirements are listed in Appendix 2, Table 4.

- **Collection pipelines (geofluid production and reinjection; NCG reinjection):** The collection pipelines are made of steel, insulated with mineral wool. The pipelines are sized and designed based on the mass flow of geofluid and NCGs. It is recommended to estimate the material amount from the pipe diameter, the selected layers thickness, and density of the materials. Table 5 in Appendix 2 presents the material and construction work per meter of collection pipeline for diameters ranging from DN300 to DN600 and insulation thickness varying from 5 to 10 cm.
- **Power plant building:** A power plant producing only electricity includes the following facilities: switchboard plant, building for transformers, building for oil collecting pit, building for emergency power generation, gas pumping station, building for gaseous fuel, building for water supply, deionised water storage tank, building for steam generator, building for water feed pump, power house, and building for support steam generator. The buildings associated with the production of hot water for district heating are a pumping station, control house, cold water works, and heating station. It is recommended to also include here the piping between machinery and the facilities. Material requirements are listed in Table 6 in Appendix 2.
- **Power plant machinery:** The main machinery components differ regarding the geothermal power plant type (flash or binary).
- **Transport to the installation site:** Any type of transport necessary for the exploration, the drilling, the power plant machinery and building should be reported (rail, road or ships).

Modelling of the operation phase

It includes all input and outputs flows in terms of materials, energy and direct emissions which are associated with the operation of the energy plant. This includes direct emissions of NCGs, energy consumption from cooling and gas treatment systems as well as electricity requirements for pumps functioning.

- **Geothermal fluid pumping:** in case the geothermal flow is not self-flowing and must be pumped to the surface (downhole pump or gas lift equipment) the electricity consumption of the pumps should be accounted for. The large flow rate often associated with geothermal systems requires a significant power consumption that can exceed in some cases 1.5 MW_{elec} per well.
- **ORC working fluid**: Most of the working fluids used in geothermal ORC systems are pure hydrocarbons, selected because of their low boiling point conditions. or specially engineered fluids or mixtures can also be encountered. In any case, these fluids have a production process per unit mass, for which it is recommended to gather the necessary

Life Cycle Inventory information. A matter of primary importance is the amount of fluid used within the circuit, and the measures taken for its makeup (fugitive emissions from seals etc.) or periodic replacement because of degradation. The ORC working fluid determines two types of environmental impact: indirect (upstream) cradle to industry gate emissions linked with the production of the fluid, and direct (fugitive) emissions. Considering the upstream impacts of the ORC fluid production may be substantial for working fluids that undergo energy intensive and complex production processes requiring high-impactful inputs or producing burdening waste products. Inventory data on the manufacturing process can be modelled using background data obtained from databases and/or manufacturers. Common working fluids used in binary plants are: Iso- or n-Butane, Iso- or n-Pentane, Siloxanes, n-Hexane, Benzene, refrigerants (R134a, R245fa, R124ze, R1234yf, …), and Ammonia/water mixtures.

- **Direct emissions to air:** The following emissions should be included in an LCA study of geothermal power plant: CO_2, CH_4, H_2S, NH_3, As, B, Ar, Hg, Rn, Sb. H_2S can be of a significant importance in some specific geothermal contexts.
  In most of the currently available methods for the characterization of impacts there is no characterization factor associated to H_2S emission to air. It is recommended to multiply the H_2S emitted mass by a 1.88 factor which corresponds to an equivalent mass of SO_2 emitted. In addition, the current characterisation methods often have difficulties to estimate the (eco-)toxicological impact of chemicals, so that it is recommended to report the emissions of the chemicals listed above separately too.
- **Working fluid loss for ORC**: Direct emissions result from working fluid leakage and loss, including annual leakage during the operation and working fluid loss when the system is disposed of. A simple estimation of these leakage is recommended to estimate the amount of refilling of the working fluid.
- **Stimulation: hydraulic, chemical or thermal:** Recommendations for the modelling of the inventory are similar to the ones for the drilling of geothermal wells in the construction phase.
- **Direct wastewater emissions:** Geothermal fluids, when not totally reinjected, become part of the liquid waste which should be inventoried as output to a treatment process. For further information on the treatment of wastewater from geothermal power plant please refer to Modelling of end of life section.
- **Land area:** With specific reference to geothermal plants, the use of land should be reported for feeding a land use indicator. Such area depends largely on the size of the plant under examination: large plants can need a network of production and reinjection

wells and considerable piping infrastructures, which should be included within the boundaries of the LCA case study.

Modelling of the maintenance

- **Equipment replacement**: The replacement of equipment should be accounted for by multiplying all the material inputs of a given equipment by a replacement factor. The replacement factor is calculated by dividing the power plant lifetime (years) by the specific lifetime of equipment (years). Tables 2 and 3 report typical lifetimes for most common pieces of equipment used in geothermal energy production.
- **Scaling residue:** During operation it is necessary to prevent and avoid scaling in the system (pipes, mechanical equipment…etc.), usually by adding inhibitor chemicals to the fluid. Upstream processes for chemicals production should be inventoried as well as the residue which is obtained as result of the cleaning procedure. This residue is sent to treatment process (see modelling of end of life section).
- **Drilling of additional wells:** Recommendations for the modelling of the inventory are similar to the ones for the drilling of geothermal wells in the construction phase.

Modelling the End of Life stage and waste treatment processes

It includes wells closure processes (i.e. cement and energy consumptions), as well as the treatment of wastes generated during wells drilling, anti-scaling maintenance, and all other residues produced (e.g. spent sorbent from emission control systems, spent lubricants, etc.). Decommissioning of power plant buildings and dismantling, sorting and recycling of machinery's components are excluded from this phase. Following this approach, all the burdens and benefits associated with the end-of-life phases (i.e. dismantling, sorting and recycling of machinery components) are allocated to the next life cycles, thus applying the so-called cut-off principle (according to the Ecoinvent modelling schemes).
Table 9 in Appendix 2 reports a list of inputs for wells closure process. Secondary data can be used for waste treatment processes. If the specific treatment process is unknown, a generic landfill process should be used.

Life Cycle Impact Assessment (LCIA)

Selection of impact indicators

For environmental Life Cycle Impact Assessment (LCIA) of geothermal systems, a selection of impact indicators is proposed. They are mainly taken after the midpoint indicators of the European product environmental footprint (PEF) recommendation (Fazio et al., 2018). The indicators are shown in Table 3 which is a direct adaptation of Table 1 of the JRC on the Environmental Footprint 3.0. methodology. Several categories are proposed and classified according to their level of priority: (1) indicators with a high priority to be applied for any type of geothermal systems (2) indicators with a moderate priority and (3) indicators with a low priority but worth to be considered depending on the type of geothermal system and the specificity of its local environmental. Indicators with a low priority might be moved to a high priority if considering the geothermal LCA for comparison with other energy pathways. The JRC has developed additional impact factors for some of the material flows not included in the original documentations. We therefore recommend that the users of this guideline directly use the characterization factors as reported in the Appendix 2 of the JRC's recommendations (Fazio et al., 2018). At least the impact categories with high level of priority should be reported in the final LCA.

Table 3 – List of impact categories and their level of robustness taken from the report on the life cycle impact categories used for the Environmental Footprint v3.0.

Impact Category	Unit	Indicator/Method	Version LCIA method	Source LCIA method	Level of priority	Level of confidence*
Climate change	Kg CO_2 eq	Radiative forcing as Global Warming Potential (GWP100)	1.0.5 (land use, land use change, biogenic), 1.0.8 (fossil), 4.0.16	IPCC 2013	High	A
Ozone depletion	Kg CFC-11 eq	Steady-state ozone depletion potential	2.0.12	WMO 1999	Medium	A
Human toxicity cancer effects	CTUh	Comparative toxic unit for humans as provided in the USEtox 2.1. **Factors have been applied on inorganics and metals to account for the fact that USEtox has been designed for organic substances.**	1.0.3	Rosenbaum et al., 2008	High	C
Human toxicity non-cancer effects	CTUh	Comparative toxic unit for humans as provided in the USEtox 2.1. model. **Factors have been applied on inorganics and metals to account for the fact**	1.0.2	Rosenbaum et al., 2008	High	C

		that USEtox has been designed for organic substances.				
Particulate matter/ respiratory inorganics	Disease incidences	Human health effects associated with exposure to PM2.5 from the PM method recommended by UNEP	2.0.11	UNEP 2016	Medium	A
Ionising radiation, human health	kBq U	Human exposure efficiency relative to U235 using the Human health model as developed by Dreicer et al 1995	1.0.11	Frischknecht et al., 2000	Medium,	B
Photochemical ozone formation	Kg NMVOC eq	Tropospheric ozone concentration increases from LOTOS-EUROS as applied in ReCiPe 2008	2.0.13	Van Zelm et al., 2008	Low	B
Acidification	Mol H+ eq	Accumulated Exceedance	1.3.9	(Seppälä et al. 2006, Posch et al, 2008)	High	B
Eutrophication, terrestrial	Mol N eq	Accumulated Exceedance	1.2.9	(Seppälä et al. 2006, Posch et al, 2008)	Low	B
Eutrophication, aquatic freshwater	Kg P eq	Fraction of nutrients reaching freshwater end compartment (P) using the EUTREND model as implemented in ReCiPe	1.0.10	(Struijs et al., 2009)	Low	B

Eutrophication aquatic marine	Kg N eq	Fraction of nutrients reaching freshwater end compartment (N) using the EUTREND model as implemented in ReCiPe	2.0.10	(Struijs et al., 2009)	Low	B
Ecotoxicity freshwater	CTUe	Comparative toxic units for ecosystems derived from USEtox 2.1.**derived from the HC20 instead of the HC50. In addition, factors have been applied on inorganics and metals to account for the fact that USEtox has been designed for organic substances.**	1.0.2	(Rosenbaum et al., 2008)	High	C
Land use	Dimensionless, aggregated index of kg biotic production/(m2*a) kg soil/ (m2*a) M3 water/(m2*a) M3 g water/(m2*a)	Soil quality index (biotic production, erosion resistance, mechanical filtration and groundwater replenishment) based on LANCA	1.0.10	(Beck et al. 2010 and Bos et al. 2016)	Medium	C

Water use	Kg world eq. deprived	User deprivation potential (deprivation-weighted water consumption) from the AWARE method	3.0.14	UNEP 2016	Medium	C
Resource use, minerals and metals	Kg Sb eq	Abiotic resource depletion from ultimate reserves using CML	1.0.10 CML v4.8	Guinée et al. (2002) and van Oers et al. (2002)	High	C
Resource use, energy carriers	MJ	Abiotic resource depletion from fossil fuels using CML	1.0.10	Guinée et al. (2002) and van Oers et al. (2002)	High	C

* as suggested in the JRC Appendix, Level A is recommended and satisfactory, Level B recommended but in need of some improvements, Level C recommended but to be applied with caution

The list of impact categories relies on the recommendations of the JRC (within the environmental footprint framework) but it is important to recognize that the confidence in each methodology varies. The human and ecotoxicological impacts quantified are bound to large levels of uncertainty, thus not allowing a clear ranking of the contributing chemicals as long as the contributing uncertainty sources are not thoroughly quantified. The last column in Table 3 is reporting the level of robustness of these impact categories. In addition, it should be noted that the current impact categories do not cover all potential environmental impacts of geothermal plants, e.g. seismic risk, noise, emissions of inorganic compounds

Reporting Inorganic emissions with toxicity impacts

Most of inorganic substances are missing in existing inventory databases, and methods are currently lacking to characterize the potential exposure and toxicity impacts related to emissions of inorganic substances except for some metals in their cationic form (e.g. Mercury). However, potential toxic impacts to human and environment should be included in an LCA study according to the most advanced LCIA method available (i.e. USETox). In any case, the obtained results should be used more as a “flag” which indicates that a potentially harmful substance with toxic properties has been released in the environment to a certain extent. This is not only related to direct emissions from operational phase but could also be related, for instance, to chemical production processes which are employed in chemical stimulation or scaling prevention processes. The potential toxic impact from an LCA analysis must never be associated to any real human and/or environmental risk. Further indication on how to interpret and to report results from toxic categories is provided in the section “Interpretation and reporting of results” and “Reporting and communication”.

The USEtox model (V 2.11) provides a database with two types of characterization factors (CFs): recommended and interim. The distinction between recommended and interim CFs reflects the level of reliability of the model calculations in a qualitative way. CFs for 'metals' are all classified as interim because of the high uncertainty related to their fate and exposure. A recommendation cannot be supported because the available data are insufficient or because the environmental mechanism model considered is too uncertain. For the remaining set of chemicals, a scientific consensus has been reached on how to model them. Applying the USETox model with only recommended CFs implies that CFs for substances like metals are missing. The USEtox Team advises to use always the recommended + interim USEtox CFs together. Otherwise no CF is applied to the emissions of substances with high uncertainty in their fate and exposure (interim), and, consequently, these substances would be characterized with zero impact. However, if the emission of a substance characterized with interim CF dominates the overall toxicity impact, the LCA results must be carefully interpreted because the level of uncertainty is high. An example can be found in metals' emissions. They are all modeled with interim CFs and, whenever present in life cycle inventories, tend to dominate the effects over organic substances by several orders of magnitude. In cases where impacts of metals dominate the profile of toxicity impact categories, it is advisable to apply a sensitivity analysis based only on the recommended CFs to see how the results, and possibly the conclusions, change. Performing a sensitivity analysis is the only meaningful reason to exclude interim CFs. LCA practitioners are strongly recommended to be careful in communicating results that are dominated by interim CFs, even though including such CFs at an initial stage of LCA certainly gives more insight than omitting them.

Software

These guidelines do not recommend the use of a specific LCA software for the life cycle impact assessment. However, the LCA software used (SimaPro, GaBi, Open LCA, etc.) should always be reported as well as its version.

Interpretation and reporting of results

General recommendations

According to the ISO Standards on LCA, interpretation is the final phase of the LCA procedure, in which the results of an LCIA are summarized and discussed as a basis for conclusions, recommendations, and decision making in accordance with the definition of the goal and scope of the study.

Results should be reported according to the followings:

a. Any single emissions to air, liquid or soil enabling the interpretation of the impacts
b. Distribution of the impacts whether Direct or Indirect Impacts enabling to report impacts related to background system (i.e., from producing electricity and from the production of common materials like steel and cement)
c. Distribution of the impacts and any other specific emissions (e.g. inorganics emissions with toxicity impacts) by phase (Development; Construction; Operation; Decommissioning)

Additional indicators could also be reported such as Primary Energy Saving (PES) and Energy Payback Time and are highly recommended whenever the geothermal LCA undertaken is meant for a comparison with other renewable energies.

Primary Energy Saving (PES)

PES is an indicator specifically defined for the evaluation of the benefits related to a thermodynamic energy conversion system that, using an amount of primary energy input, produces electricity and heat compared to two different systems producing separately the two fixed amounts of electricity and heat services using two different primary energy sources. PES accounts for the overall primary energy saving in combined electricity and heat production. A full description of PES is given in Appendix 3. PES can also be used to balance the low energy content of heat compared to electricity and can thus be a relevant indicator for renewable energy technologies comparison. Comparison between CHP installation and Wind and Photovoltaic systems using the PES indicator is given in Appendix 4.

Energy payback time

Energy payback time (EPBT) is defined as the period required for a renewable energy system to generate the same amount of electric energy (in terms of primary energy equivalent) that was used to produce the system itself.

$$Energy\ Payback\ Time = \frac{E_{mat} + E_{manuf} + E_{trans} + E_{inst} + E_{EOL}}{E_{agen}/\eta_G - E_{O\&M}} \quad (1)$$

where

E_{mat} Primary energy demand (in MJ oil-eq) to produce materials

E_{manuf} Primary energy demand (in MJ oil-eq) to manufacture the geothermal installation

E_{trans} Primary energy demand (in MJ oil-eq) to transport materials used during the life cycle

E_{inst} Primary energy demand (in MJ oil-eq) to install the system

E_{EOL} Primary energy demand (in MJ oil-eq) for end-of-life management

E_{agen} Annual electricity generation

$E_{O\&M}$ Annual primary energy demand (in MJ oil-eq) for operation and maintenance

η_G Grid efficiency, the primary energy to electricity conversion efficiency at the demand side (kWh electricity per MJ oil-eq)

The reasoning and assumptions applied to identify the relevant grid mix shall be documented. Based on the above definition, there are two existing conceptual approaches to calculate the EPBT of geothermal systems

1. **Geothermal installations as replacement of the set of energy resources used in the power grid mix.** This approach calculates the time needed to compensate for the total (renewable and nonrenewable) primary energy required during the life cycle of a geothermal system. The annual electricity generation (E_{agen}) is converted into its equivalent primary energy, based on the efficiency of electricity conversion at the demand side, using the current average (in attributional LCAs) or the long-term marginal (in decisional/consequential LCAs) grid mix where the geothermal plant is being installed.

2. **Geothermal Energy as replacement of the non-renewable energy resources used in the power grid mix.** This approach calculates the EPBT by using the non-renewable primary energy only (as recommended by Frischknecht et al. (1998)); renewable primary energy is *not* accounted for on the demand side or during the operation phase. This approach calculates the time needed to compensate for the non-renewable energy required during the life cycle of a geothermal installation. The annual electricity generation (E_{agen}) is likewise converted to primary energy equivalent considering the non-renewable primary energy to electricity conversion efficiency of the average (in attributional LCAs) or the long-term marginal (in

decisional/ consequential LCAs) grid mix where the geothermal installation is being installed. The result of using this approach must be identified as Non-Renewable Energy Payback Time (NREPBT) to clearly distinguish it from the EPBT derived from the first approach. The formula of NREPBT is identical to that of EPBT described above, except for replacing “primary energy” with “non-renewable primary energy”. Accordingly, grid efficiency, η_G, accounts for only non-renewable primary energy.

Both EPBT and NREPBT depend on the grid mix underlying the electricity conversion on the demand side; however, excluding the renewable primary energy makes NREPBT more sensitive to local or regional (e.g. product-specific use of hydropower) conditions, which may not be extrapolated to large global scales. On the other hand, EPBT metric with an average large-scale (e.g. EU, or U.S., or World) grid conversion efficiency may not capture local or regional conditions.

Reporting and communication

Important aspects which should be documented in the LCA report are summarized below.

1. Explicit goal of the study including the
   - Purpose of the study
   - Technical and modelling assumptions (e.g. static or prospective LCA, current performance or expected future development)
   - Type of LCA model applied (attributional, consequential, etc.)
   - Name of the entity commissioning the study
   - Name of the third-party verifier, if relevant
2. System boundaries (which life cycle stages are included and which ones are excluded, excluded processes, etc.)
3. Assumptions related to the production of major input materials (e.g. steel (primary and/or secondary production) and electricity source (if known))
4. LCA approach used (process-based, environmentally-extended input-output tables, hybrid analysis)
5. Characteristics of the geothermal resource:
   - Reservoir type
   - Geothermal Fluid Composition
   - Gas content
   - Temperature
   - The site-specific power use (e.g. diesel or electricity mix)

6. List of inorganic and metal emissions as suggested in section “Modelling of the operation phase”
7. LCI database(s) used (e.g. Ecoinvent, GaBi, ELCD, Franklin, other), including the version numbers
8. Data quality assessment
9. Allocation method used
10. Impact category indicators used, including the version numbers
11. LCA software used (e.g. Open LCA, SimaPro, GaBi, other), including the version numbers
12. Geothermal plant description
    - Geothermal technology (Hydrothermal with or without stimulation)
    - Type of energy conversion technology (e.g. direct or ORC)
    - Expected annual electricity/heat production or load factor (hours/year) and energy output decay
    - Lifetime of installation (years)
    - Plant size (MW)
    - Number of wells (production and reinjection) and depth of the wells
    - Characteristics related to the products:
        - Steam: The distribution system pressure, feed and return temperature and flow rate
        - Hot water: The distribution system feed and return temperature and flow rate

This key plant description based on these last 7 items should always be reported in the captions of figures and tables showing the results of the LCA.

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Appendix 1 – Short guide to the use of Exergy as an allocation scheme in geothermal installations

The primary function of a geothermal system is to produce electricity or heat. In multi-generation energy systems, like Combined Heat and Power plants (CHP) these products may be generated simultaneously. Heat from CHP can be used for hot water, space heating directly or by district heating, industrial heating and also for cooling by using it to drive absorption chillers.

Exergy is a commonly accepted measure of the quality or usefulness of the various energy forms and material streams flowing through a system and exiting as products and wastes. The most common application in geothermal energy systems is the combined production of heat and power (CHP). The exergy approach has some major strong points:

- It reflects the difference in terms of energy quality among the two functions provided by the system
- It is not dependent on the nation
- It is largely used in LCA studies related to the geothermal sector (Frick et al., 2010; Martin-Camboa et al., 2015)
- It is judged as the fairest method, from a thermodynamic point of view, for dividing the benefits of the CHP production between electricity and heat (Tereshchenko et al., 2015)

Exergy represents the maximum useful work that could be obtained from the system as it is brought to the specified reference environment from system state. Typically, the reference environment is specified in terms of temperature, pressure, and chemical composition. In other words, exergy measures the value of the various forms of energy associated to a material system at given conditions, expressed by its temperature, pressure, and chemical composition, from which depends the maximum work achievable from the system. From the definition of exergy, mechanical and electrical energies are equivalent to exergy because they can be integrally converted into work. On the other hand, heat is not pure exergy as the Second Principle of Thermodynamics states that heat cannot be completely converted into work. Indeed, the exergy of heat increases with temperature, because the maximum achievable work from a heat source increases with the temperature: if temperature was infinite, the related heat would be pure exergy.

The use of the exergy of material streams, considering their mass flow rate, allows evaluating systems providing electricity, heat, and cold as output products. In case of chemicals as secondary output products of the system, the use of chemical exergy is recommended (Kotas, Szargut et al., 1985). For a material stream, the physical exergy is defined as shown in Equations (2) and (3).

$$e = (h - h_o) - T_o(s - s_0) \text{ [kJ/kg]} \tag{2}$$

$$Ex_{ph} = \dot{m} \cdot e \text{ [kW]} \tag{3}$$

where h is the enthalpy and s the entropy of the stream at the system state conditions; h_o and s_o refer to the reference conditions (p_o = 101,325 kPa, T_o= 298,16 K) and $\dot{m}$ is the mass flowrate.

For a multi-generation system producing electricity, heat, and another material (e.g., chemicals), exergy can be used to characterise the system flows.

The exergy associated with electricity (Ex_{el}) is equivalent to work-energy (E_{el}) as stated in Equation (4).

$$Ex_{el} = E_{el} \tag{4}$$

The exergy of heat and/or cold supplied by a thermal interaction is equivalent to the work output of a Carnot heat engine operating between the heat interaction and the environment. Heat-exergy is defined as Ex_Q and can be expressed as displayed in Equation (5).

$$Ex_Q = \theta \cdot Q \tag{5}$$

where θ (Carnot factor or exergetic temperature, accounting for the value of heat) is expressed in Equation (6).

$$\theta = \left(1 - \frac{T_o}{T_Q}\right) \tag{6}$$

Where T_Q and T_0 represent respectively the temperature of the thermal interaction and that of the reference environment temperature. T_Q is the entropy-average temperature of the heat produced by the CHP unit and can be calculated from Equation (7).

$$T_Q = \frac{Q}{(\Delta S)} \tag{7}$$

Where ΔS is the overall entropy variation of the heat interaction (from delivery to return in the case of a district heating system). The previous equation can be applied for systems distributing either steam (with condensate recovery) or water or other heat transfer fluids. In the specific case of distributing a single-phase heat transfer fluid, T_Q can be evaluated as a log-mean temperature (Equation (8)).

$$T_Q = \frac{T_D - T_R}{\log\left(T_D / T_R\right)} \tag{8}$$

where T_D is the delivery temperature and T_R is the return temperature of the district heating system (primary circuit at plant gate).

Table 4 shows some examples of Carnot factors for systems providing heat at different delivery and return temperatures.

Table 4 – Carnot factors for typical district heating conditions (Ref. temperature T_o = 25 °C)

Thermal product delivery and return temperatures, T_D/T_R	Carnot factor θ
High-temperature district heating 90°C/70°C	0.184
Medium-temperature district heating 60°C/40°C	0.108
Low-temperature district heating 45°C/30°C	0.072

When a product material stream is also present, its physical and chemical exergy should be considered (Equation (9)).

$$Ex_{MS} = Ex_{ph} + Ex_{ch} \tag{9}$$

Where Ex_{MS} represents the Exergy of the material output product streams, which is in general mainly composed of chemical exergy, Ex_{ch}. The physical exergy can also be relevant if the products are delivered under valuable pressure and temperature conditions. Generally, the chemical exergy of a material stream is represented by its work potential referred to possible interaction with the reference environment (which must be defined also in terms of chemical composition). The typical example is that of fuels which, not naturally present in the reference environment, are transformed through a chemical reaction into combustion products (typically CO_2 and H_2O in gas phase), which are present in limited amounts in the reference environment: the exergy released by the reaction is the chemical exergy of the fuel. Examples related to geothermal applications are wells where significant concentration of natural gas (mainly CH_4) are present, justifying its use as a fuel; the same approach can be used to evaluate production of other valuable material streams.

Using the definitions given above, the allocations by product exergy can then be made proportionally to the exergy of the products (Equations (10)-(12)).

$$\alpha_{El} = \frac{Ex_{el}}{(Ex_{el} + Ex_Q + Ex_{Ch})} = \frac{E_{el}}{(E_{el} + \theta \cdot Q + Ex_{MS})} \tag{10}$$

$$\alpha_Q = \frac{Ex_Q}{(Ex_{el} + Ex_Q + Ex_{Ch})} = \frac{\theta \cdot Q}{(E_{el} + \theta \cdot Q + Ex_{MS})} \quad (11)$$

$$\alpha_{MS} = \frac{Ex_{MS}}{(Ex_{el} + Ex_Q + Ex_{Ch})} = \frac{Ex_{ph} + Ex_{ch}}{(E_{el} + \theta \cdot Q + Ex_{MS})} \quad (12)$$

Where $\alpha_{El} + \alpha_Q + \alpha_{MS} = 1$.

Ex_{el}, Ex_Q, and Ex_{MS} are the net exergy outputs of the electric, thermal (heat), and material products respectively. The exergy of each output is defined according to the equations listed above.

The above guidelines are addressed to assess, though exergy, the multi-product issue about geothermal plants, seen as a whole with no detail about internal sub-processes; in principle, also the LCI is considered as a whole. However, the use of exergy is also recommended to solve allocation problems, which may arise depending on the parallel/series arrangement with respect to the use of the resource. In principle, LCA recommends that allocation should be avoided when it is clear that a component serves one single product. Figure 3 represents a simple but common case where no allocation is needed. The heat and electricity are produced in parallel with respect to the resource, so that it is clear which components are dedicated to heat or electricity production. The production and reinjection wells are serving both: their LCI can be split proportionally to the mass flows directed to heat and electricity respectively. The use of exergy can be avoided for internal allocation.

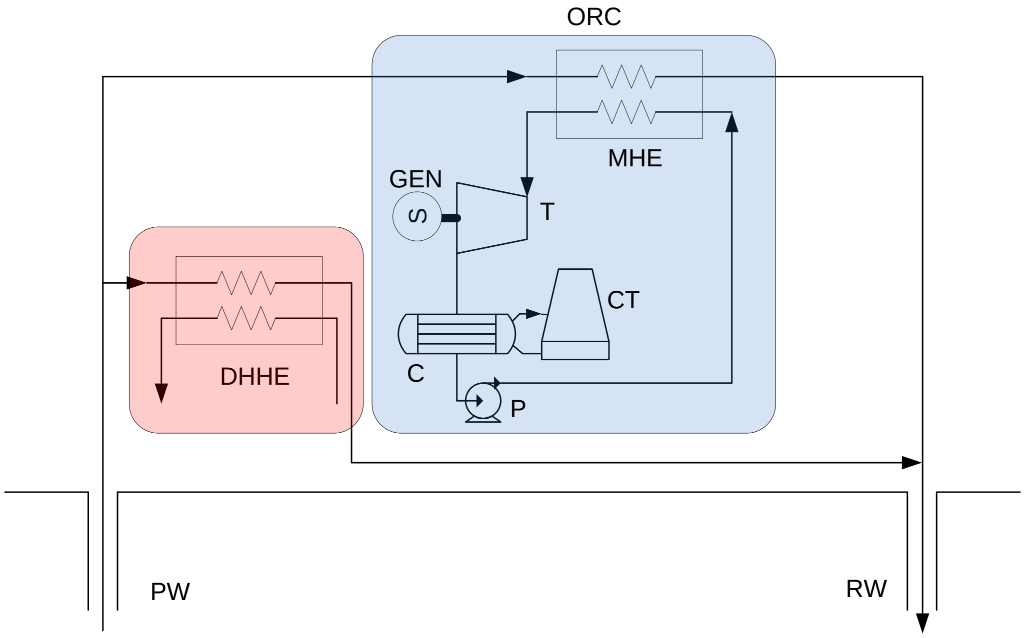

Figure 3 – Geothermal CHP Plant – Parallel arrangement where PW = Production Well; RW = Reinjection Well; DHHE = District Heating Heat Exchanger (primary supply); ORC = Organic Rankine Cycle; MHE = Main Heat Exchanger; GEN = Generator; T = Turbine, C = Condenser, CT = Cooling Tower, P = Pump

Figure 4 represents another frequent case: heat and electricity are produced in a series arrangement, so that heat represents a heat recovery with respect to the process of producing electricity. The products are Ex_{el} for the ORC section producing electricity; and $Ex_Q = \theta \cdot Q$ for the heat recovery District Heating section, placed in series. In this case, the LCI of the Production and Reinjection wells (including separator, piping etc.) should be allocated proportionally to power E_{el} for electricity, and to the Heat-Exergy $Ex_Q = \theta Q$ for the heat supplied to the district heating network. Table 5 and Table 6 provide synthetic guidelines for exergy-based allocation of the LCI referring to the main plant components.

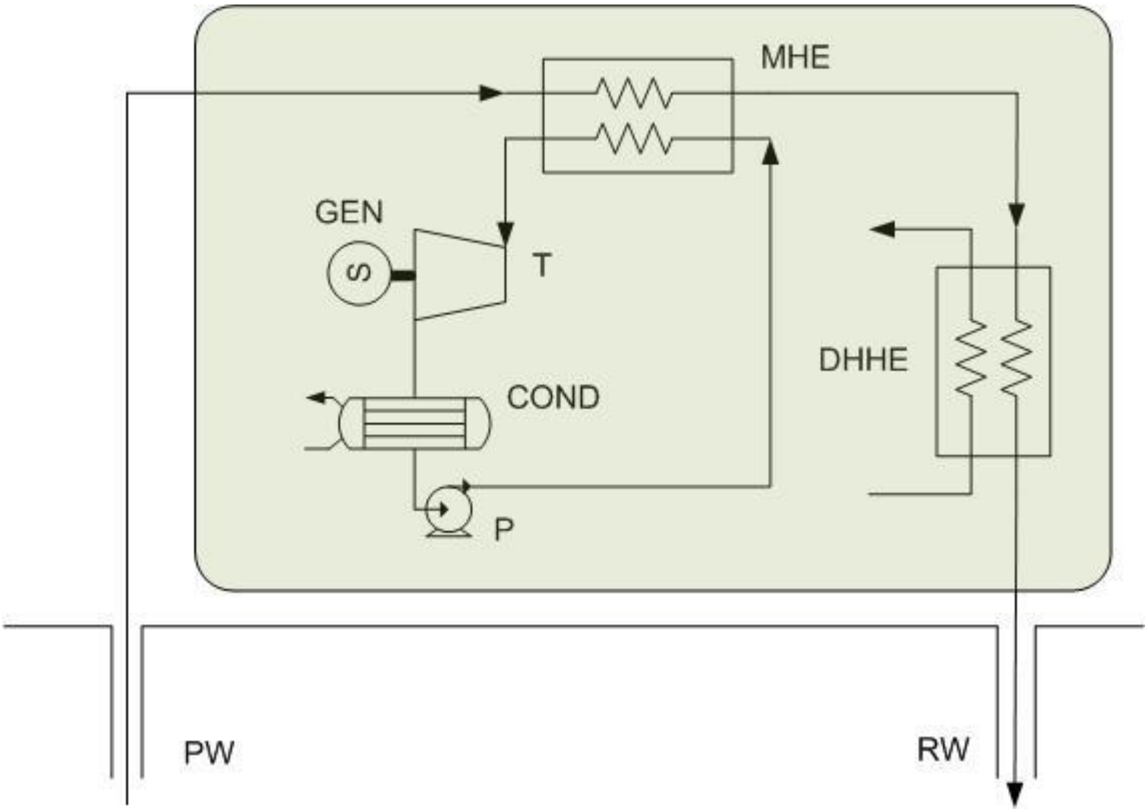

Figure 4 – Geothermal CHP Plant – Series arrangement *where PW = Production Well; RW = Reinjection Well; DHHE = District Heating Heat Exchanger (primary supply); ORC = Organic Rankine Cycle; MHE = Main Heat Exchanger; GEN = Generator; T = Turbine, C = Condenser, CT = Cooling Tower, P = Pump*

Table 5 – Allocation based on exergy outputs of sub-processes (series arrangement)

System	Product outputs	Allocation ratio
Whole	$Ex_T = Ex_{el} + Ex_Q$	1
Electricity	Ex_{el}	A = Ex_{el} / Ex_T
District Heating	Ex_Q	B = Ex_Q / Ex_T

Table 6 – Relative allocation of the LCI of the plant components (series arrangement)

Component	Electricity	District heating
PW Production Well	A	B
RW Reinjection Well	A	B
MHE Main Heat Exchanger	1	0
T Turbine	1	0
P Pump	1	0
COND Condenser	1	0
Cooling Tower	1	0
GEN Electric Generator	1	0
DHHE District Heating Heat Exchanger	0	1

More complex allocations can be necessary when Hybrid parallel/series arrangements are adopted within the system. An example is shown in Figure 3, where a two-pressure level Organic Ranking Cycle (ORC) is proposed with the high-pressure Turbine HPT feeding a district heating network (while the low-pressure turbine LPT is only dedicated to electricity). The heat recovery District heating section is placed in series to the high-pressure loop (HPT) and has no connection to the low-pressure circuit. Allocation should be done considering the sub-processes served by each component and the exergy outputs of the sub-processes. Table 7 and Table 8 provide synthetic guidelines for exergy-based allocation of the LCI, referring to the main plant components for this specific case study.

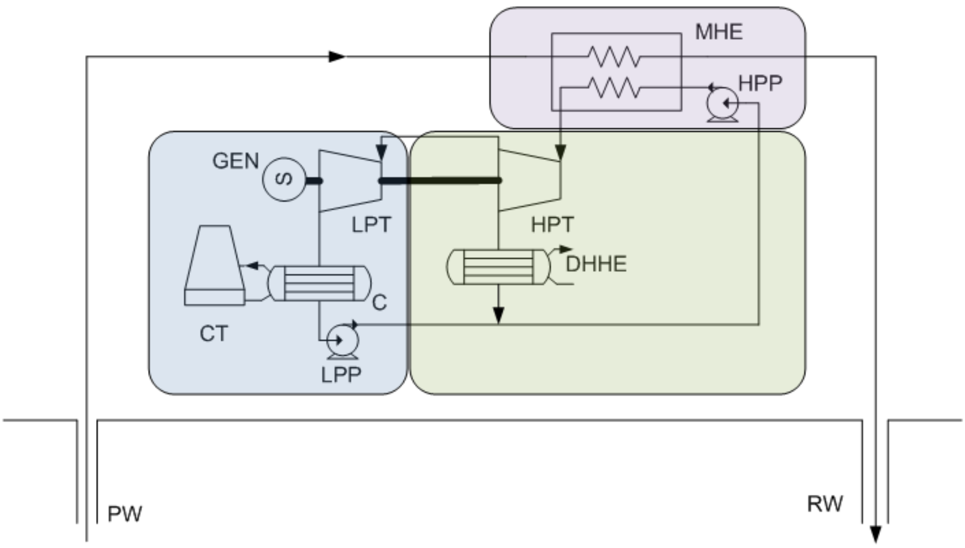

Figure 5 – Geothermal CHP Plant – Hybrid arrangement (case study) where HPT = High Pressure Turbine; LPT = Low Pressure Turbine; HPP = High Pressure Pump; LPT = Low Pressure Pump

Table 7 – Allocation based on exergy outputs of sub-processes (Hybrid arrangement)

System	Product outputs	Allocation ratio
Sub 1 (Violet)	$Ex_T = Ex_{el\ LPT} + Ex_{el\ HPT} + Ex_Q$	1
Sub2 (Green)	$Ex_B = Ex_{el\ HPT} + Ex_Q$	B = Ex_B / Ex_T
Sub3 (Blue)	$Ex_A = Ex_{el\ LPT}$	A = Ex_A / Ex_T
Electric Generator	$Ex_{el} = Ex_{el\ LPT} + Ex_{el\ HPT}$	C = $Ex_{el\ HPT}$ / Ex_{el} D = $Ex_{el\ LPT}$ / Ex_{el}

Table 8 – Relative allocation of the LCI of the plant components (Hybrid arrangement)

Component	LCI A	LCI B
PW Production Well	A	B
RW Reinjection Well	A	B
MHE Main Heat Exchanger	A	B
HPT Turbine	0	1
DHHE District Heating Heat Exchanger	0	1
HPP High Pressure pump	A	B
LPT Turbine	1	0
COND Condenser	1	0
Cooling Tower	1	0
LPP Low Pressure pump	1	0
GEN Electric Generator	C	D

A more detailed and effective use of exergy coupled to LCA is applied by energy systems experts through an exergo-environmental analysis (Tsatsaronis, 2011): in this case, the LCI is kept separate for each component, and its environmental cost (weighted or in specific categories) is evaluated. The progressive build-up of the environmental cost of the products is performed through a complete reconstruction of the process referring to the system lifetime, considering for each component the environmental cost of construction and operation (consumption of fuel or chemicals, operation and maintenance) and the environmental cost of exergy destruction taking place in the component. This approach identifies inside the system the critical components and is recommended when the objective is optimization (that is, modification of the system to improve its overall environmental performance; or system control/maintenance strategies).

References to Appendix 1

Kotas, T.J., The Exergy Method of Thermal Plant Analysis, Butterworths, 1985.

Szargut, J., Morris, D.R., Steward, F.R., Exergy Analysis of Thermal, Chemical and Metallurgical Processes, Hemisphere, 1988.

Tsatsaronis, G., Exergoeconomics and Exergoenvironmental Analysis, Chapt. 15, Thermodynamics and the Destruction of Resources, Cambridge University Press, 2011, //doi.org/10.1017/CBO9780511976049.019

Appendix 2 – Reference average values as a support for modelling the inventory

Foreword to Appendix 2

This appendix is based on data collected mostly from GEOENVI case studies and the main issue here is whether these case studies are representative enough to recommend the related values as valid default values in all cases. This is still a debate to have and coordination with the RINA-VITO project is advised.

Appendix 2

These data are provided to support the elaboration of the inventory when no specific data are available. We propose a series of average data for different GEOENVI case studies presented in Table 9. These average data can be used as first approximation in case no installation-specific data is available. The best strategy to generate an inventory is however to use as much as possible specific data related to the installation.

Table 9 - Description of the different plants analysed in the GEOENVI case studies. Per recommended value, the reference plant is listed using the ID specified in this table.

	Rittershoffen	Bagnore	Hellisheidi	Balmatt	Dora II
Geothermal source type	Liquid	Liquid	Liquid/Vapour	Liquid	Liquid
Energy generation technology	Direct heat use - EGS	Flash - hydrothermal	Single and double flash - hydrothermal	ORC	ORC
Final energy use	Industrial heat use	Electricity + Heat	Electricity + Heat	Electricity + Heat	Electricity
Installed capacity	27 MW_{th}	61 MW_e 21.1 MW_{th}	303.3 MW_e 133 MW_{th}	0.25 MW_e 8 MW_{th}	9.5 MW_e
ID used in this Appendix	RT	BG	HL	BA	DO

Modelling of the construction phase

Drilling of the well

Table 10 - Reference value(s) for diesel/or energy consumption per meter of well drilled and waste produced per well. Calorific value of Diesel was assumed to be 38 MJ/l.

Energy	Unit	Reference value MIN-MAX (Average)
Diesel	GJ/m	2.4 (HL) – 12 (BG) (6.7) - 4.21-5.39 (RT)
Electricity	kWh/m	455-790 (BA) 920 (pers. Com. Deep Geothermal well in Europe)
Materials	Unit	Reference value MIN-MAX (Average)
Water	m^3/m	1.3(RT) – 9 (HL) (4.3)
Chemicals (generic including lubricant)	kg/m	3.6(DO) – 66 (BG) (29.5)
Waste produced (to treatment/landfill)	Unit	Reference value MIN-MAX (Average)
Drilling waste (to landfill)	kg/m	13 (DO) -2152(BG) (955)

Casing and cementing

Table 11 - Reference values for casing and cementing

Materials	Unit	Reference value MIN-MAX (Average)
Steel	kg/m	75 (RT) – 208 (BG) 45 – 251 (125)
Cement	kg/m	36 (HL) – 777 (BG) - 147-177 (BA) (218) 35-270

Stimulation

Table 12 - Reference values for stimulation

Energy	Unit	Reference value MIN-MAX (Average)
Diesel (thermal stimulation)	GJ/treatment	7531 (RT) - 7600 (DO) (7565)
Diesel (chemical-hydraulic) stimulation)	GJ/treatment	1533 (RT)
Materials	**Unit**	**Reference value MIN-MAX (Average)**
Water (chemical stimulation)	m^3/treatment	250 (BA) – 4230 (RT)*1000 (1660)
Water (hydraulic stimulation)	m^3/treatment	27,000 +/- 10,000 m3 per job for EGS 15,000 +/- 5,000 m3 for hydrothermal
Chemicals	m^3/treatment	39 (RT) – 2000(DO) (710)

** ground water, produced during production test*

Wellhead construction

Table 13 - Reference values for wellhead construction

Materials	Unit	Reference value MIN-MAX (Average)
Steel, unalloyed	kg/well	7 428 (RT) – 17 660 (DO) (13 221)
Steel, stainless INOX 316 L	kg/well	16 (HL)
Concrete	kg/well	18 (HL) – 18 520 (BG) (9 269)
Portland cement	kg/well	13771 (RT) – 259286 (BG) (117686)
Aluminium	kg/well	1 218 (HL) – 1500 (DO) (1359)
Iron	kg/well	4 000 (DO) – 8 568 (BG) (6284)
Excavation	m^3/well	250 (DO) – 6851 (RT) (1940)
Filling	m^3/well	250 (DO) – 3135 (RT) (1723)

Collection pipelines

Table 14 - Reference values for collection pipelines based on Karlsdóttir et al., 2015. and on data provided by ENEL

Materials	Unit	Reference value MIN-MAX (Average)
Steel	kg/m	173 (BG) – 213 (DO) (194)
Mineral wool	kg/m	0.12 (DO) - 47.20 (BG) (27)
Aluminium	kg/m	2 (DO) - 6.2 (HL) (4.3)
Cement	kg/m	0.07 (DO) - 0.30 (HL) (0.2)

Power plant building

Table 15 - Reference values for power plant building

Materials	Unit	Reference value MIN-MAX (Average)
Concrete	kg/kW	22.75 (RT) -
Cement	kg/kW	5.22 (RT) - 19.92 (BG) (14.69)
Steel, low alloyed	kg/kW	5.31(BG)- 10.53 (DO) (7.45)
Aluminium	kg/kW	0.19 (RT) - 8.84 (BG) (4.52)
Copper	kg/kW	0.29 (RT) - 17.7 (BG) (9)
Plastic	kg/kW	0.93 (RT) - 18.59 (BG) (9.76)
Mineral wool	kg/kW	0.98 (RT)
Excavation	m^3/kW	0.10 (RT)
Filling	m^3/kW	0.01 (RT)
Stainless steel	kg/MW	621 – 629

** power output*

Power plant machinery

Table 16 - Reference values for machinery and power production components.

Technology	Component	Materials	Unit	Reference value MIN-MAX (Average)
ORC	Turbine	Steel	kg/KW	3.579 (DO)
ORC	Compressor	Steel	kg/KW	0.189 (DO)
ORC	Compressor	Plastic	kg/KW	0.006 (DO)
ORC	Compressor	Aluminium	kg/KW	0.009 (DO)
ORC	Air cooler	Steel	kg/KW	0.029 (DO)
ORC	Air cooler	Aluminium	kg/KW	0.007 (DO)
ORC	Heat exchanger	Steel	kg/KW	0.072 (DO) - 1.574 (BG) (0.823)
Flash	Turbine	Steel	kg/KW	2.951 (BG)
Flash	Compressor	Steel	kg/KW	1.967 (BG)
Flash	Condenser	Steel	kg/KW	3.344 (BG)
Flash	Air cooler	Steel	kg/KW	0.393 (BG)
Flash	Air cooler	Plastic	kg/KW	2.951 (BG)
Flash	Air cooler	Fibre Glass	kg/KW	1.475 (BG)
Energy use	Component	Materials	Unit	Reference value MIN-MAX (Average)
Electricity	Generator	Steel	kg/KW	1.579 (DO) - 2.361 (BG) (1.970)
Electricity	Generator	Copper	kg/KW	0.246 (DO) - 2.000 (BG) (1.123)
Electricity	Transformer	Steel	kg/KW	1.895 (DO)
Electricity	Transformer	Plastic	kg/KW	0.105 (DO)
Electricity	Transformer	Copper	kg/KW	2.020 (DO)
Heat	Heat exchanger	Steel	kg/KW	2.533 (RT)
Heat	Heat exchanger	Stainless steel	kg/KW	0.769 (RT)

Modelling of the operation phase

The use of primary data is required.

Modelling of the maintenance phase

Table 17 - Average fugitive emission factors taken from "White Paper: Upstream climate impacts from production of R-134a and R-1234yf refrigerants used in mobile air conditioning systems" and https://www.sciencedirect.com/science/article/pii/S0360544218323156#tbl6

Equipment	Type	Emission rate, kg/hour/unit
Valves		
	Gas/vapor	0.0060
	Light liquid	0.0040
	Heavy liquid	0.0002
Pump		
	Light liquid	0.0086
	Heavy liquid	0.0018
Compressors		
		0.2285

Modelling of the well closure

Table 18 - Average values for the well closure process.

Energy	Unit	Reference value MIN-MAX (Average)
Diesel consumption	l /well	20.000-30.000 (25000 (BG))
Materials	Unit	Reference value MIN-MAX (Average)
Portland Cement	kg /well	25000 (BG)
Inert	kg /well	5000 (BG)

Appendix 3 – Primary Energy Saving (PES)

PES is an indicator specifically defined for the evaluation of the benefits related to a thermodynamic energy conversion system that produces fixed amounts of electricity and heat by recovering at least part of the energy released to the environment in the form of heat. PES accounts for the overall primary energy saving in combined electricity and heat production compared to their separated production from two different primary energy sources.
PES is defined in Equation (13) according to the Directive 2004/8/EC of the European Parliament[2].

$$PES = \left(1 - \frac{1}{\frac{\eta_{CHP\ H}}{\eta_{Ref\ H}} + \frac{\eta_{CHP\ E}}{\eta_{Ref\ E}}}\right) \cdot 100\ \% \qquad (13)$$

Where:

PES is the primary energy savings.

$\eta_{CHP\ H}$ is the heat efficiency of the cogeneration production defined as annual useful heat output divided by the fuel input used to produce the sum of useful heat output and electricity from cogeneration.

$\eta_{Ref\ H}$ is the efficiency reference at *national* level value for separate heat production.

$\eta_{CHP\ E}$ is the electrical efficiency of the cogeneration production defined as annual electricity from cogeneration divided by the fuel input used to produce the sum of useful heat output and electricity from cogeneration.

$\eta_{Ref\ E}$ is the efficiency reference at *national* level value for separate electricity production.

PES may be very effective in assessing systems with co-production of electricity and heat. PES is country dependent (through $\eta_{Ref\ H}$ and $\eta_{Ref\ E}$, which primarily depend upon the reference fuel for separate heat and electricity production) and possibly variable in time. Moreover, this is in line with current European legislation as PES is defined according to the EU Directive for Combined Heat and Power, 2004/08/CE. Following this Directive, the Commission established harmonized efficiency reference values for separate production of electricity and heat, but they are variable across different countries because of fuel mix, technological level and climate.

[2] DIRECTIVE 2004/8/EC OF THE EUROPEAN PARLIAMENT - *Official Journal of the European Union, L 52/50 EN 21.2.2004*

PES is a relatively simple parameter, easy to understand and to use for non-thermodynamic experts and decision makers.

PES offers the possibility to evaluate both the primary energy saving potential of geothermal CHP against the actual primary energy consumption both at national level and at average EU28 level. Finally, PES can be used as a relevant indicator to compare geothermal energy to other renewables, especially those providing CHP utilities like, for example, biomass.

Within Annex B of EN 15316-4-5:2017, a template to specify the reference efficiency is provided, as well as informative default values ($\eta_{Ref\ E}$=0.4, $\eta_{Ref\ H}$=0.9 for all types of fuels). To gain generality and harmonization across different countries, average values for the efficiency reference are proposed. In the following Table 19 values of $\boldsymbol{\eta_{Ref\ H}}$ and $\boldsymbol{\eta_{Ref\ E}}$ for some European countries are reported, as well as the average efficiencies for the EU28, calculated in agreement with EUROSTAT data[3]. The relative differences in efficiencies for separated electricity and heat production are defined in Equations (14) and (15) and reported on the last two columns of Table 19.

$$\Delta\eta_{\mathrm{RefE}} = \frac{(\eta_{\mathrm{RefE\ NG}} - \eta_{\mathrm{RefE\ National}})}{\eta_{\mathrm{RefE\ NG}}} \cdot 100 \qquad (14)$$

$$\Delta\eta_{\mathrm{RefH}} = \frac{(\eta_{\mathrm{RefH\ NG}} - \eta_{\mathrm{RefH\ National}})}{\eta_{\mathrm{RefH\ NG}}} \cdot 100 \qquad (15)$$

[3] EUROSTAT database, Energy statistics, https://ec.europa.eu/eurostat/web/energy/data/database

Table 19 – Relative differences between countries related values of $\eta_{Ref\ H}$ and $\eta_{Ref\ E}$ and the values related to Natural Gas (NG) fed CHPs

Main activity producer [GWh gross]	Electricity only	Electricity CHP	Heat only	Heat CHP	$\eta_{Ref\ E}$	$\eta_{Ref\ H}$	$\Delta\eta_{Ref\ E}$ [%]	$\Delta\eta_{Ref\ H}$ [%]
Year	2017	2017	2017	2017				
Italy, total	184 138	91 392	3 759	42 155	0.49	0.90	8.16	0.0
France. total	530 072	11 252	17 542	21 166	0.35	0.90	51.4	0.0
Germany. total	503 234	93 140	35 267	93 152	0.42	0.88	26.2	2.3
Iceland. total	1 4628	4 611	6 196	2 475	0.44	0.89	20.5	1.1
Turkey. total	27 3506	3 488		6 254	0.48	-	10.2	-
Average EU28	2 495 661	501 187	168 831	403 256	0.40	0.89	32.5	1.1
Average EU28 + Iceland + Turkey	2 783 794	509 286	175 028	411 986	0.41	0.89		
Values suggested in Annex B of EN 15316-4-5:2017					0.40	0.90		

As reported in Table 19 the average EU 28 values of reference efficiencies for separate heat and power production are very close to the ones suggested in Annex B of EN 15316-4-5:2017. For this reason. these values are proposed as reference for the harmonization. possibly to be yearly updated in agreement with EUROSTAT data.

Appendix 4 – Renewable Energies: Geothermal Heat and Power versus PV and Wind – A case study using exergy and PES

Foreword to Appendix 4

This appendix covers two major goals: (1) the comparison of different renewable energies thanks to a multicriteria approach with three impact indicators (2) the added value of using PES versus Exergy for this CHP example.

Change to Impact categories referring to EF v3 as recommended in the main guidelines have to be considered in a further version of the guidelines.

This appendix is based on LCA results for an Italian geothermal installation not yet published. Please consider this appendix as a temporary one to be confirmed as soon as the full LCA publication will be available.

Appendix 4

The following example compares the impacts on climate change, acidification, and resource depletion of the production of 1MWh electricity from three different installations:

1) 20 MW_{el} geothermal powerplant (**C1**) localized in the Larderello geothermal region, producing 151 200 MWh/yr of electricity
2) Photovoltaic power plant (**PV**, 20 MW_{el} nominal peak power, 24 786 MWh/year average production);
3) Wind farm (**Wind**, 18 MW_{el} nominal power, 42 069 MWh/year average production).

In addition, this example illustrates how the choice of PES (defined in Appendix 3) as an alternative allocation method influences the outcomes of the geothermal powerplant compared to the use of the recommended approach of exergy. In fact, a district heating unit, designed to provide heat to a neighbouring town by exploiting the excess available geothermal heat, was recently started up in the C1 geothermal plant. When completed, the district heating will provide a 6 744 kW_{th} nominal heating power (20 880 MWh/yr of thermal productivity), serving the neighbouring town with a hot water primary district heating circuit.

Finally, this example also shows how PES can be used as a weighting factor when comparing the results of LCA of renewable energy technologies. This procedure can benefit combined heat and power plants by better accounting for the added value of heat production.

The amount of heat actually provided to the district heating by the geothermal CHP needs to be quantified. To do so, an estimate of the winter heat load of the town was performed, based on average local climatic data. The Degree Days (DD) approach was considered as an approximate parameter to determine the seasonal heat load (E Climatic Zone Mid-severe, 2303 DD). The degree days are defined in Equation (16).

$$DD_{heating} = (1\ day) \sum_{Seasonal\ heating\ days} DT_{in-out} \qquad (16)$$

In Italy, the heating period allowed for climatic zone E is from October 15th to April 15th (determining the seasonal heating days in the formula). On this basis, and considering the monthly average daily temperature, the heat load was estimated as proportional to the indoor – outdoor average daily temperature difference during the heating season, having set the indoor temperature at 20 °C. The nominal design load of the CHP was referred to the coldest month (January), for which the indoor – outdoor average daily temperature difference is 20 – 5.4 = 14.6 °C. The temperature differences for the other months were scaled referring to this difference (nominal). The climatic data and heat load fraction (HLF) are reported on the following Table 20 and Figure 6 – District heating winter seasonal Heat Load Fraction for C1. The HLF is defined as the ratio between the month daily representative indoor – outdoor average temperature difference and the maximum month average indoor – outdoor temperature difference (coldest month, corresponding to the design heat load) (Equation (17).

$$HLF = \frac{(DT_{in-out})_{current\ month}}{(DT_{in-out})_{MAX}} \qquad (17)$$

Table 20 – Average monthly climatic data and Heat Load Fraction

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Outdoor temperature . T_{av} ºC	5.4	5.9	8	11.2	15.1	19.1	22.2	22.1	19	14.3	9.7	6.5
DT_{in-out} (20 °C-T_{av})	14.6	14.1	12	8.8	4.9	0.9	-2.2	-2.1	1	5.7	10.3	13.5
Heat Load Fraction (HLF)	1.00	0.97	0.82	0.60	0	0	0	0	0.07	0.39	0.70	0.92
Heating degree days (HDD)	453	395	372	132	0	0	0	0	0	177	309	419

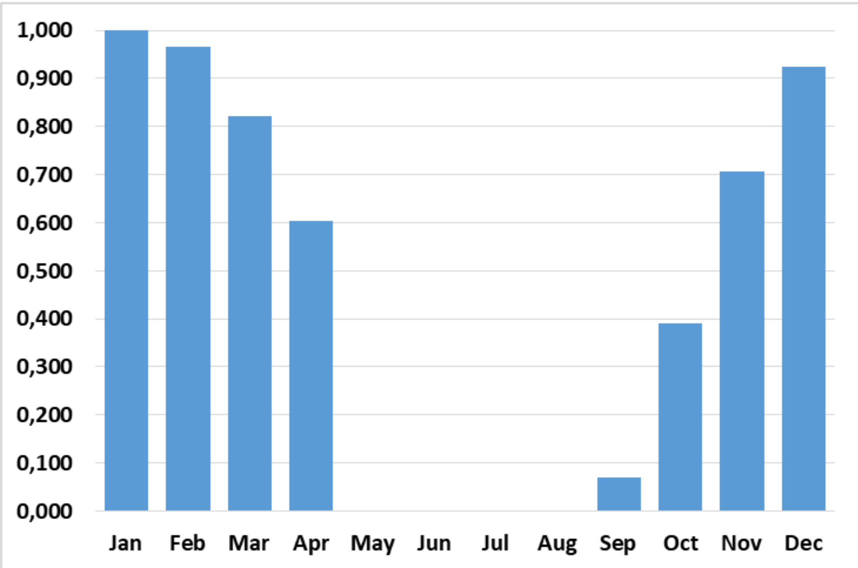

Figure 6 – District heating winter seasonal Heat Load Fraction for C1

Referring to these data. the overall average annual heating load factor was evaluated at about 41%. roughly corresponding to 3096 hours/year. On this basis and applying the definition of exergy reported in Appendix 1, the exergies of the geothermal CHP related to electricity (Ex_{EL}) and heat (Ex_Q) productions were calculated. as well as their sum (Ex_{TOT}) representing the total produced output exergy (Table 21).

Table 21 – Exergy analysis - Geothermal CHP plant C1

Plant ID	C1 (E zone)
Location	Larderello region. Italy
Geothermal source type	Dry steam
Energy generation technology	Flash
Final energy use	Electricity and heat
District heating temperatures (primary)	
T_D. ºC (delivery)	90
T_R. ºC (return)	65
Carnot factor.	0.149
Ex_Q . MWh/year	3 120
Ex_{El} . MWh/year	151 200
Ex_{TOT} . MWh/year	154 320

Considering the limited HLF (41%) and the low exergy value of the delivered heat due to the low temperature (typical of district heating). heat accounts for 2.02% only of the overall exergy output. Therefore. exergy characterises the geothermal power station as mainly an electricity station. despite being nominally sized for about 7 MW_{th} vs 20 MW_{el} and actually producing a valuable amount of district heating.

PES allows a more effective evaluation of the direct use of heat with respect to exergy. To this end. besides PES being nondimensional. it is possible to calculate the overall E_{PES} [GWh/yr]. that is. the amount of primary energy saved (at national level or in a specific project) by the energy-efficient use of Combined Heat and Power installation. E_{PES} is the dimensional version of PES (as from Appendix 3) defined in Equation (18).

$$E_{PES} = \frac{E_{yr}}{\eta_{Ref\ E}} + \frac{Q_{yr}}{\eta_{Ref\ Q}} \quad [\frac{GWh}{yr}] \qquad (18)$$

Where:

E_{yr} = useful yearly electricity output from the CHP (e.g. nominal CHP electrical power by yearly working hours) [GWh/yr]

Q_{yr} = yearly heat output from the CHP actually delivered to utilities (e.g. nominal CHP heat power by HLF) [GWh/yr]

In other words E_{PES} allows calculating another share for electricity which does not penalize heat because of its low temperature level as does exergy. Table 22 – Electricity and Heat shares based on Yearly average PES data referred to ITalian. EUropean and Natural Gas efficiencies namely shows that the heat share of E_{PES} is still limited (6 to 8%. depending on the national or EU reference values adopted) because the result is being still penalized by the low HLF (41%) but not by the low temperature level as it is the case for exergy. Dealing with the final use of heat (comfort heating for dwellings) low temperature should not represent a penalty. On the other hand, the penalization due to the seasonality should reasonably remain as the CHP installation is actually active substituting primary fossil energy only in heat load periods.

Table 22 – Electricity and Heat shares based on Yearly average PES data referred to ITalian. EUropean and Natural Gas efficiencies

						Share according to E_{PES}	
						Electricity $\frac{\frac{E_{yr}}{\eta_{Ref\,E}}}{E_{PES}} \cdot 100$	Heat $\frac{\frac{Q_{yr}}{\eta_{Ref\,Q}}}{E_{PES}} \cdot 100$
$\eta_{Ref\,E}$ (IT)	0.49	$\eta_{Ref\,Q}$ (IT)	0.9	E_{PES} (IT) [GWh/yr]	332	93%	7%
$\eta_{Ref\,E}$ (EU)	0.41	η_{Ref} (EU)	0.89	E_{PES} (EU) [GWh/yr]	392	94%	6%
$\eta_{Ref\,E}$ (NG)	0.53	η_{Ref} (NG)	0.9	E_{PES} (NG) [GWh/yr]	308	92%	8%

The LCA of the three power plants (Geothermal, PV and Wind) was performed referring to ILCD midpoint impact evaluation. Results for the specific category Climate Change expressed with Greenhouse gas emissions (GHG in CO_2 eq) are reported in Table 23.

Table 23 – Comparison of GHG emissions for the three power plants (FU=1 MWh Electricity)

Average Electricity GEO C1 El_{GEO} [MWh/year]	CO_{2eq} El_{GEO} [kg/MWh]	Average Electricity PV El_{PV} [MWh/year]	CO_2 eq El_{PV} [kg/MWh]	Average Electricity Wind El_{wind} [MWh/year]	CO_2 eq El_{wind} [kg/MWh]
151 200	433	24 786	114	42 069	28

The large GHG emissions of the geothermal plant are due to the high original content of CO_2 in the resource (nearly 8%). Part of these gases would reach the surface as natural emissions; a scenario where 40% of GHG emissions are discounted was added to show this effect. Moreover. one additional scenario was performed with no emissions treatment of the gas stream (including AMIS system. which removes effectively H_2S and Hg). These additional GEO scenarios are labelled GEO_40% and GEO_NA (No AMIS) respectively.

The results normalized by PES and exergy for each technology as reported in Table 4 are summarized in Figure 7 (Climate Change), Figure 8 (Acidification) and Figure 9 (Mineral, fossil & renewable resource depletion). In all categories the use of PES allows to consider the economy of primary resources in consequence of the positive contribution of thermal production in the case of the geothermal plant. Indeed as it is clear from Figure 7 to Figure 9, the use of exergy as an allocation method is practically a replacement of electricity has no impact for all considered impact categories due to very low valorisation of seasonally exploited low-grade district heating. The fundamental benefit for the local community of using the produced heat which otherwise should be provided with fossil fuels is not considered. This confirms that PES is recommendable in cases of CHP. PES can also be calculated for systems having only electricity output like PV and Wind as done in the example. Obviously in this case it doesn't add any further peculiarity over electricity or exergy.

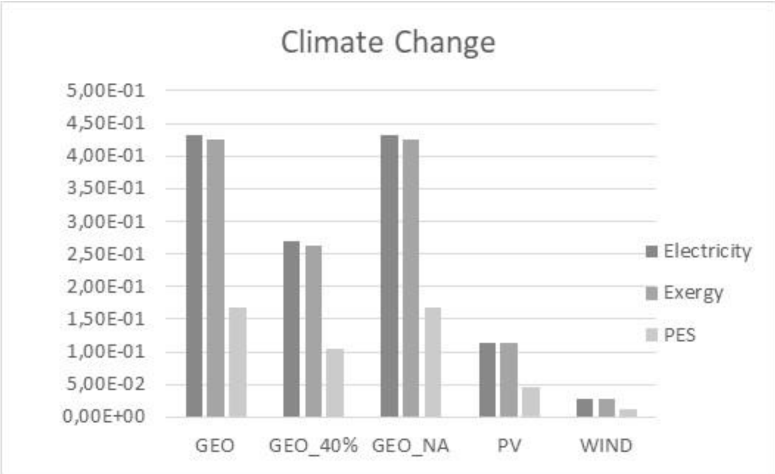

Figure 7 – ILCD 2011 MidPoint + Climate change (kg CO_{2eq}/kWh)

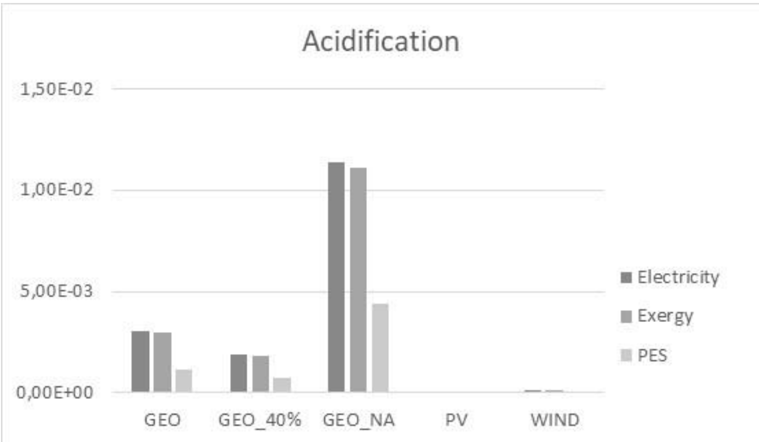

Figure 8 – ILCD 2011 MidPoint + Acidification (mol H+ eq/kWh)

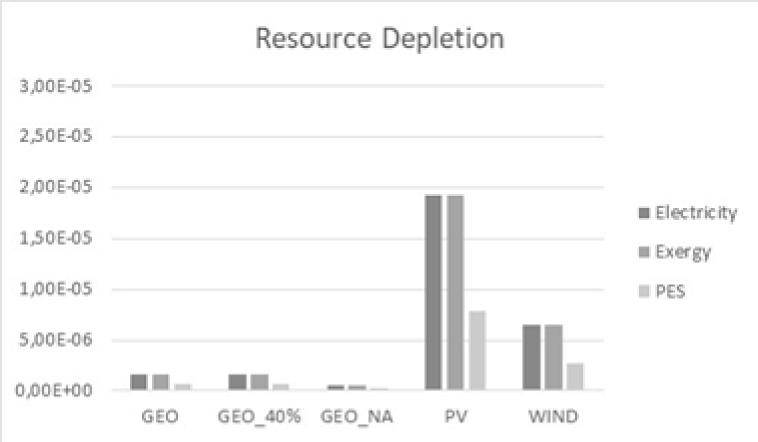

Figure 9 – ILCD 2011 MidPoint + Mineral. fossil & ren resource depletion (kg Sb_{eq}/kWh)

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