Environmental assessment of GEOENVI case studies: a selection of GEOENVI case studies following the harmonized LCA guidelines

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Contents

Table of figures

List of tables

List of abbreviations

ACI	Acidification
CC	Climate change
CF	Characterization Factor
CS	Case Study
CTU	Comparative Toxic Unit
EC	European Commission
EF	Environmental Footprint
Eto	Ecotoxicity, freshwater
EUf	Eutrophication, freshwater
EUm	Eutrophication marine
EUt	Eutrophication, terrestrial
FU	Functional Unit
GWe	Gigawatt electric
GWth	Gigawatt thermal
HTC	Human toxicity, cancer
HTN	Human toxicity, non-cancer
ILCD	International Reference Life Cycle Data System
IR	Ionising radiation, human health
J	Joule
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
Lnd	Land use
LSP	Line Shaft Pump
MWe	Mega Watt electric
MWth	Mega Watt thermal
NCG	Non-Condensable Gas
ODP	Ozone depletion Potential
ORC	Organic Rankine Cycle
PM	Particulate Matter Formation Potential

POz	Photochemical ozone formation, human health effects
REn	Resource use, fossils
RMi	Resource use, minerals and metals
Wat	Water use

Executive summary

This deliverable reports the activity undertaken in Task 3.2 concerning the application of the Life Cycle Assessment (LCA) guidelines proposed in D3.2 on a selection of case studies whose life cycle data were provided by the partners consortium of the European project GEOENVI [Grant agreement n°818242 -- 2018-2020]. The general scope was to implement and validate the modelling approach proposed in the D 3.2 and to have feedback on potential methodological adjustment and improvement of the first version of the LCA guidelines. Such revision will be accomplished in accordance also with feedback received from the geothermal community, as expected by the GEOENVI WP5 activities.

The LCA guidelines proposed in D3.2 include some innovative aspects in terms of LCA applied to geothermal systems, mainly linked with the use of the Environmental Footprint (EF) 3 database and impact assessment method, developed by the European Commission Joint Research Centre (JRC). A description of the EF method, the differences between version 2 and version 3 and the difference with the ILCD method are reported to highlight the conversion procedure required to assess the case studies.

The investigated case studies were selected to be representative of the main available geothermal energy conversion technologies in Europe and they describe real operating or pilot/project power plants located in Italy, France, Iceland, Belgium, Hungary and Turkey. The general modelling approach described in the D 3.2 was applied to all case studies but detailed LCA results are presented only for the case study of Rittershoffen, France, that was selected as reference case study due to the completeness of its inventory, which also allows to highlight any hotspots. All the results for the other case studies are reported as total score in each impact category due to the time-consuming procedure required to assess the system model in EF3, since this was not yet available in commercial software at the time of writing this deliverable. Nevertheless, when a given case study presented a peculiarity or a deviation from what suggested in the LCA guidelines, this was clearly reported to the corresponding case study.

As a general remark, no comparative purpose should be intended when interpreting the LCA characterized results of the different case studies. This is because the quality and reliability of the data varies among the power plants, in relation to the differences concerning the conversion technology, the installed and working capacity, the country-specific regulations in terms of emissions reporting and to the actual functioning of the case study (i.e. real operating plant against a pilot or project plant). Furthermore, given the definite and consistent methodological framework reported in D3.2, a reference to the publication “Study on geothermal plants and applications emissions: overview and analysis” performed by the

Directorate-General for Research and Innovation (European Commission) , Ernst & Young , RINA Consulting S.p.A and Vito NV (https://op.europa.eu/s/olBt) is suggested for any other general considerations (natural emissions, sensitivity analysis, etc.).

General Introduction

Methodological guidelines have been developed within the GEOENVI project (Parisi et al. 2020) to facilitate the application of Life Cycle Assessment (LCA) to geothermal installations. The objective of the LCA guidelines was to provide a common and accepted basis to evaluate the life cycle environmental impacts of geothermal energy systems by providing advice on (i) building life cycle inventories (LCI) of geothermal systems, (ii) choosing among the available life cycle impact assessment (LCIA) methods and the impact category indicators, and (iii) documenting the LCA reports on geothermal energy production.

In this deliverable, the application of the above mentioned LCA guidelines to real case studies was tested. The general scope was to implement and validate the modelling approach proposed in the D 3.2 and to have feedback on potential adjustment and improvement of the first version of the LCA guidelines. To this aim, a selection of case studies was proposed for which the GEOENVI consortium provided life cycle data during the development of Task 3.2.

As a general remark, no comparative purpose should be intended when interpreting the LCA characterized results of the different case studies. This is because the quality and reliability of the inventory data vary among the power plants, in relation to differences concerning the conversion technology, the installed and working capacity, the country-specific regulations in terms of emissions reporting and to the actual functioning of the case study (i.e. real operating plant against a pilot or project plant).

The environmental footprint project

Starting from 2013, the Communication from the Commission Building the Single Market for Green Products (COM/2013/196) established the Environmental Footprint (EF or, more specifically, the Product- and Organisation- Environmental Footprint, PEF and OEF). The goal was to set up a common method to measure the life cycle environmental performances able to produce reliable and transparent results.

This extensive work began in 2013 and developed till 2018 with the so-called pilot phase. Then the final PEF and OEF documents were approved and, currently, the EF method is being tested on accepted Product and Organization Category Rules (PEFCR and OEFCR). The last version

of the EF method, namely EF3, was built-up through a complex working flow which lead to the development of an impact assessment method coupled with a background database. This, contrary to the most common LCA approach, is considered rigid. This means that to be compliant with the EF3 method, the EF3 background database and EF3 impact assessment method need to be used jointly without modification. Further information regarding the implementation are provided in the Methodological approach section of this deliverable. This rigidity allows to reach the expected goal for the development of a Single Market for Green Products, so to obtain a common method to measure the life cycle environmental performances in a given reference sector.
At the time of writing this deliverable, the EF3 impact assessment method was available, while the background database was still in version EF2. Therefore, a conversion of the dataset built using the EF2 database is needed to implement the EF3 impact assessment method. The conversion procedure here applied is implemented following guidance from JRC. Data repository was available at the JRC developer web page[1].

Motivation and objectives

The LCA guidelines were developed within the GEOENVI project (D 3.2) to offer guidance for consistency, balance, and quality with the aim of enhancing the credibility of LCA findings. They include some innovative aspects in terms of LCA applied to geothermal systems (including general energy systems) mainly linked with the use of the EF3 database and impact assessment method developed by the European Commission Joint Research Centre (JRC).
The objectives of Deliverable 3.3 are:

- To test the applicability of LCA guidelines (D 3.2) to different case studies which are representative of the main available geothermal energy conversion technologies in Europe.
- To check the suitability of the EF3 (database and impact assessment method) when it comes to modelling of geothermal energy systems.
- To highlight potential improvements of the guidelines document.

[1] https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml

Description of the geothermal energy conversion technologies adopted in the case studies

Table 1 summarizes the main features of the selected case studies. The case studies are representative for different geothermal energy conversion technologies, plant size, geothermal sources, geographical areas, amount of generated energy and its final use. The relevant sites for intense power production in the CSs are represented by the Italian Bagnore (CS1) and the Icelandic Hellisheiði (CS3) power plants.

Table 1 Geothermal power plants selected and main features

	Bagnore (Italy)	Rittershoffen (France)	Hellisheidi (Iceland)	Balmatt (Belgium)	Demo Plant (Hungary)	Dora-II (Turkey)
Geothermal source type	Liquid - hydrothermal	Liquid- EGS	Liquid/Vapour - hydrothermal	Liquid	Liquid	Liquid
Energy generation technology	Flash	Direct heat use	Single and double flash	Direct use + ORC	ORC	ORC
Final energy use	Electricity + Heat	Industrial heat use	Electricity + Heat	Heat + Electricity (self-consumption)	Electricity	Electricity
Installed capacity	61 MWe 21.1 MWth	27 MWth	303.3 MWe 133 MWth	6.6 MWth 0.25 MWe	3.75 MWe	9.5 MWe
ID used in this deliverable	***CS1***	***CS2***	***CS3***	***CS4***	***CS5***	***CS6***

CS1 Bagnore (Italy)

The geothermal system of Bagnore is composed of flash type geothermal power plants whose primary scope are the production of electricity. Such plants produce also heat which is delivered through a heat transfer network for industrial uses. The analysed system is in southern Tuscany, Italy, in the Monte Amiata area. The Bagnore geothermal system is composed of two distinct power plants, namely Bagnore 3 and Bagnore 4, which share the production and reinjection wells. The total installed power is 61 MWe, 21 MWe for Bagnore 3 (20 MWe flash + 1 MWe Organic Rankine Cycle) and 40MWe for Bagnore 4 (2 X 20MWe flash). The annual production is about 533 GWhe/y. The power plant is also designed with a thermal power of 21.1 MWth, which can produce 32 GWhth/y for industrial purposes.

The geothermal source is a high enthalpy source presenting a content of non-condensable gases (NCGs) of about 7% in mass. The main NCGs compound in mass fraction is CO_2 (6.7

% in mass over the total geothermal flow rate). The temperature of the geothermal source at the wellhead is about 210 °C with a specific enthalpy of 2,800 J/kg.

CS2 Rittershoffen (France)

The geothermal heat plant of Rittershoffen has been developed to supply heat to the industrial processes of a starch plant. This industrial user, located in Beinheim, France, totals 100 MW_{th} of thermal needs. The geothermal heat plant, with an installed capacity of 27.5 MW_{th}, has been successfully providing an average of 22.5 MW_{th} and 180 GWh/year of heat to this starch plant since June 2016.

The targeted reservoir is a Triassic sandstone and the top of a fractured carboniferous granite basement located at 2500 m depth. The first well, GRT-1, was drilled in 2012 and the first testing results after drilling showed a low productivity index. A stimulation program, including thermal, chemical, and hydraulic stimulation, was therefore designed and successfully performed in 2013 (Baujard et al. 2017) Induced seismicity was very low and virtually unnoticeable for the surrounding population. The second well, GRT-2, was drilled in 2014. On the contrary to GRT-1, GRT-2 had a very good productivity index during the testing phase after drilling. Thus, the Rittershoffen geothermal power plant is classified as an EGS because of the stimulation program performed on GRT-1, but also because of the total reinjection of the discharged geothermal fluids in the reservoir inducing a micro-seismicity activity at reinjection side during geothermal exploitation.

The geothermal brine is a Na-Ca-K-Cl dominated brine with a Total Dissolved Solids content of approximately 100 g/L and a Non-Condensable Gas (NCG) content, mainly CO_2, of 0.24% in weight mass (Mouchot et al. 2018) As a result, the heat plant was designed with a pressurized geothermal loop: A downhole Line Shaft Pump (LSP) pressurizes the geothermal brine in the surface equipment over the Gas break-out pressure to prevent any NCG emission during operation. The wellhead production temperature at GRT-2 reaches 170°C and the flowrate is regulated at 75-85 kg/s, according to the starch plant's heat demand. The geothermal heat is transferred to a secondary loop using several tubular heat exchangers and the brine is fully reinjected without additional pumps at 85°C into the injection well GRT-1. The secondary loop of the heat plant, containing freshwater, is then connected to a 15 km long transport loop to transfer the heat to the starch plant.

CS3 Hellisheiði (Iceland)

The plant is owned and operated by Orka Náttúrunnar and was initiated in 2006 mainly due to the increased demand for hot water in the society (Orka náttúrunnar 2020). It is situated within the Hengill area in SW-Iceland, one of the country's largest geothermal reservoir, that hosts several sub-areas of geothermal activity (Orkustofnun, n.d.). The area covers approximately 112 km^2 based on the distribution of heat, surface alteration, and resistivity measurements of 5 ohm line (Reykjavíkur Orkuveita 2015). The Hellisheiði plant produces 303 MW_e and 133 MW_{th} in a double flash cycle, with planned capacity of 267 MW_{th} within the next 30 years (Karlsdottir et al. 2020) and uses both geothermal fluid from Hellisheiði and Hverahlíð sub-areas, in the western part of the Hengill area and south of Hengill, respectively (Orkustofnun, n.d.). The aim of drilling for Hellisheiði power plant is to penetrate feed zones located by known fractures and fissures within the geothermal reservoir, with high permeability, for maximum productivity of each well. In total 47 geothermal wells have been drilled, the most recent well drilled for power production is HE-66, in 2020 (Orkustofnunar, n.d.). Wells for Hellisheiði power plant are mostly drilled through hyaloclastite (basaltic breccia, pillow basalt, and basaltic tuff), basaltic lava, and intrusions at deeper levels, of various composition (Níelsson 2011). The heat source of the geothermal system are intrusions in the crust. Alteration temperature, based on the observed composition of alteration minerals in the drill cuttings, often indicates >300°C within the geothermal reservoir, and the relationship between suggested alteration temperature and measured rock temperature has proven to be variable (Níelsson 2011) . The well depth is mainly in the range of 1800-2800 m, some reaching depth >3000 m (Orkustofnunar, n.d.). 17 injection wells are used to inject the geothermal fluid back into the ground. An air purification plant is located at the power plant that utilizes the Carbfix and Sulfix process to purify about 75% of the hydrogen sulphide and about 30% of the carbon dioxide dissolved in geothermal water for re-injection (Sigfússon et al. 2018). The gas content in the geothermal fluid has proven to be quite variable over time, with the most abundant dry gas species CO_2 and H_2S (Karlsdottir et al. 2020).

CS4 Balmatt (Belgium)

Balmatt is a deep geothermal demonstration project in Mol, Belgium, initiated in 2009 by VITO. In 2015 – 2016, VITO drilled two deep geothermal wells (3,610 and 4,341 m MD) on its premises in Mol-Donk. The geothermal capacity installed mainly consists of thermal capacity (6.6 MW_{th}) and a smaller ORC demonstration electrical capacity (0.25 MW_e). Among others, the geothermal plant will include facilities for materials research (e.g. corrosion testing and development of coatings) and a bypass for testing heat exchanger or prototypes of innovative binary systems under real conditions. Moreover, at the Balmatt site new stimulation and production techniques and equipment can be tested. The depth of the top of the fractured carboniferous limestone geothermal reservoir was encountered between 3,170 and 3,300 meters at the project location. Since the partial completion of the plant on 14th May 2019, it has operated for 16 days accumulatively, with a last joint period of 10 days. On Sunday 23rd June 2019, 2 days after terminating the longest operational period, a power failure was followed by an earthquake measuring 2.1 on the Richter scale. As a consequence, the Balmatt plant is currently not operational. An international research program lead by VITO has been launched including investigations of available historical data. It aims, among others, to better monitor and control seismicity and eventually to enable a safe restart. During the testing phase, the production temperature observed ranged from 121 to 126 °C and the average production flowrate achieved was between 70 and 150 m^3/h provided by an Electrical Submersible Pump (ESP).

The geothermal brine is highly saline with TDS of about 165 g/L, mainly dominated by Na-(Ca)-Cl elements, with a Gas Liquid Ratio of about 2.3 Nm^3/m^3. The gas consists mainly of CO_2 (~75 vol.%) and CH_4. Due to the high amount of dissolved gasses, surface installations are operated under a pressure of 40 bars to avoid degassing (NCG emissions), linked flashing and corrosion issues. Two heat exchangers with a total capacity of 6.6 MW transfer the geothermal heat to a secondary loop with fresh water. The brine is fully reinjected by the reinjection pump in the injection well MOL-GT-02.

Once in full operation, the plant will be used to supply 50 GWh/year:

- 50% for heat delivery (25,000 MWh_{th}): supply heat to an existing district heating network providing energy to VITO's research facilities, as well as facilities of SCK-CEN and Belgoprocess. There is a temperature regime of 95-70 °C.
- 50% for electricity production (10% efficiency: 2,500 MWh_e)

The amount of electricity consumed by the pumps is 3,300 MWh, so all produced electricity will be self-consumed.

CS5 Demonstrative Plant (Hungary)

The system is working with one production (~126°C) well and two reinjection wells. The wells were drilled before power plant construction had started. The surface system was built in 2016-2017, the power plant started to produce electricity in November 2017. This is a demonstration power plant. The built-in capacity is 3.75 MW. The exploited geothermal fluid transfers its heat to the ORC working fluid (R245fa) through heat exchangers. The ORC working fluid evaporates and the steam pass through a turbine which is connected to a generator and generate electricity. The exhaust steam from the turbine pass through a condenser where it is condensate into liquid phase and the cycle can start again. The utilized geothermal fluid is reinjected into the original geothermal reservoir without any pollution, it is circulated in a high pressurized closed loop (inhibitor is not used). The geothermal power plant currently produces only electricity, although, it is designed to be able to service heat and/or supply thermal water for spa (which is currently in concept study phase). Cooling is ensured with a hybrid system which combines cold water cooling (from 2 shallow well) and air cooling. Lifetime of the power plant is 30 years.

CS6 Dora-II (Turkey)

Dora-II has an installed power of 9.5 MWe and is one of the 5 geothermal power plants in Salavatlı-Aydın Geothermal field. Salavatlı geothermal field in Turkey has been developed and operated in the last 15 years, and during this period 5 power plants with a total power generation capacity of 72 MWe were installed. Salavatlı Geothermal field is situated at middle of the Menderes Metamorphic Massive (MMM) and at the northern half of actual Büyük Menderes Graben. Büyük Menderes Graben is a geological structure where the geothermal systems are being encountered as most frequently in Turkey. Büyük Menderes Graben has several prospects which are suitable for the formation of geothermal resources. Most of these fields have developed at reservoirs with medium enthalpies, with 120-180°C temperatures. These temperatures are being raised through to the asymmetrical axis of the Graben and reach up to 240°C. The geothermal reservoirs have generally been developed at different lithological units of metamorphic basement. A typical characteristic of this Basement is the location of originally deep situated gneisses over the upper units of metamorphic as result of a regional over thrusting. All wells intersect Quaternary to Recent Alluvial deposits, Pliocene and Miocene deposits, gneiss, micaschist, marble, quartzschist succession. Depth to the top of Metamorphic Basement vary between 316-1280 m, and this surface being deeper to south of the field.

Dora-II was commissioned in 2010. This project has two production and two reinjection wells. AS3 and AS4 are production wells which have 175 °C temperature and 1352 and 1300 m depth, respectively. ASR3 and ASR4 which have 1920 and 1178 m depth and they are using for reinjection. Dora-II is a binary power plant and designed for 845 t/h geothermal fluid.

Dora-II is an exemplary project for the cascade use of geothermal energy. There is a greenhouse with 42 da (heating capacity of 18.6 MWth) and a commercial CO_2 factory with capacity of 120,000 tons annually. Thanks to NCG factory, NCG emission of Dora-II is almost zero.

In the Salavatlı field, geothermal waters circulate in fractures and faults in carbonated rocks. Therefore, geothermal water contains high levels of bicarbonate. The site initially had 1.4% NCG (mass fraction in water) dissolved NCG. NCG is mainly composed of 98-99% pure CO_2. H_2S ratio is around 1%. Remaining are generally hydrocarbon gases. Declines in NCG rates over time for production wells due to dilution of reservoir gas by “degassed” injectate were observed. After ten years production, NCG ratio is decreased from 1.4% to 0.4%.

Methodological approach

Database

The database used to model the geothermal systems is the EF database as provided by Green Delta and designed to be uploaded in the OpenLCA software. All relevant information can be found here (https://nexus.openlca.org/database/Environmental%20Footprints). Modelling through the OpenLCA software allowed us to obtain a single inventory process of the entire life cycle for each case study in EF 2. The inventory process generated for Rittershoffen was then converted in EF3 compatible file (LCI) following the instruction from JRC and the LCI evaluated using the tool Look@LCI (Zampori, Fazio, and Diaconu 2018) to obtain LCIA results compliant with EF3. The conversion procedure is required since the processes built using the EF2 background database are not compliant with the EF3 impact assessment method. Therefore, prior the computation of potential impacts by EF3, the conversion of the EF2 files is needed. The selection of the EF database and the conversion procedure were required since the LCA guidelines suggest implementing the EF 3 as the impact assessment method.

Important aspects of the EF method

The main feature of the EF database used in this report is that data for different process categories are supplied by different providers. The list of process categories and corresponding providers is reported in Table 2. The process Life Cycle Inventory (LCI) datasets comply with EF recommendations. Among other requirements, to be in accordance with EF Life Cycle Inventory (LCI) data sets shall be compliant with:

- EF elementary flows: the nomenclature shall be aligned with the most recent version of the EF reference package available on the EF developer’s page at the following link https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml.

- For the process data sets and products/elementary flow, the nomenclature shall be compliant with the "ILCD Handbook – Nomenclature and other conventions" (JRC European commission 2011).

Table 2 Main categories of processes with the corresponding providers as contained in the EF database. Source https://eplca.jrc.ec.europa.eu/LCDN/contactListEF.xhtml

Area of interest	Provider	Node URL
EF representative products	European commission	http://eplca.jrc.ec.europa.eu/EF-node/
Energy and transport	Thinkstep	http://lcdn.thinkstep.com/Node/
Packaging	Thinkstep	http://lcdn.thinkstep.com/Node/
Agrofood	Quantis	https://lcdn.quantis-software.com/PEF/
Metals	Thinkstep	http://lcdn.thinkstep.com/Node/
Chemicals for Paint	CEPE ecoinvent	http://lcdn-cepe.org
Others	Quantis	https://lcdn.quantis-software.com/PEF/
Chemicals	Ecoinvent	http://ecoinvent.lca-data.com/
End of Life	Thinkstep	http://lcdn.thinkstep.com/Node/
Feed	Fefac	http://lcdn.blonkconsultants.nl/Node/
Incineration	Thinkstep	http://lcdn.thinkstep.com/Node/
Plastics	Thinkstep	http://lcdn.thinkstep.com/Node/
Textiles	Cycleco	https://node.cycleco.eu/node/
Electronics	Thinkstep	http://lcdn.thinkstep.com/Node/
Cooling and freezing transport	Thinkstep	http://lcdn.thinkstep.com/Node/
Glass recycling	RDC	http://soda.rdc.yp5.be/login.xhtml?stock=FEVE_EF_comp

The LCIA method adopted in this deliverable is the latest release of the Environmental footprint method, EF3. Within the EF3 some LCIA methods have been changed compared to the ILCD method (Fazio et al. 2018). This change in LCIA method implied adaptations of some elementary flows. Some changes also occurred in comparison to the EF2 release (May 2018). More in detail, compared to the ILCD scheme, the EF scheme presents some changes and adaptations that can be summarized as follows:

- Three methods are completely new or updated according to the newest releases of the old methods adopted in ILCD/EF. One method has been deeply reviewed. Nine sub-methods (i.e. partial sets of Characterization factors (CFs) for specific group of substances) have been released for three impact categories. Annex II provides a summary of the main differences between ILCD and EF and (Fazio et al. 2018) give a detailed explanation of all differences.
- The elementary flow list has been adapted and expanded according to the needs of the new methods.
- Within the new methods some flows have been spatially differentiated (i.e. regionalization of flows).

- For several flows that were not characterized (both in newly added methods and in the pre-existing ones that were not modified), a CF has been set based on a direct proxy for a specific substance/compartment was available.
- Specific exceptions, integrations or corrections have been implemented in different methods.

All the additional files that have been released, including an exhaustive list of all the changes occurred in the transition phase between the ILCD and the EF3, can be seen at http://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml for details.

Table 3 reports the list of the impact categories included in the EF3 impact assessment method together with the level of recommendation provided by the JRC and detailed in the work by Fazio and co-authors (Fazio et al. 2018).

Table 3 List of LCIA methods included in the EF3 with their corresponding level of recommendation. Level I indicate a reliable method behind the calculation of characterization factors for elementary flows whereas a level III indicates a high uncertainty related to the method. These levels are not to be mixed up with the geothermal guidelines priority levels as explained already in the guidelines document D3.2.

LCIA method	Level of recommendation
Climate change; midpoint;	I
Ozone depletion; midpoint;	I
Cancer human health effects; midpoint;	III
Non-cancer human health effects; midpoint;	III
Respiratory inorganics; midpoint;	I
Ionizing radiation - human health; midpoint;	II
Photochemical ozone formation; midpoint - human health;	II
Acidification; midpoint;	II
Eutrophication terrestrial; midpoint;	II
Eutrophication freshwater; midpoint;	II
Eutrophication marine; midpoint;	II
Ecotoxicity freshwater; midpoint;	III
Land use; midpoint;	III
water use; midpoint;	III
Resource use mineral and metals; midpoint;	III
Resource use energy carriers; midpoint;	III
According to ILCD levels**: “Level I”** (recommended and satisfactory), "**Level II”** (recommended but in need of some improvements) or "**Level III**” (recommended, but to be applied with caution)	

Main differences between EF2 and EF3 results

The differences between results obtained using the EF2 and EF3 databases are mainly due to the impact assessment method adopted. In fact, the bulk of the background data is still based on the EF2 database, and only minor modifications happened when converting the EF2 elementary flows to EF3. The modifications occurring during the conversion are related to the emission compartment of flows as well as to their regionalization. However, these modifications do not really influence the overall results except for (eco)-toxicity categories. Therefore, excluding the toxicity related categories, the results obtained applying the EF2 method are comparable to those obtained applying the EF3 for most of the categories.

An example of comparison between the two methods is performed for the results of the CS2 reference case study and reported in Table 4.

Table 4 Percentages of variation between results obtained by applying the EF2 and EF3 impact assessment methods to the CS2 reference case study. The database employed is the same for both calculations

Impact Category	Unit	Impact result EF2	Variation	Impact result EF3
Acidification	mol H^+ eq	2.3E-05	0%	2.3E-05
Climate change	kg CO_2 eq	4.7E-03	0%	4.7E-03
Ecotoxicity, freshwater	CTUe	8.0E-04	15390%	1.2E-01
Eutrophication marine	kg N eq	7.3E-06	0%	7.3E-06
Eutrophication, freshwater	kg P eq	2.9E-08	-1%	2.8E-08
Eutrophication, terrestrial	mol N eq	7.7E-05	0%	7.7E-05
Human toxicity, cancer	CTUh	1.3E-11	-93%	8.9E-13
Human toxicity, non-cancer	CTUh	2.4E-10	-64%	8.6E-11
Ionising radiation, human health	kBq ^{235}U	1.8E-02	0%	1.8E-02
Land use	soil quality index	2.4E-02	-57%	1.0E-02
Ozone depletion	kg CFC-11eq	3.1E-11	0%	3.1E-11
EF-particulate Matter	Disease incidences	3.7E-10	0%	3.7E-10
Photochemical ozone formation	kg NMVOC eq	2.1E-05	0%	2.1E-05
Resource use, fossils	MJ	2.4E-01	0%	2.4E-01
Resource use, minerals and metals	kg Sb eq	4.1E-08	0%	4.1E-08
Water use	m^3 water eq. deprived	3.3E-03	0%	3.3E-03

Lines highlighted in red show the largest difference between the two versions of the methods and are related to toxicity impact categories. The characterization factors adopted in toxicity related categories were deeply revised in the EF3 update as reported in (Fazio et al. 2018). All changes can be tracked back consulting the changelog released along with the EF3 method itself (EC-JRC, n.d.). In both the EF2 and EF3 methods, the USEtox® model is used to generate the CFs for the toxicity related categories, but in the EF3 a significantly larger number substances were characterized beside an update of those already present. The upgrade was performed by integrating the large amount of information contained in the REACH database (European Commission 2006), from the EFSA (European Food Safety Authority) (Kovarich et al. 2020) and the PPDB (Pesticide Properties Database) with the USEtox model (Lewis et al.

2016). The inclusion of more CFs for different substances results in very different impact between EF2 and EF3 methods besides a different approach used to address CFs uncertainty for human toxicity categories, as described in (Fazio et al. 2018).

Another main change from the EF2 to the EF3 method is related to the regionalization of elementary flows. The regionalization of flows allows to account for the different regional situations around the world by assigning different CFs depending on the place where the flow exists (i.e. the impact due to the use of 1m^3 of water which takes place in Spain is different from the impact that would occur if the same water flow was used in Iceland). This approach was already adopted in the EF2 version for the “Water use” impact category but, in the EF3 it was extended also to “freshwater eutrophication”. Therefore, a different impact result is calculated.

Also the “land use” impact category makes use of regionalized flows but the result’s variation showed in Table 4 between the two methods, is probably caused by an issue related to the non-regionalized flows (even present in the model) and calculated with the OpenLCA software. In fact, the land use method is not changed from EF2 to EF3. This seems to be an issue related to the implementation of EF method by the OpenLCA developers.

Important aspects to consider when assessing Toxicity related categories

As reported in the Table 3, toxicity-related categories Ecotoxicity freshwater, Human toxicity carcinogenic and Human toxicity non carcinogenic (namely ETo, HTC and HTN) are classified with level III due to high uncertainties, and they should therefore be applied with caution. The uncertainty related with CFs calculation for toxicity categories is known and essentially connected to the difficulty in accounting for all interaction and transformation that a chemical can undergo before exposure. Exposure itself can happen through multiple ways. These limitations are even more evident for heavy metals emissions due to intrinsic properties of the USEtox model which is conceived to work well with organic compounds but not with metals due to their very different chemical properties in respect to organic compounds.

A way to evaluate the reliability of the results generated by these methods is the analysis of the elementary flows contributing mostly to the impact category. When the major contribution to the total impact in toxicity-related categories is due to metal emissions, the result must be considered with a large uncertainty.

In CS2 a simple analysis of the elementary flows, where the flows contributing to less than 2% of the different impact categories were cut-off, is performed and the results are shown in Table 5. It is clear the large prevalence of inorganic compounds which lead to a high uncertain result.

Table 5 Contribution of elementary flows to the total impact on Human Toxicity carcinogenic category.

Flow	Result (CTUh)	Flow Contrbution %
nickel Emissions to air, unspecified	2.9E-13	32.7%
chromium Emissions to fresh water	1.4E-13	15.3%
formaldehyde Emissions to air, unspecified	1.3E-13	14.5%
chromium Emissions to air, unspecified	6.5E-14	7.3%
lead Emissions to air, unspecified	6.4E-14	7.1%
mercury Emissions to air, unspecified	6.3E-14	7.0%
arsenic (v) Emissions to fresh water	3.1E-14	3.4%
chromium Emissions to non-urban air or from high stacks	1.8E-14	2.0%
benzo[a]pyrene Emissions to non-urban air or from high stacks	1.7E-14	2.0%

Modelling of the CS2 case study

The general modelling approach described in the D 3.2 was applied to all case studies. However, the conversion from EF2 to EF3 is time consuming and it was decided to calculate the detailed LCA only for one reference case study. Rittershoffen (i.e. CS2) was selected as reference case study due to the completeness of its inventory, which also allows to highlight any hotspots. All the results for the other case studies are reported in Section "Characterized results in EF3 for all other case studies" but only as total impact in each category thus no detailed contribution of phases and processes to the total impact can be derived. When a given case study presented a peculiarity related to the CS itself, or a deviation from what suggested in the guidelines, this was clearly reported to the corresponding case study ID as defined in **Error! Reference source not found.**. For instance, some peculiarities might derive from the n ational regulatory framework. In some countries a specific compound can be regulated by an emission limit whereas, in other countries, the same compound does not have a corresponding limit. Therefore, the sampling of the compound could be flawed affecting the LCA inventory, and so the LCA result.

Goal and scope

The goal of the LCA performed in the D 3.3 is to assess the environmental performances connected with energy production from the selected GEOENVI case studies by following the approach described in the LCA guidelines (D3.2).

The scope of the LCAs is to test (and eventually improve) the LCA guidelines when applied to a set of real case studies.

Functional unit

The CS2 produces only heat and therefore the functional unit selected is 1 kWh_{th} of heat delivered.

System boundaries

According to the LCA guidelines (D3.2) and as reported in Figure 1, the system boundaries of all LCA studies are defined as follow:

The core module entails:

1. Construction: the exploration activity, drilling of the wells and stimulations, wellheads, collection pipelines, power plant building, and all the necessary plant machinery/equipment items. The construction of heat district is excluded from this phase.
2. Operational & Maintenance: energy requirements for geothermal fluid exploitation, scaling and corrosion prevention, equipment replacement and direct emissions to air.
3. End of life: procedures for correct closure of the wells, and the treatment of wastes produced from all previous phases.

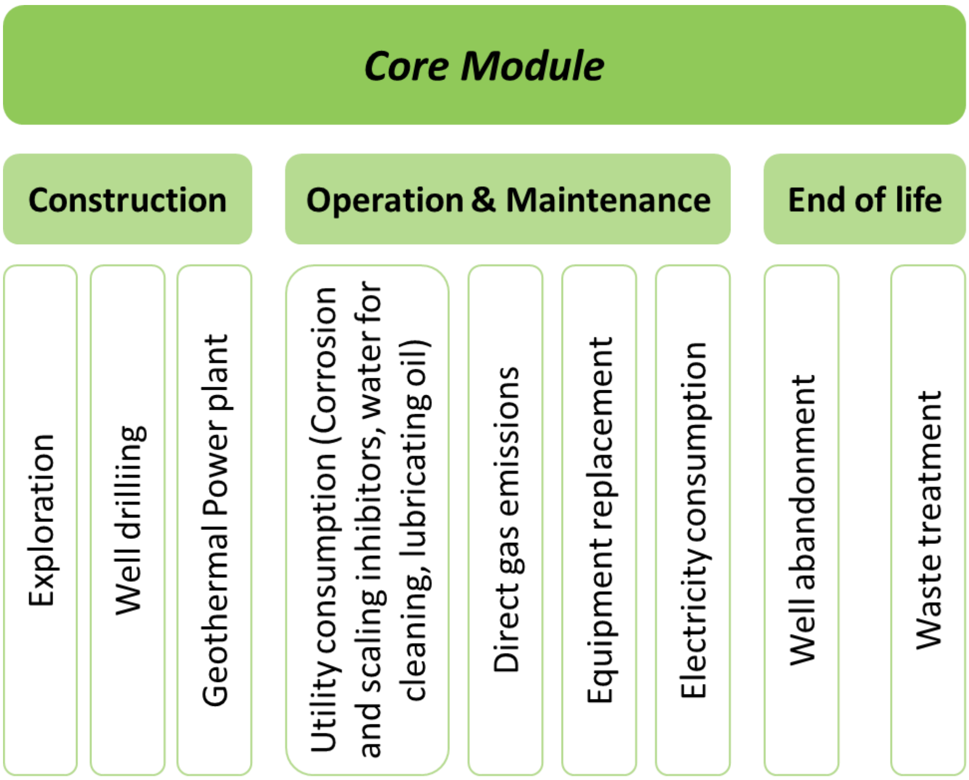


Figure 1 Graphical representation of the core module for the CS2 geothermal plant.

Construction

Exploration

Prior to the drilling phase, geophysical exploration of the area's underground on which the installation is foreseen to be built is necessary. In the Upper Rhine Graben context, the geophysical technic mostly used is seismic exploration (2D or 3D). The exploration phase is modelled by including diesel consumption for seismic vibrators during the acquisition (about 6000 kg of diesel in total) and the distance travelled by the staff during this phase, assumed to be 880 km.

Well drilling

Drilling platform

Prior to drilling, the drilling platform, including retention basins, is built. This process consisted of concrete and diesel consumption for an amount of 1.44 x 10^7 kg and 2.42 x 10^4 kg, respectively.

Deep well Drilling

The well drilling process requires energy, provided for this model by diesel, drilling mud as well as steel and cement for the casing. Cuttings produced during well drilling are another important inventory flow. Material requirements are reported in Table 6. The output includes the emission of CO_2 during testing of the well and a generic waste to landfill.

Table 6 Inventory flows for drilling of 2 deep wells, total lengths of 6518 m

Deep well drilling			
INPUT Flow	Amount	Unit	Provider
activated bentonite	9.11E+03	kg	activated bentonite production, production mix, at plant, technology mix, 100% active substance - GLO
CS2 – DrillingMud*	5.48E+05	kg	CS2 - DrillingMud
Diesel consumption in construction machine	9,38E+05	kg	Diesel combustion in construction machine, diesel driven - GLO
Electricity	8,45E+05	MJ	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV - FR
Portland cement	3.59E+05	kg	Portland cement, production mix, at plant, raw material extraction, production of clinker, and cement grinding, CEM I 32.5 - EU-28+EFTA
silica sand	1.86E+05	kg	silica sand production, production mix, at plant, technology mix, 100% active substance - RER
Steel cold rolled (St)	5.14E+05	kg	Steel cold rolled coil, single route, at plant, blast furnace route, carbon steel - EU-28+EFTA
Transport	4.94E+09	kgkm	Articulated lorry transport, Euro 4, Total weight 28-32 t (without fuel), consumption mix, to consumer, diesel driven, Euro 4, cargo, 28 - 32t gross weight / 22t payload capacity - EU-28+3

Transporting capacity	1.53E+09	kgkm	Transoceanic ship, containers, consumption mix, to consumer, heavy fuel oil driven, cargo, 27.500 dwt payload capacity, ocean going - GLO
OUTPUT Flow	Amount	Unit	Provider
carbon dioxide	3.12E+05	kg	
Waste (unspecified)	2.15E+06	kg	Landfill of inert material (other materials), production mix (region specific sites), at landfill site, landfill including leachate treatment and with transport without collection and pre-treatment, The carbon and water content are respectively of 0% C and and 0% Water (in weight %) - EU-28+EFTA

**The drilling mud was further modelled as consisting of 36% water, 11% bentonite, 10% calcium carbonate, 8% carboxmethylcellulose, 27% inorganic chemicals, 1% citric acid, 1% soda ash, 3% sodium chloride, 1% sodium hydroxide (Kanna et al. 2017; Pratiwi, Ravier, and Genter 2018).*

Stimulation

Energy requirements for the hydraulic and chemical stimulation are reported in Table 7 Inventory flows for chemical and hydraulic stimulation performed on one well and transportation of materials to the site. The chemical stimulation was modelled as a mix of 50% water, 25% potassium chloride, and 25% organic chemicals assuming a density of 1.45 kg/l for the latter (Pratiwi, Ravier, and Genter 2018).

Table 7 Inventory flows for chemical and hydraulic stimulation performed on one well and transportation of materials to the site

Chemical stimulation			
INPUT Flow	Amount	Unit	Provider
Diesel consumption in construction machine	1.16E+01	kg	Diesel combustion in construction machine, diesel driven - GLO
freshwater - FR	4.00E+01	m3	
Hydrochloric acid	1.45E+04	kg	Hydrochloric acid production, production mix, at plant, technology mix, 100% active substance - RER
Potassium chloride as K2O_at plant_EU-28+3_S	1.20E+04	kg	Potassium chloride, at plant, as K2O, per kg K2O - EU-28+3
Transport	1.33E+7	kgkm	Articulated lorry transport, Euro 4, Total weight 28-32 t (without fuel), consumption mix, to consumer, diesel driven, Euro 4, cargo, 28 - 32t gross weight / 22t payload capacity - EU-28+3
Hydraulic stimulation			
INPUT flow	Amount	Unit	Provider
Diesel consumption in construction machine	1.22E+03	kg	Diesel combustion in construction machine, diesel driven - GLO
freshwater - FR	4.20E+03	m3	

Geothermal power plant

Building construction

The building housing of all the electrical and pressure equipment for heat generation was modelled by adapting the Ecoinvent process 'building construction, hall, steel construction' to fit the background processes available in the EF2 database Table 8.

Table 8 Inventory flows for the building construction

CS2 - Building			
Flow	Amount	Unit	Provider
Aluminium continuous casting ingot	2.08E+03	kg	Aluminium ingot (silicon and magnesium main solutes), single route, at plant, primary production, aluminium casting and alloying, 2.7 g/cm3 - EU-28+EFTA
Cable	3.17E+05	m	Cable, three-conductor cable, production mix, at plant, technology mix, three-conductor cable, 1m, 60 g/m - EU-28+EFTA
Clay brick (pored)	7.40E+04	kg	Bricks vertically perforated (EN15804 A1-A3), production mix, at plant, technology mix, vertically perforated - EU-28
Diesel consumption in construction machine	1.75E+04	kg	Diesel combustion in construction machine, diesel driven - GLO
Electricity	4.73E+05	MJ	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV - FR
Gravel (2/32)	3.68E+05	kg	Gravel, production mix, at plant, wet and dry quarry, drying, grain size 2/32 - EU-28+EFTA
Portland cement	3.74E+04	kg	Portland cement, production mix, at plant, raw material extraction, production of clinker, and cement grinding, CEM I 32.5 - EU-28+EFTA
Steel electrogalvanized coil	5.55E+04	kg	Steel electrogalvanized coil, single route, at plant, steel sheet electrogalvanization, 1.5 mm sheet thickness, 0.02 mm zinc thickness - EU-28+EFTA
Steel forging part (St)	2,04E+03	kg	Forging of steel parts, single route, at plant, forging, 1 kg forged part - EU-28+EFTA
Thermal insulation flat roof_EU-28+3	2.56E+03	Item(s)	Thermal insulation of a building element, consumption mix, flat roof application, 1 m^2, Uc of 0,14 W/m^2K - EU-28+3

Pipes

Geothermal brine, in the geothermal loop, and freshwater, in the secondary loop, are transported to the heat exchanger using pipes made of steel, insulated with rockwool and aluminium in this order. The amounts of each material are estimated assuming a cylindrical shape of the pipe. The transport of the materials is modelled with an average distance of 500 km. Inventory in Table 9 Inventory flows for construction of 200m of geothermal pipes, 160m of freshwater pipe and transportation to the site.

Table 9 Inventory flows for construction of 200m of geothermal pipes, 160m of freshwater pipe and transportation to the site

CS2 - Pipes			
Flow	Amount	Unit	Provider
Aluminium ingot	2.76E+03	kg	Aluminium ingot mix, production mix, to consumer, primary production, aluminium ingot product, primary production - EU-28+EFTA
Aluminium sheet	2.76E+03	kg	Aluminium sheet rolling, single route, at plant, primary production, aluminium deep- drawing, 2.7 g/cm3 - EU-28+EFTA
Glass wool	3.35E+03	kg	Glass wool, production mix, at plant, fleece, density between 10 to 100 kg/m3 - EU-28
Steel cold rolled (St)	2.67E+04	kg	Steel cold rolled coil, single route, at plant, blast furnace route, carbon steel - EU-28+EFTA
Transport	1.64E+07	kgkm	Articulated lorry transport, Euro 4, Total weight 28-32 t (without fuel), consumption mix, to consumer, diesel driven, Euro 4, cargo, 28 - 32t gross weight / 22t payload capacity - EU-28+3

Production pump

The production pump is modelled Table 10 as a line shaft pump whose material requirements are estimated according to its power output: 100 kg steel/kW, 25 kg chromium steel/kW, and 9 kg motor/kW. The motor was hereby assumed to consist of 50% steel and 50% copper, according to expert's recommendations. The number of line shaft pumps (LSP) depends on the number of production wells. The transport of the LSP was modelled with 44,200 km travelled by transoceanic ship and 7,600 km by 16-32 metric ton lorry EURO4 category.

Table 10 Inventory flows for LSP production and transportation to the site

CS2 – Production Pump			
Flow	Amount	Unit	Provider
Copper wire (Cu; 0.06mm)	1.19E+04	kg	Copper Wire Drawing, single route, at plant, wire drawing, 8.92 g/cm3 - EU-28+EFTA
global mix copper concentrate	1.19E+04	kg	Copper Concentrate (Mining, mix technologies), single route, at plant, copper ore mining and processing, Copper - gold - silver - concentrate (28% Cu; 22.3 Au gpt; 37.3 Ag gpt) - GLO
Stainless steel (hot rolled)	6.61E+04	kg	Stainless steel hot rolled, production mix, at plant, hot rolling, stainless steel - ROW
Steel cold rolled (St)	2.76E+05	kg	Steel cold rolled coil, single route, at plant, blast furnace route, carbon steel - EU-28+EFTA
Transport	3.77E+08	kgkm	Articulated lorry transport, Euro 4, Total weight 28-32 t (without fuel), consumption mix, to consumer, diesel driven, Euro 4, cargo, 28 - 32t gross weight / 22t payload capacity - EU-28+3
Transporting capacity	1.35E+10	kgkm	Transoceanic ship, containers, consumption mix, to consumer, heavy fuel oil driven, cargo, 27.500 dwt payload capacity, ocean going - GLO

Injection pump

The inventory flows for the injection pump Table 11 are calculated using the following mass weight percentages, according to expert's recommendations: 25% steel, 12% chromium steel, 8% aluminium, 8% copper, 38% cast iron, and 9% super duplex steel.

Table 11 Inventory flows for injection pump construction and transportation to the site

CS2 – Injection Pump			
Flow	Amount	Unit	Provider
Aluminium ingot	4.15E+03	kg	Aluminium ingot mix, production mix, to consumer, primary production, aluminium ingot product, primary production - EU-28+EFTA
Aluminium sheet	4.15E+03	kg	Aluminium sheet rolling, single route, at plant, primary production, aluminium deep- drawing, 2.7 g/cm3 - EU-28+EFTA
Cast iron	1.97E+04	kg	Cast iron, single route, at plant, electric arc furnace route, from steel scrap, secondary production, > 2,06 % carbon content - EU-28+EFTA
Copper wire (Cu; 0.06mm)	4.15E+03	kg	Copper Wire Drawing, single route, at plant, wire drawing, 8.92 g/cm3 - EU-28+EFTA
global mix copper concentrate	4.15E+03	kg	Copper Concentrate (Mining, mix technologies), single route, at plant, copper ore mining and processing, Copper - gold - silver - concentrate (28% Cu; 22.3 Au gpt; 37.3 Ag gpt) - GLO
Stainless steel (hot rolled)	1.24E+04	kg	Stainless steel hot rolled, production mix, at plant, hot rolling, stainless steel - ROW
Steel cold rolled (St)	1.30E+04	kg	Steel cold rolled coil, single route, at plant, blast furnace route, carbon steel - EU-28+EFTA
Transport	2.59E+07	kgkm	Articulated lorry transport, Euro 4, Total weight 28-32 t (without fuel), consumption mix, to consumer, diesel driven, Euro 4, cargo, 28 - 32t gross weight / 22t payload capacity - EU-28+3

Heat exchanger

The inventory flows for the heat exchanger Table 12 are calculated using the following weight percentages: 23% super duplex steel, 74% unalloyed steel, 2% aluminium, 1% rockwool. Materials transport is modelled with an average distance of 500 km.

Table 12 Inventory flows for heat exchanger construction and transportation to the site

CS2 - HeatExchanger			
Flow	Amount	Unit	Provider
Aluminium ingot	5.54E+03	kg	Aluminium ingot mix, production mix, to consumer, primary production, aluminium ingot product, primary production - EU-28+EFTA
Aluminium sheet	5.54E+03	kg	Aluminium sheet rolling, single route, at plant, primary production, aluminium deep- drawing, 2.7 g/cm3 - EU-28+EFTA
Glass wool	2.77E+03	kg	Glass wool, production mix, at plant, fleece, density between 10 to 100 kg/m3 - EU-28
Stainless steel (hot rolled)	6.37E+04	kg	Stainless steel hot rolled, production mix, at plant, hot rolling, stainless steel - ROW
Steel cold rolled (St)	2.05E+05	kg	Steel cold rolled coil, single route, at plant, blast furnace route, carbon steel - EU-28+EFTA

Transport	1.38E+08	kgkm	Articulated lorry transport, Euro 4, Total weight 28-32 t (without fuel), consumption mix, to consumer, diesel driven, Euro 4, cargo, 28 - 32t gross weight / 22t payload capacity - EU-28+3

Filter

Filters are modelled as consisting up to 100% of unalloyed steel, Table 13.

Table 13 Inventory flows for filters construction and transportation to the site

CS2 - Filters			
Flow	Amount	Unit	Provider
Steel cold rolled (St)	9.31E+02	kg	Steel cold rolled coil, single route, at plant, blast furnace route, carbon steel - EU-28+EFTA
Transport	4.66E+05	kgkm	Articulated lorry transport, Euro 4, Total weight 28-32 t (without fuel), consumption mix, to consumer, diesel driven, Euro 4, cargo, 28 - 32t gross weight / 22t payload capacity - EU-28+3

Valve

Valves consist up to 82% of unalloyed steel and 18% of chromium steel, Table 14.

Table 14 Inventory flows for valves construction and transportation to the site

CS2 - Valves			
Flow	Amount	Unit	Provider
Stainless steel (hot rolled)	3.26E+03	kg	Stainless steel hot rolled, production mix, at plant, hot rolling, stainless steel - ROW
Steel cold rolled (St)	1.48E+04	kg	Steel cold rolled coil, single route, at plant, blast furnace route, carbon steel - EU-28+EFTA
Transport	9.05E+06	kgkm	Articulated lorry transport, Euro 4, Total weight 28-32 t (without fuel), consumption mix, to consumer, diesel driven, Euro 4, cargo, 28 - 32t gross weight / 22t payload capacity - EU-28+3

Air cooler

An air cooler is also modelled which consists of 99% unalloyed steel and 1% rockwool, Table 15.

Table 15 Inventory flows for air cooler construction and transportation to the site

CS2 - AirCooler			
Flow	Amount	Unit	Provider
Glass wool	1.57E+02	kg	Glass wool, production mix, at plant, fleece, density between 10 to 100 kg/m3 - EU-28
Steel cold rolled (St)	1.55E+04	kg	Steel cold rolled coil, single route, at plant, blast furnace route, carbon steel - EU-28+EFTA

Transport	7.85E+06	kgkm	Articulated lorry transport, Euro 4, Total weight 28-32 t (without fuel), consumption mix, to consumer, diesel driven, Euro 4, cargo, 28 - 32t gross weight / 22t payload capacity - EU-28+3

Operation and maintenance

Corrosion inhibitor, scaling inhibitor, salt, water for cleaning operations, and lubricating oil are used during the operation and maintenance of the plant. These materials inventory flows are reported in Table 16.

The mass of scaling is disposed-off as inorganic waste in landfill. It is assumed that 881 km are travelled every three years for their disposal.

In addition, direct gas releases might also take place during this phase.

Further, the maintenance of the equipment implies that certain parts are replaced throughout the geothermal plant's lifetime. The replacement rates are taken directly from the LCA guidelines.

Finally, the electricity requirement necessary to operate the geothermal power plant has been derived from the nominal powers of the production and injection pumps.

Table 16 Inventory flows for the operational phase over 30 years of time horizon

Operation and maintenance			
Flow	Amount	Unit	Provider
benzo[thia]diazole-compound	1.84E+02	kg	benzo[thia]diazole-compound production, production mix, at plant, technology mix, 100% active substance - GLO
CS2 – AntiCorrosionAgent *	3.67E+05	kg	CS2 - AntiCorrosionAgent
Electricity	4.75E+08	MJ	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV - FR
freshwater - FR	2.10E+04	m3	
lubricating oil	1.97E+05	kg	lubricating oil production, production mix, at plant, technology mix, 100% active substance - RER
Sodium chloride powder	2.00E+05	kg	Sodium chloride powder production, production mix, at plant, technology mix, 100% active substance - RER
Transport	2.64E+06	kgkm	Articulated lorry transport, Euro 4, Total weight 28-32 t (without fuel), consumption mix, to consumer, diesel driven, Euro 4, cargo, 28 - 32t gross weight / 22t payload capacity - EU-28+3
Vehicle kilometers	2.25E+08	m	Passenger car, average, consumption mix, to consumer, technology mix, gasoline and diesel driven, Euro 3-5, passenger car, engine size from 1,4l up to >2l - GLO

OUTPUT flow	Amount	Unit	Provider
carbon dioxide (fossil)	9.87E+05	kg	
methane (fossil)	8.81E+03	kg	
Waste (unspecified)	9.00E+03	kg	Landfill of polluted inorganic waste, production mix (region specific sites), at landfill site, landfill including leachate treatment and with transport without collection and pre-treatment - EU-28+EFTA

** Anticorrosion agent is dosed in continuous flow to the geothermal fluid. 1 Kg of additive is made up of: 0.05 kg of ammonium chloride; 0.3 kg of ethylene glycol; 0.1 kg of glycerine*

End of life

Well abandonment is described by the amount of diesel, cement, bentonite and silica required during the well closure process, inventory in Table 17. According to the LCA guidelines, the end of life excludes the decommissioning of power plant buildings and dismantling, sorting, and recycling of machinery's components (Parisi et al. 2020).

Table 17 Inventory flows for the forecast end of life activities to be performed on 2 wells.

End of life			
Flow	Amount	Unit	Provider
activated bentonite	1.41E+03	kg	activated bentonite production, production mix, at plant, technology mix, 100% active substance - GLO
Diesel consumption in construction machine	3.15E+04	kg	Diesel combustion in construction machine, diesel driven - GLO
Portland cement	3.10E+04	kg	Portland cement, production mix, at plant, raw material extraction, production of clinker, and cement grinding, CEM I 32.5 - EU-28+EFTA
silica sand	1.46E+04	kg	silica sand production, production mix, at plant, technology mix, 100% active substance - RER

Lifetime

The lifetime of CS2 was set to 30 years according to the guidelines.

Replacement of equipment: Renewal of 1/3 of heat exchangers every 10 years.

Replacement every 10 years of 15 t of steel (pipes, valves) 1 t of stainless steel (valves).

Replacement of 29 t of steel and 13,7 t of stainless steel from production pump.

Database

The database used to model the background processes is the EF database as provided by Green Delta and designed to be uploaded in the OpenLCA software. All relevant information can be found here (https://nexus.openlca.org/database/Environmental%20Footprints). Following the general procedure described in “methodological approach”, the final results are computed with Look@LCI tool making use of the EF3 method.

Data quality

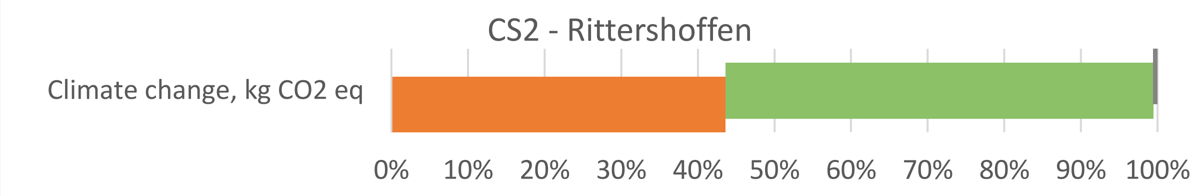
The LCI developed by (Pratiwi, Ravier, and Genter 2018) was used as a reference model and completed by new information in collaboration with the plant operator. The use of primary data for most activities, based on real drilling, building and operation, ensures a high data confidence index.

Results of the reference case study of Rittershoffen

This Section reports EF3 results for the reference CS2 case study. First, results for the impact categories with high priority are reported and described individually and according to the LCA guidelines. The remaining categories with moderate and low priority are described in a general way and only significant deviations from the common trend in phases and processes contribution to the total impact are analysed in more detail.

Impact categories with a high priority

Climate Change (CC)



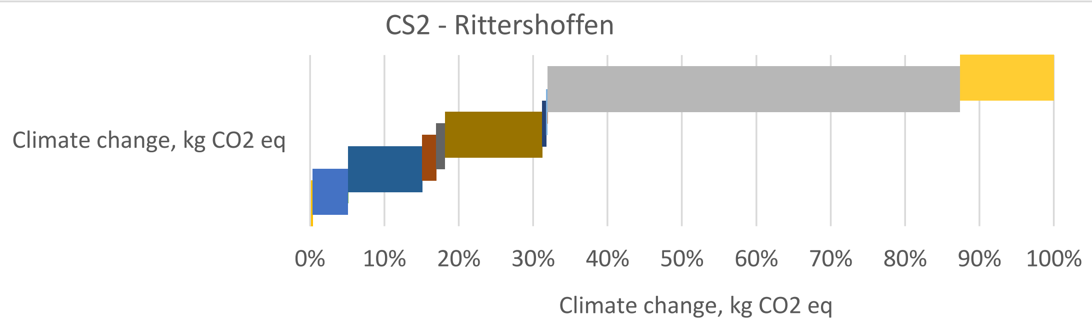
	Climate change, kg CO2 eq
Construction	2.11E-03
Operation and Maintenance	2.71E-03
End of Life	2.71E-05

Figure 2 Contribution of the three main phases on the total impact on Climate Change category (CC). Geothermal source type: liquid, energy conversion technology: direct heat use, load factor: 77%, annual energy output decay: <0.1%, lifetime installation: 30 years, installed capacity: 27 MWth, number of wells: 2 (GRT-1 : 2580 mMD, GRT-2 : 3196 mMD, 3 938 total drilled).

Figure 2 shows the contribution of the main phases to the total impact of the Life Cycle (LC) of CS2 on the CC category (4,81E-03 CO_2 eq/FU). The major contribution to the total impact is due to the Operation and Maintenance phase which amounts to about 56% of the total impact.

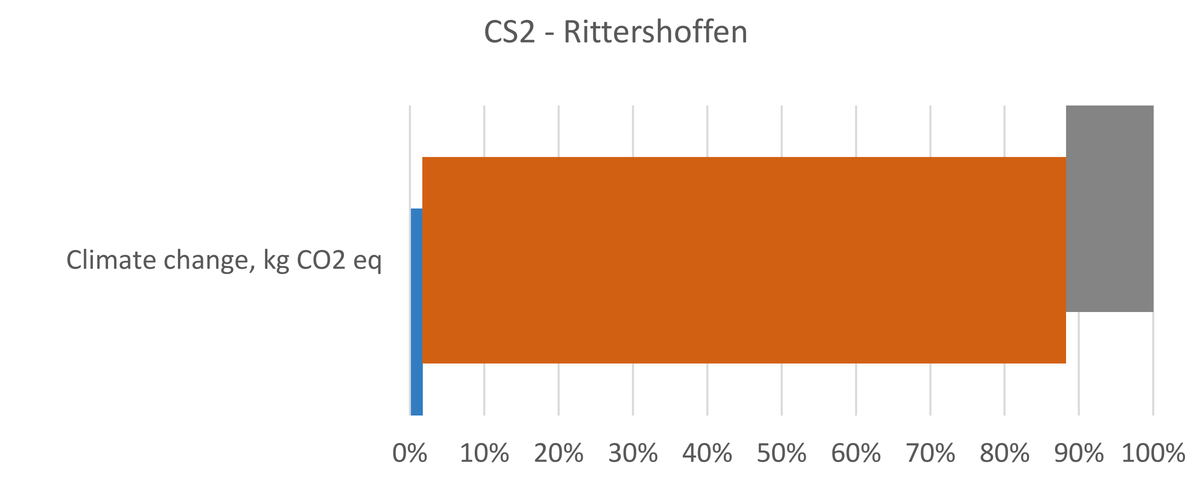
Within this phase, the impact is dominated by the internal electricity (i.e. French national mix) consumption that account for 87% of the impact on CC (see Figure 4). The second contribution is represented by the Commissioning phase that covers almost the entire remaining part of the impact on CC category (i.e. 44 % of the total impact on CC). In this phase, the process that has a significant influence on the impact is the drilling (about 55% of the commissioning phase, see Figure 3). As expected, most of the impact from the drilling activity is linked to the direct emissions of CO_2 due to diesel combustion for operating the drilling rigs. Concerning the powerplant construction the main influence on the impacts is due to the construction of the heat exchanger (i.e. 10 % of the commissioning phase) and the production pumps (13% of the commissioning). In this case the indirect emissions of CO_2 from background production processes are responsible for most of the impact of these two processes.

The end of life phase does not contribute significantly to the impact on CC (about 1 %).



	Climate change, kg CO2 eq
Power plant - Air cooler	8.26E-06
Power plant - Building	9.91E-05
Power plant - Filters	4.91E-07
Power plant - Heat exchanger	2.11E-04
Power plant - Injection pumps	4.00E-05
Power plant - Pipes	2.43E-05
Power plant - Production pumps	2.75E-04
Power plant - Valves	1.21E-05
Well drilling - Chemical stimulation	3.05E-06
Well drilling - Hydraulic stimulation	8.44E-07
Well drilling - Deep well drilling	1.17E-03
Well drilling - Drilling platform	2.67E-04

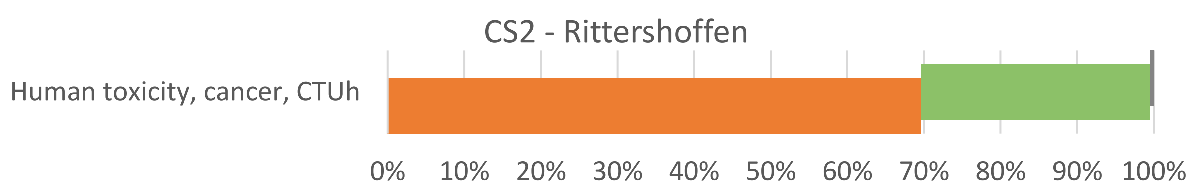
Figure 3 Contribution of processes to the total impact of the commissioning phase.



	Climate change, kg CO2 eq
Operation and Maintenance - Anti corrosion agent -	4.62E-05
Operation and Maintenance - Electricity -	2.34E-03
Operation and Maintenance - Others	3.17E-04

Figure 4 Contribution of processes on the total impact of the operation and maintenance phase.

Human Toxicity, cancer effects (HTC)



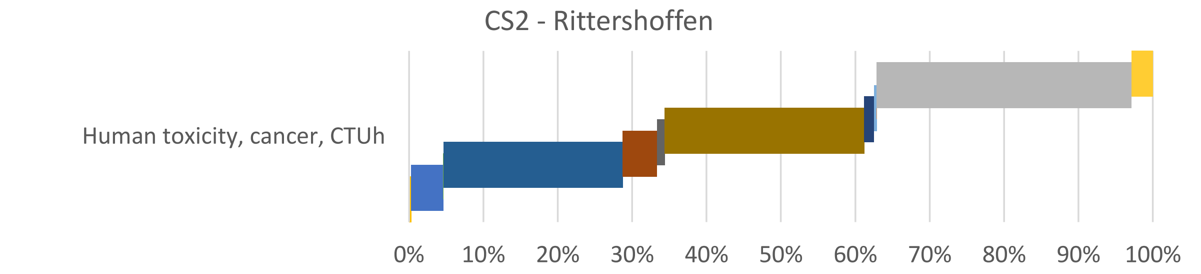
	Human toxicity, cancer, CTUh
Construction	7.22E-13
Operation and Maintenance	3.10E-13
End of Life	4.66E-15

Figure 5 Contribution of the three main phases on the total impact on the Human Toxicity, cancer effects (HTC) category.

Figure 5 shows the contribution of the main phases to the total impact of the Life Cycle (LC) of CS2 on the HTC category (1,02E-12 CTUh[2]/FU). The commissioning phase has the largest contribution (i.e. 70 %) to the total impact on HTC category. Within this phase (see Figure 6), about 62% of its impact is due to powerplant construction, and more specifically by the processes of heat exchanger (i.e. 24% of the total impact from commissioning phase) and production pump construction (i.e. 27% of the total impact from commissioning phase). In both processes, the substances that contribute the most to the impact are indirect (background) emissions of Nickel to air, followed by emissions of chromium to freshwater and chromium to air and are linked to the steel requirements. The remaining impact of the commissioning phase is due to deep well drilling activity (i.e. 34% of commissioning phase, see Figure 6).

The second contribution to the total impact on HTC is represented by the operation and maintenance phase with a share of 30%. Internal electricity consumption determines the 75% of the impact of this phase.

[2] The comparative toxic unit for human toxicity impacts (CTUh) expresses the estimated increase in morbidity (the number of disease cases) in the total human population per unit of mass of the chemical emitted.



	Human toxicity, cancer, CTUh
Power plant - Air cooler	2.21E-15
Power plant - Building	3.10E-14
Power plant - Filters	1.29E-16
Power plant - Heat exchanger	1.74E-13
Power plant - Injection pumps	3.33E-14
Power plant - Pipes	7.41E-15
Power plant - Production pumps	1.94E-13
Power plant - Valves	9.21E-15
Well drilling - Chemical stimulation	2.74E-15
Well drilling - Hydraulic stimulation	1.52E-16
Well drilling - Deep well drilling	2.47E-13
Well drilling - Drilling platform	2.07E-14

Figure 6 Contribution of processes to the total impact of the commissioning phase on the Human Toxicity, cancer effects (HTC) category.

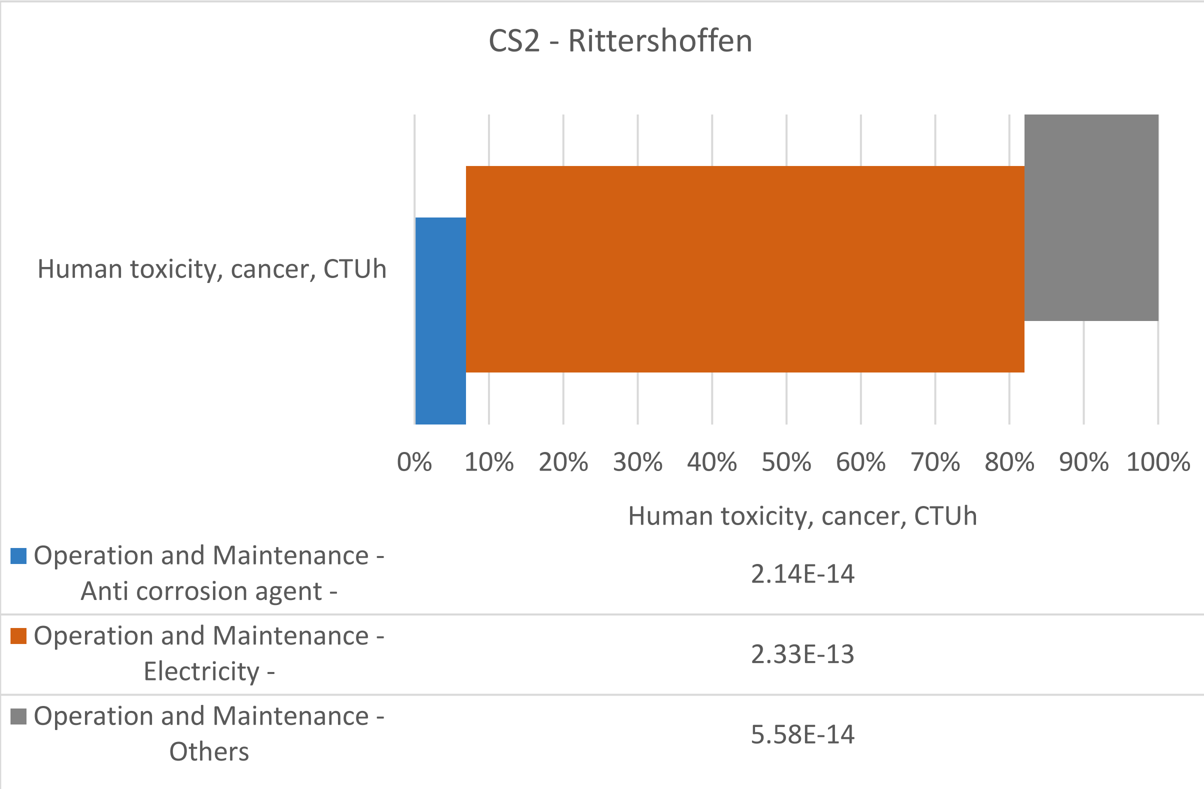


Figure 7 Contribution of processes on the total impact of the operation and maintenance phase on the Human Toxicity, cancer effects (HTC) category.

Human Toxicity, non-cancer effects (HTN)

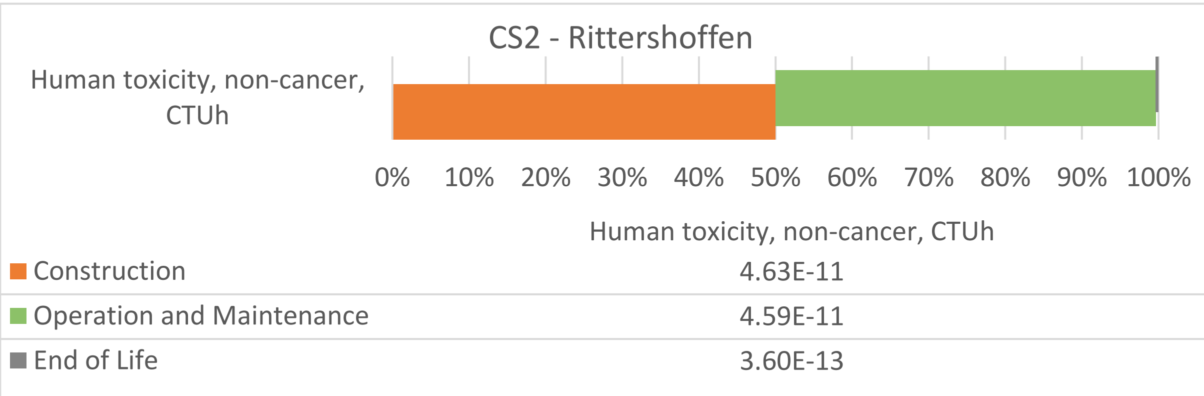
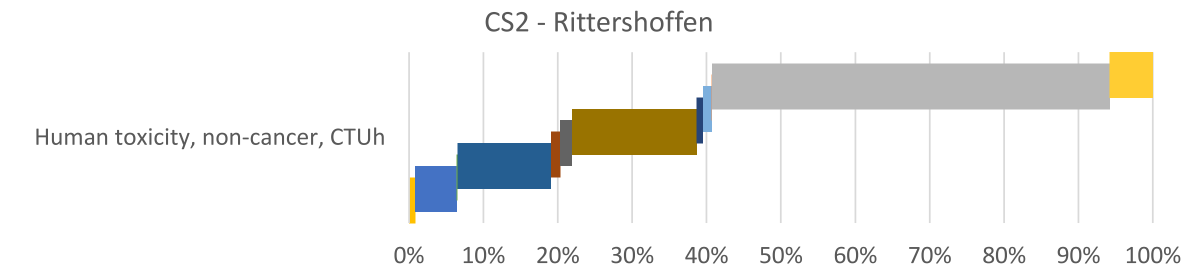


Figure 8 Contribution of the three main phases on the total impact on the Human Toxicity, non-cancer effects (HTN) category.

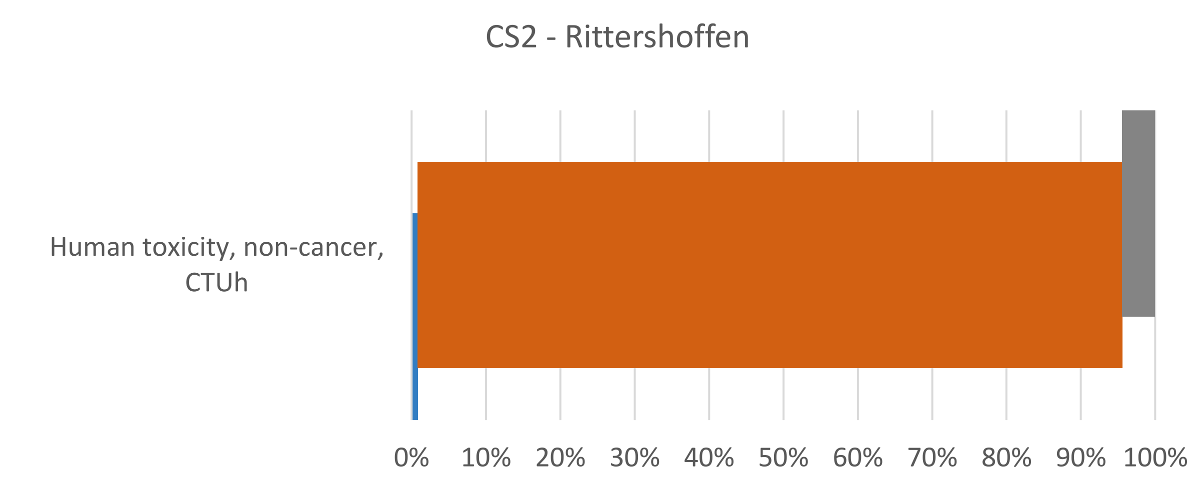
Figure 8 shows the contribution of the main phases to the total impact of the Life Cycle (LC) of CS2 on the HTN category (9,22E-11CTUh/FU). The impact on HTN is equally shared between the commissioning and operation and maintenance phases. As observed for the HTC category, also in the case of HTN the impact on the commissioning phase is determined by the deep well drilling activity (i.e. 53% of the impact from commissioning) and heat exchanger (i.e. 13%) and production pumps construction (17%) as shown in Figure 9. The major contribution to HTN impact is due to lead (Pb) and carbon monoxide indirect emission to air during the mentioned processes.

Concerning the operation and maintenance phase (see Figure 10), the internal electricity consumption determines 95% of the impact of this phase. In detail, the responsible for such impact is the emission of chlorine to freshwater during electricity generation background process.



	Human toxicity, non-cancer, CTUh
Power plant - Air cooler	3.76E-13
Power plant - Building	2.61E-12
Power plant - Filters	2.25E-14
Power plant - Heat exchanger	5.82E-12
Power plant - Injection pumps	5.80E-13
Power plant - Pipes	7.32E-13
Power plant - Production pumps	7.75E-12
Power plant - Valves	3.95E-13
Well drilling - Chemical stimulation	5.41E-13
Well drilling - Hydraulic stimulation	1.08E-14
Well drilling - Deep well drilling	2.47E-11
Well drilling - Drilling platform	2.68E-12

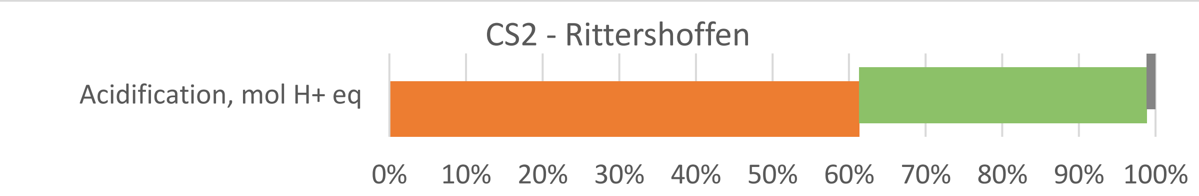
Figure 9 Contribution of processes to the total impact of the commissioning phase on the Human Toxicity, non-cancer effects (HTN) category.



	Human toxicity, non-cancer, CTUh
Operation and Maintenance - Anti corrosion agent -	3.81E-13
Operation and Maintenance - Electricity -	4.35E-11
Operation and Maintenance - Others	2.03E-12

Figure 10 Contribution of processes on the total impact of the operation and maintenance phase on the Human Toxicity, non-cancer effects (HTN) category.

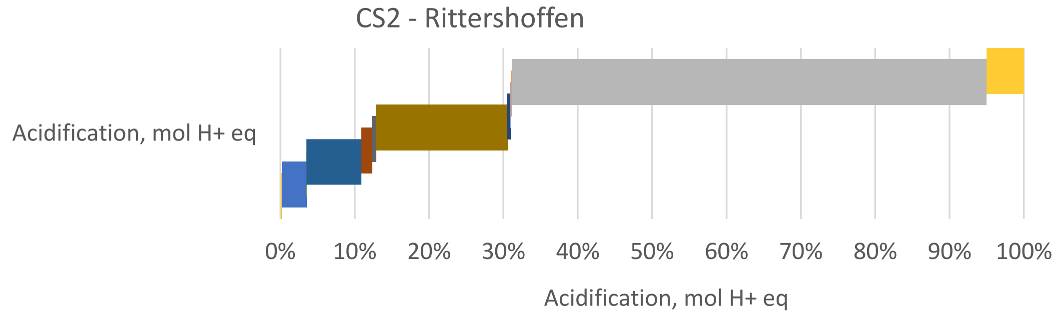
Acidification (AC)



	Acidification, mol H+ eq
Construction	1.45E-05
Operation and Maintenance	8.86E-06
End of Life	2.61E-07

Figure 11 Contribution of the three main phases on the total impact on the Acidification (AC) category.

Figure 11 reports the impacts of main phases to the AC category. The observed pattern is similar to the already described CC, HTC and HTN categories with slightly different contribution percentages. Deep well drilling, production pumps and heat exchanger construction play the major role in determining the impact from the commissioning phase (see Figure 12). Operation and maintenance phase are dominated by electricity requirements as shown in Figure 13. Direct emissions of sulphur and nitrogen dioxides to air from diesel combustion are the two substances that contribute the most to the impact on AC category.



	Acidification, mol H+ eq
Power plant - Air cooler	2.56E-08
Power plant - Building	4.79E-07
Power plant - Filters	1.51E-09
Power plant - Heat exchanger	1.06E-06
Power plant - Injection pumps	2.06E-07
Power plant - Pipes	8.08E-08
Power plant - Production pumps	2.55E-06
Power plant - Valves	5.82E-08
Well drilling - Chemical stimulation	1.78E-08
Well drilling - Hydraulic stimulation	9.63E-09
Well drilling - Deep well drilling	9.20E-06
Well drilling - Drilling platform	7.25E-07

Figure 12 Contribution of processes to the total impact of the commissioning phase on the Acidification (AC) category.

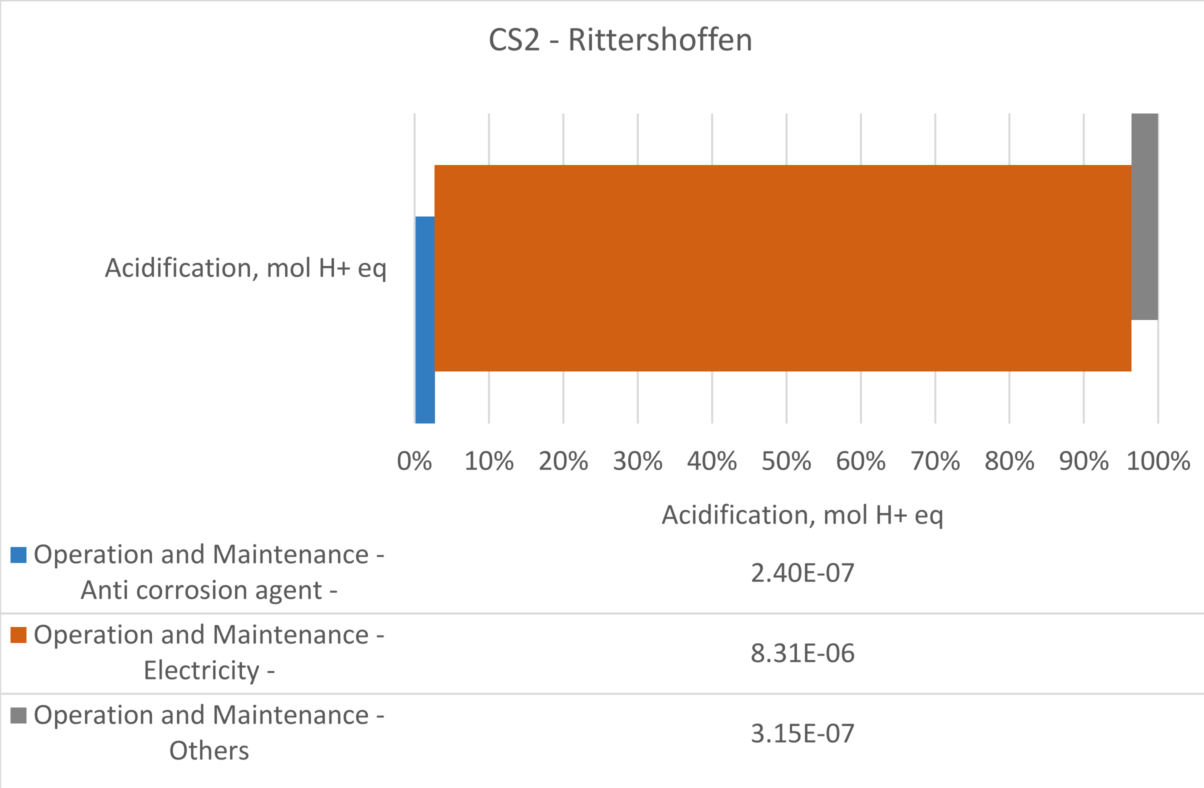


Figure 13 Contribution of processes on the total impact of the operation and maintenance phase on the Acidification (AC) category.

Ecotoxicity freshwater (Eto)

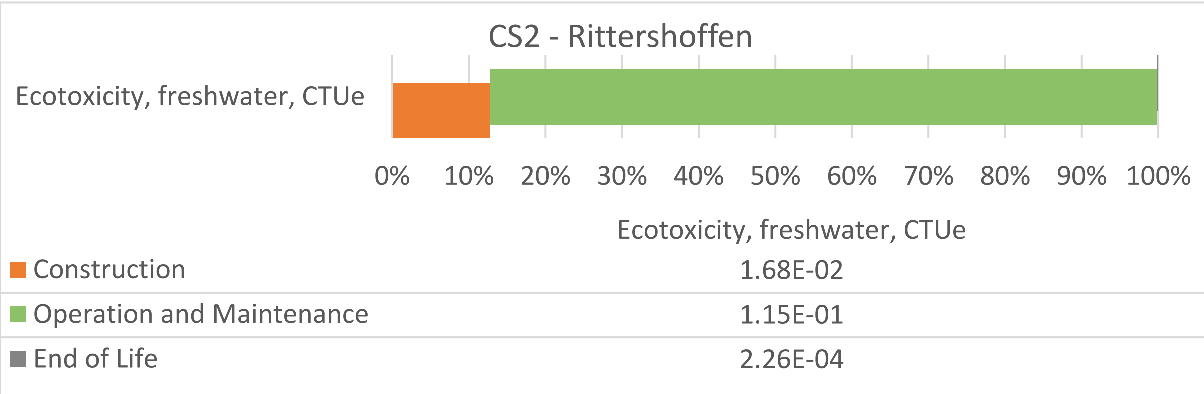
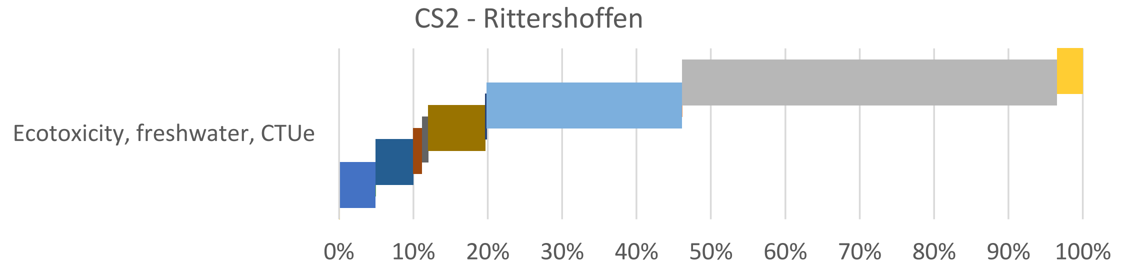


Figure 14 Contribution of the three main phases on the total impact on the Ecotoxicity, freshwater (Eto) category.

Figure 14 reports the contribution of the three main life cycle phases on the Eto category. Among the categories with high priority, Eto shows a slightly different behaviour. Operation and maintenance phase determine 87% of the total impact in this category. The impact of operation and maintenance phase on the Eto category is dominated (90%) by the electricity consumption (French mix) (see Figure 16).

Within the commissioning phase, the chemical stimulation activity plays an important role in determining the impact (i.e. 26 %) together with the deep well drilling (i.e. 50%) as already observed for all the other categories analysed so far. The impact from chemical stimulation is determined by indirect sulphur emission to fresh water.



	Ecotoxicity, freshwater, CTUe
Power plant - Air cooler	1.89E-05
Power plant - Building	8.06E-04
Power plant - Filters	9.66E-07
Power plant - Heat exchanger	8.46E-04
Power plant - Injection pumps	2.02E-04
Power plant - Pipes	1.38E-04
Power plant - Production pumps	1.29E-03
Power plant - Valves	4.01E-05
Well drilling - Chemical stimulation	4.40E-03
Well drilling - Hydraulic stimulation	8.23E-06
Well drilling - Deep well drilling	8.46E-03
Well drilling - Drilling platform	5.78E-04

Figure 15 Contribution of processes to the total impact of the commissioning phase on the Ecotoxicity, freshwater (Eto) category.

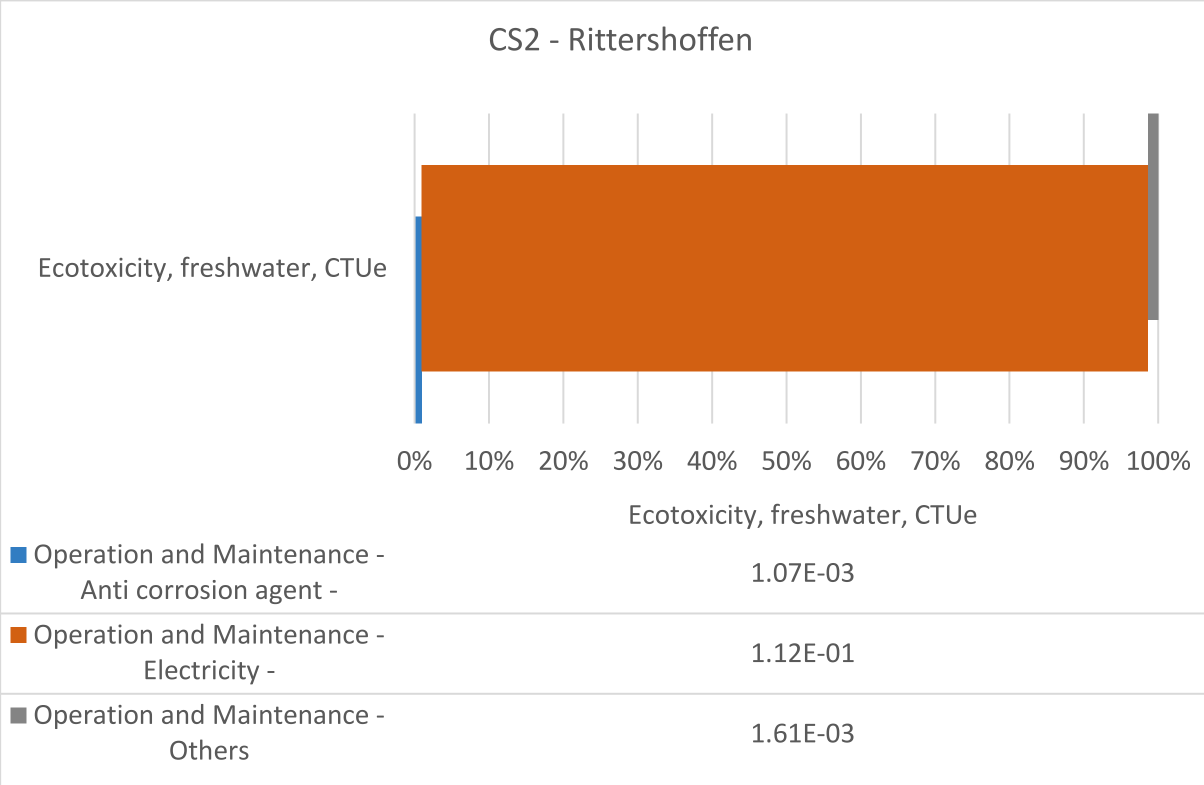


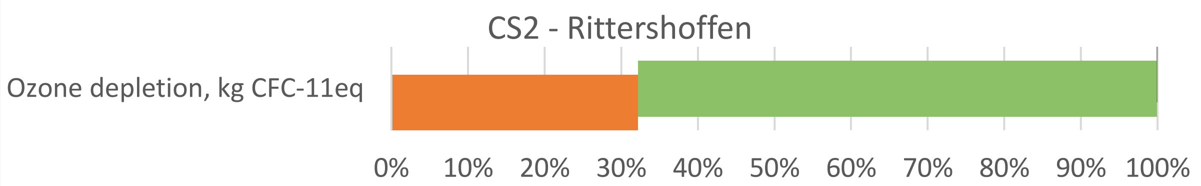
Figure 16 Contribution of processes on the total impact of the operation and maintenance phase on the Ecotoxicity, freshwater (ETo) category.

Impact categories with a moderate priority

The potential impacts on Ionising radiation, human health (IR) and Land Use (Lnd) impact categories are dominated by the operation and maintenance phase. On the contrary, the potential impact on Particulate matter (PM) category is mainly due to the commissioning phase.

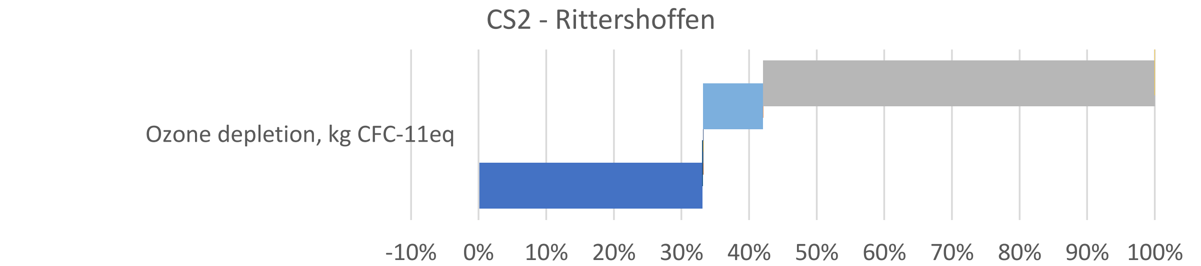
The impact categories featuring a moderate priority show a similar trend to the one observed for high priority categories in terms of contribution of processes to the impact of phases. A noticeable difference is observed for the impacts of the commissioning phase on the IR categories which are determined by the power plant building infrastructure for a 33% and 27%, respectively (see Figure 18 and Figure 24).

Ozone depletion potential (ODP)



	Ozone depletion, kg CFC-11eq
Construction	9.88E-12
Operation and Maintenance	2.08E-11
End of Life	2.77E-14

Figure 17 Contribution of the three main phases on the total impact on the ODP category.



	Ozone depletion, kg CFC-11eq
Power plant - Air cooler	-2.37E-17
Power plant - Building	3.27E-12
Power plant - Filters	-1.43E-18
Power plant - Heat exchanger	5.36E-15
Power plant - Injection pumps	4.16E-15
Power plant - Pipes	2.45E-15
Power plant - Production pumps	5.02E-16
Power plant - Valves	1.21E-17
Well drilling - Chemical stimulation	8.71E-13
Well drilling - Hydraulic stimulation	3.14E-18
Well drilling - Deep well drilling	5.72E-12
Well drilling - Drilling platform	9.31E-16

Figure 18 Contribution of processes to the total impact of the commissioning phase on the ODP category.

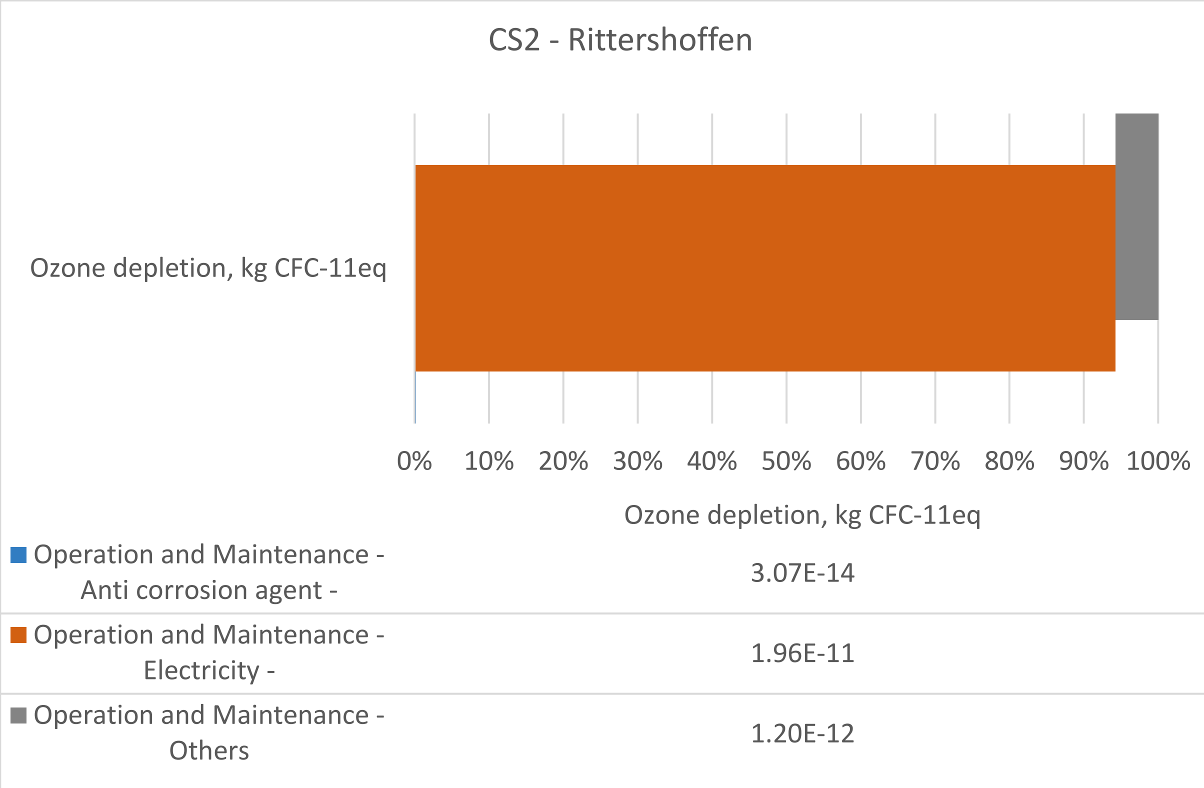


Figure 19 Contribution of processes on the total impact of the operation and maintenance phase on the ODP.

Particulate matter (PM)

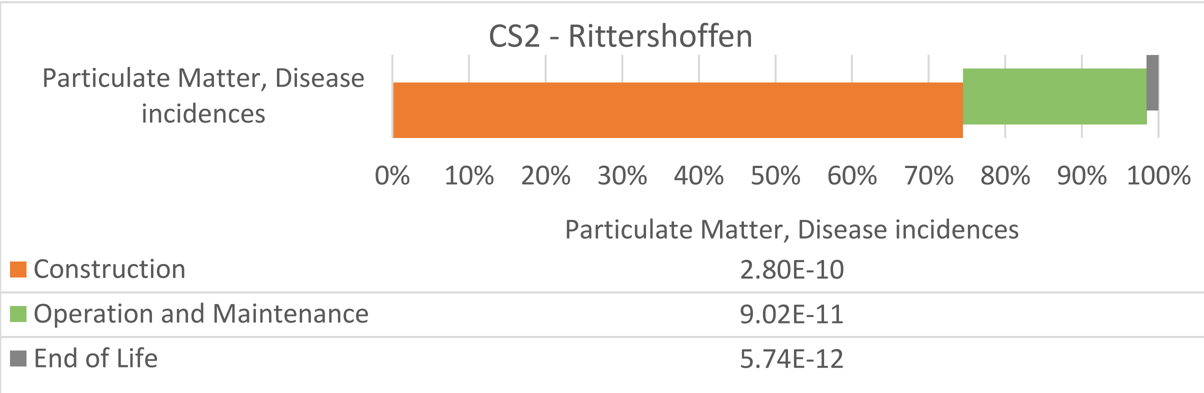
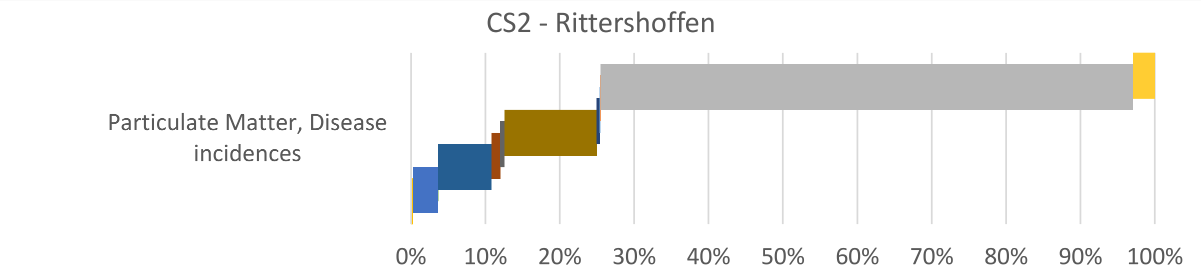
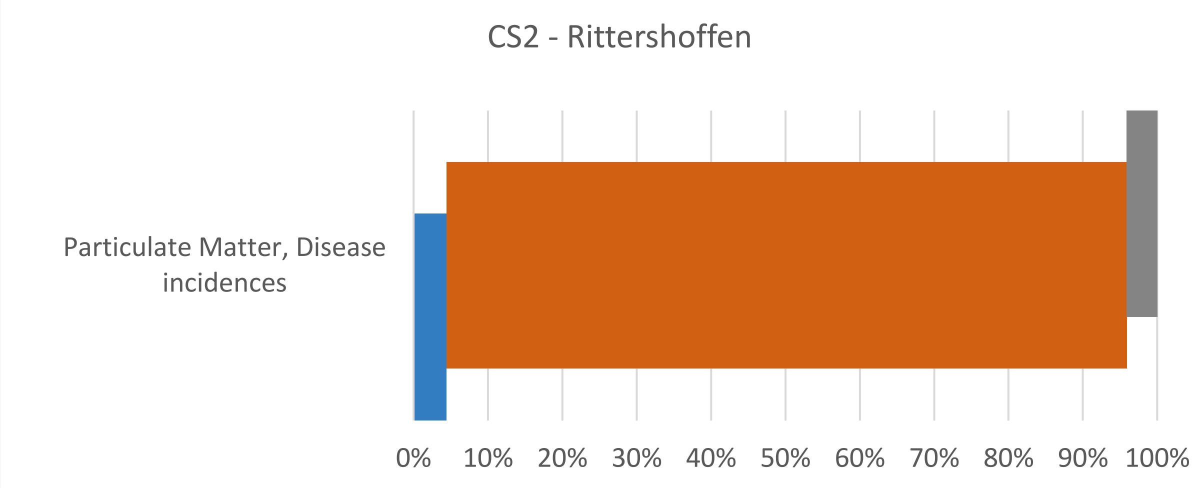


Figure 20 Contribution of the three main phases on the total impact on the PM category.



	Particulate Matter, Disease incidences
Power plant - Air cooler	7.18E-13
Power plant - Building	9.40E-12
Power plant - Filters	4.28E-14
Power plant - Heat exchanger	2.01E-11
Power plant - Injection pumps	3.24E-12
Power plant - Pipes	1.61E-12
Power plant - Production pumps	3.45E-11
Power plant - Valves	1.20E-12
Well drilling - Chemical stimulation	2.09E-13
Well drilling - Hydraulic stimulation	2.19E-13
Well drilling - Deep well drilling	2.00E-10
Well drilling - Drilling platform	8.23E-12

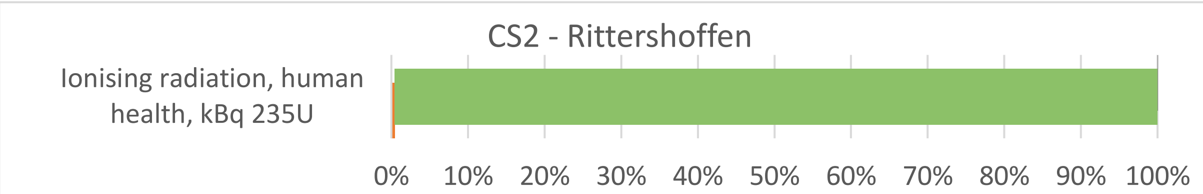
Figure 21 Contribution of processes to the total impact of the commissioning phase on the PM category.



	Particulate Matter, Disease incidences
Operation and Maintenance - Anti corrosion agent -	3.98E-12
Operation and Maintenance - Electricity -	8.25E-11
Operation and Maintenance - Others	3.72E-12

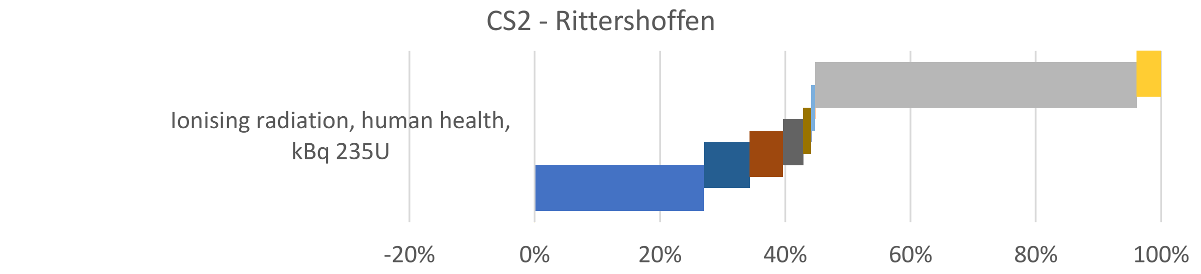
Figure 22 Contribution of processes on the total impact of the operation and maintenance phase on PM category.

Ionising radiation, human health (IR)



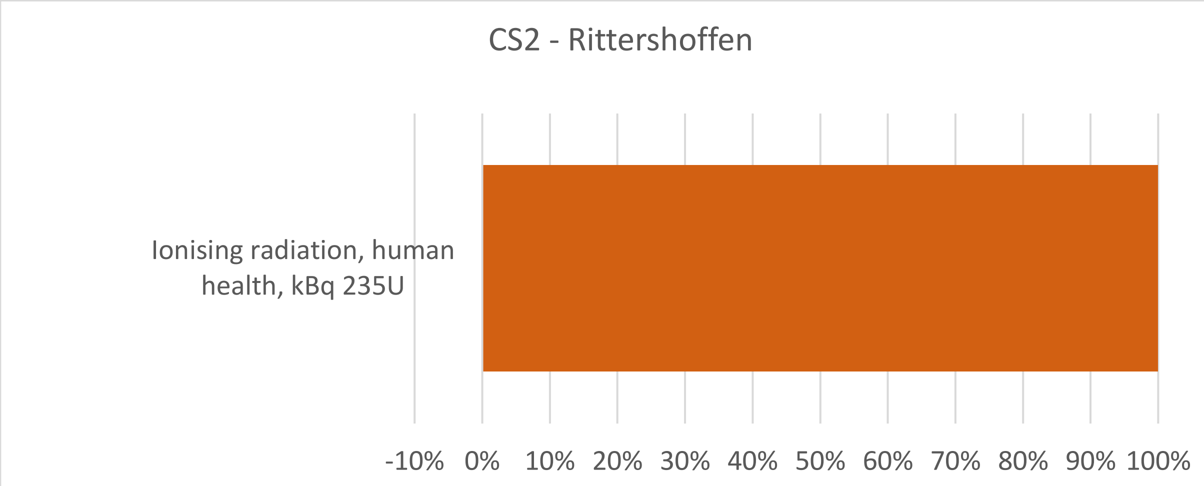
	Ionising radiation, human health, kBq 235U
Construction	8.15E-05
Operation and Maintenance	1.83E-02
End of Life	2.33E-07

Figure 23 Contribution of the three main phases on the total impact on the IR category.



	Ionising radiation, human health, kBq 235U
Power plant - Air cooler	-8.58E-11
Power plant - Building	2.20E-05
Power plant - Filters	-3.84E-10
Power plant - Heat exchanger	5.96E-06
Power plant - Injection pumps	4.32E-06
Power plant - Pipes	2.66E-06
Power plant - Production pumps	9.99E-07
Power plant - Valves	3.77E-08
Well drilling - Chemical stimulation	4.99E-07
Well drilling - Hydraulic stimulation	3.55E-09
Well drilling - Deep well drilling	4.19E-05
Well drilling - Drilling platform	3.15E-06

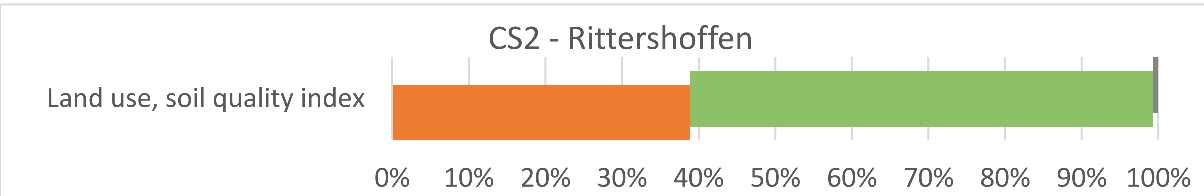
Figure 24 Contribution of processes to the total impact of the commissioning phase on IR category.



	Ionising radiation, human health, kBq 235U
Operation and Maintenance - Anti corrosion agent -	3.76E-06
Operation and Maintenance - Electricity -	1.83E-02
Operation and Maintenance - Others	-5.65E-06

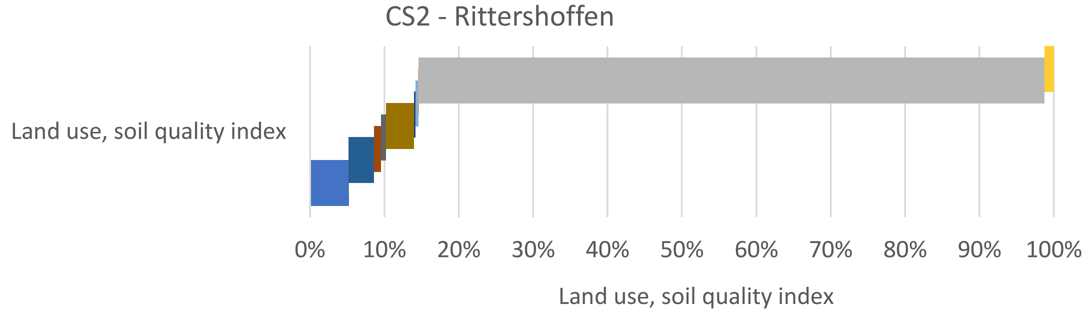
Figure 25 Contribution of processes to the total impact of the commissioning phase on the IR category.

Land use (Lnd)



	Land use, soil quality index
Construction	5.27E-03
Operation and Maintenance	8.18E-03
End of Life	9.37E-05

Figure 26 Contribution of the three main phases on the total impact on the Lnd, soil quality index category.



	Land use, soil quality index
Power plant - Air cooler	6.47E-06
Power plant - Building	2.67E-04
Power plant - Filters	3.59E-07
Power plant - Heat exchanger	1.79E-04
Power plant - Injection pumps	4.91E-05
Power plant - Pipes	3.58E-05
Power plant - Production pumps	1.96E-04
Power plant - Valves	8.85E-06
Well drilling - Chemical stimulation	1.97E-05
Well drilling - Hydraulic stimulation	3.39E-06
Well drilling - Deep well drilling	4.42E-03
Well drilling - Drilling platform	6.73E-05

Figure 27 Contribution of processes to the total impact of the commissioning phase on the Lnd, soil quality index category.

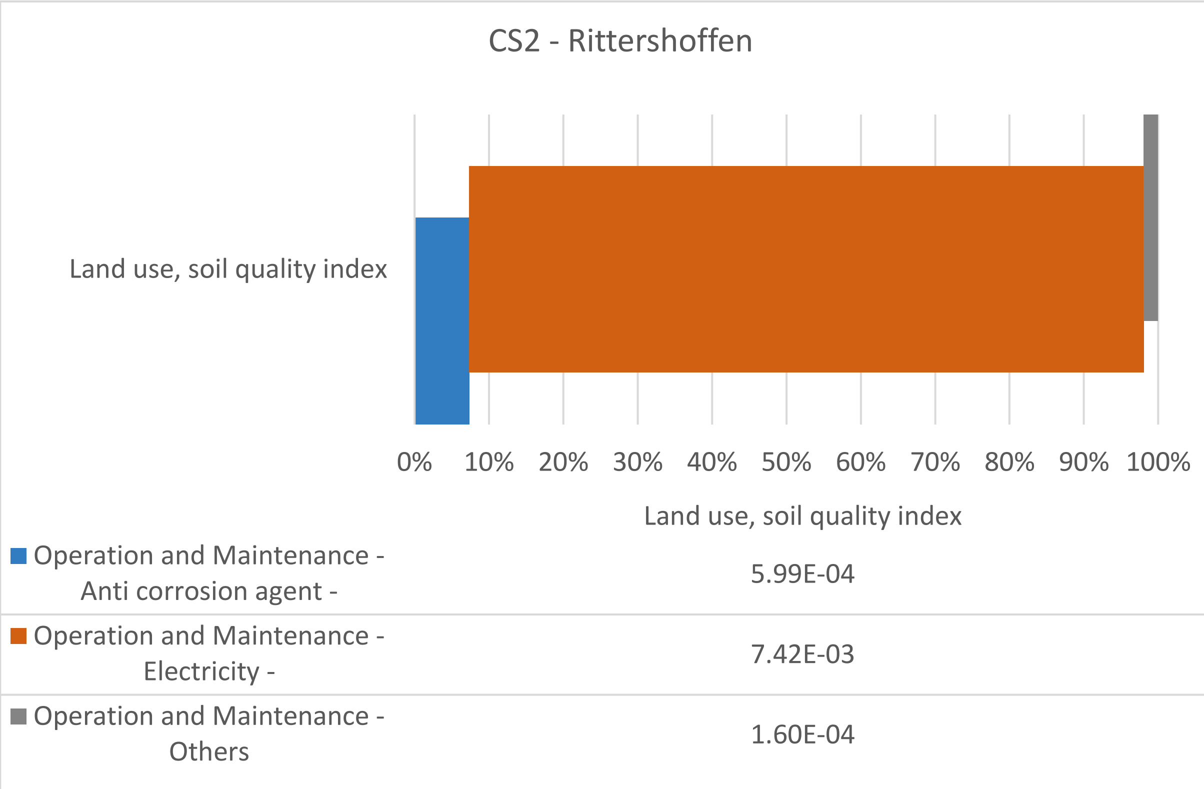


Figure 28 Contribution of processes on the total impact of the operation and maintenance phase on the Lnd, soil quality index category.

Characterized results in EF3 for all other case studies

This Section reports the most important outcomes from a methodological point of view that have been found when applying the LCA guidelines to the complete set of case studies. Table 18 reports the characterized result in EF3 per functional unit (1 kWh electricity or heat produced in 30 years) of the selected case studies.

The selected case studies represent different settings in terms of energy conversion technology, environmental conditions, geothermal source, plant size and operation conditions, and, therefore, their environmental performances must be interpreted related to the specific context and no comparative purpose of the presented result should be considered. This restriction is due not only to the different setting but also to different data availability and quality for the selected power plants. In fact, some inventory data is estimated since no real data has been measured yet due to the nature of the installation (i.e. pilot plant and/or future project plant). In other cases, some inventory data (i.e. emissions to air) is not measured for the same set of compounds since not included in the corresponding national regulation. This situation applies, in particular, to the Italian plant of Bagnore (CS1) that is the only case study which accounts for Mercury emission to air, since national regulation are very strict regarding air emissions. Moreover, particular attention should be dedicated to the impact on (eco)-toxicity categories (Eto, HTC and HTN) since these are characterized by a low level of reliability (level of recommendation 3 in Table 3). In fact, emissions of metals dominate the human toxicity categories for all case studies due to indirect emissions from background processes and direct emissions (i.e. Bagnore) as well.

Another important observation is related to the impact of H_2S emissions on the ecotoxicity freshwater category. The EF3 impact assessment method has now a characterization factor for H_2S emission to air. As a result, for those case studies that account for direct emission of H_2S (CS1, CS3 and CS6), this emission dominates the impact on Ecotoxicity freshwater category. The potential toxic impact from an LCA analysis must never be associated to any real human and/or environmental effect. Considering these findings, the Section "Reporting Inorganic emissions with toxicity impacts" of the LCA guideline (i.e. D 3.2) is of particular relevance.

An allocation issue was found for the CS3 (Hellisheiði). According to the guidelines the allocation of impacts between electricity and heat production should have followed a system expansion and substitution approach. In short, the system expansion approach consists in including in the system the heat production as an "avoided burden". The production of heat from geothermal exploitation should substitute the "traditional" process of heat production (e. g. from natural gas or oil combustion). However, most of heat production in Iceland is from geothermal source, more in detail it accounts for almost 90% of total heat required for space heating in 2019 (Orkustofnun 2020). Therefore, no representative heat production process could be employed to function as a substitute for the heat produced by CS3. Consequently, the allocation procedure adopted was based on the exergy content.

Table 18 EF3 results for al the case studies toghter with recommendation level suggested by JRC

Impact Category	Recommendation level	Unit	CS1	CS2	CS3	CS4	CS5	CS6
CC	I	kg CO_2 eq	1.0E+00	4.8E-03	2.6E-02	5.1E-02	2.0E-02	3.0E-01
HTC	III	CTUh	1.7E-10	1.0E-12	7.0E-13	6.9E-12	2.6E-11	1.8E-12
CTN	III	CTUh	2.0E-08	9.2E-11	7.4E-11	9.1E-10	1.8E-10	2.1E-10
AC	II	mol H^+ eq	2.0E-03	2.4E-05	1.1E-05	1.1E-04	1.6E-04	6.5E-05
Eto	III	CTUe	1.5E+02	1.3E-01	2.6E+01	2.2E-01	2.3E-01	3.6E+02
ODP	I	kg CFC-11eq	6.8E-11	2.4E-11	1.8E-11	1.6E-11	7.9E-10	1.4E-11
PM	I	Disease incidences	3.3E-07	3.7E-10	2.6E-10	2.1E-09	2.5E-09	1.9E-09
IR	II	kBq ^{235}U	2.2E-04	1.8E-02	2.2E-05	5.5E-03	4.8E-04	4.5E-05
Lnd	III	soil quality index	1.4E-02	1.3E-02	3.0E-03	7.7E-02	3.4E-02	2.0E-02
POz	II	kg NMVOC eq	1.9E-04	2.2E-05	1.1E-05	1.1E-04	9.7E-05	1.1E-04
Eum	II	kg N eq	1.5E-03	7.5E-06	3.7E-06	3.7E-05	3.3E-05	2.9E-05
EUf	II	kg P eq	3.1E-07	3.2E-08	7.2E-09	2.1E-06	1.4E-06	2.7E-08

EUt	II	mol N eq	1.3E-01	7.9E-05	4.2E-05	3.6E-04	3.8E-04	3.2E-04
REn	III	MJ	8.6E-02	2.5E-01	1.7E-02	3.9E-01	2.2E-01	6.1E-02
RMi	III	kg Sb eq	1.5E-07	4.2E-08	4.5E-08	4.4E-07	6.3E-07	8.8E-08
Wat	III	m^3 water eq. deprived	2.3E-01	3.3E-03	1.7E-02	2.2E-03	2.1E-01	5.9E-02

Conclusions

The presented work aimed at applying the LCA guidelines developed within the GEOENVI project to a set of case studies with the objectives of testing their applicability, checking the suitability of the EF3 (database and impact assessment method) when it comes to modelling of geothermal energy systems and eventually highlighting potential improvements of the proposed methodological tool.

The following conclusions can be drawn:

1) Applicability of the developed LCA guidelines:
    a. The level of detail of LCIs was found to be different for the selected case studies even though the data gathering campaign was based on the same template. Besides the obvious differences linked to the conversion technology adopted to exploit the geothermal energy, some other differences were observed and associated to the nature of the case study (i.e. real operating plant against a pilot or project plant) and the country-specific regulations in terms of emission reporting. As a result, the quality and reliability of the data varies between the case studies (i.e. measured – primary - vs estimated - average). Different national legislations lead to different list of emissions that must be monitored and documented, and consequently, to different availability of data. For instance, direct Mercury emissions were inserted as an LCI input only for one case study (CS1).
    b. The preferred allocation procedure suggested in the LCA guidelines was found to be not applicable to the Icelandic Hellisheiði power plant (CS3). This was linked to the unavailability of a suitable representative process to work as a substitute for heat production (in Iceland "average" heat production is from geothermal).
2) Suitability of the EF3 (database and impact assessment method):
    a. The EF impact assessment method showed some advantages and some drawbacks. The EF database was found to be less populated than other commercial databases (e.g. Ecoinvent, Gabi, etc.). The production processes of some materials were missing or had to be replaced by a proxy which was available in the EF database (i.e. *Glass wool, production mix, at plant, fleece, density between 10 to 100 kg/m3* was used as proxy for *stone wool production, packed* available in Ecoinvent database).

b. The EF 3 method is not yet implemented in available commercial LCA software and a conversion procedure was therefore needed to obtain results as suggested in the LCA guidelines (i.e. EF3 impact assessment method). Converting results from EF2 to EF3 it is, at present conditions, a time consuming and error prone procedure. Furthermore, the level of detail that the user can achieve is limited since the impact evaluation tool developed by the JRC works only with system process[3].
c. The EF2 database is consistent and transparent. The results can be easily reproduced and checked for potential modelling mistakes thanks to a functionality built in look@LCI.
d. The EF3 impact assessment method relies on the most advanced impact assessment methods upon which the scientific community has reached a unanimous consensus. Even though it is currently challenging to employ the EF3 impact assessment method, this should be still suggested as the LCIA method since its implementation in commercial software is foreseen in the early future. For the time being, the suggestion is working with the EF2 impact assessment method (or equivalent versions depending on the LCA software nomenclature). It is still valid that the EF impact assessment method is optimized for the use in conjunction with the EF database and the match between these two guarantees a high level of comparability of results.

3) Potential improvements of the LCA guidelines
   a. The LCA guidelines should be revised regarding how to deal with direct H_2S emissions. The current version of the EF3 impact assessment method has a characterization factor for H_2S emission and therefore, this should be entered as such and not as completely oxidized SO_2, as suggested in the first version of the LCA guideline document.
   b. The interpretation of the results also suggests paying extreme attention on how to report and discuss (eco)-toxic impact related categories. The results obtained in the present deliverable showed that the toxicity categories (i.e. high priority category in the LCA guidelines) are dominated by metal emissions. Even though the EF3 impact assessment method applies some “correction” to the

[3] A system process is a process constituted by a list of input-output elementary flows which result from the sum of all the processes along the supply chain.

characterization factors of metals emissions to account for the methods uncertainty, the results of such impact category must still be considered as affected by high uncertainty. Extreme caution should be taken when discussing toxic categories. Furthermore, the results from all impact categories should always be reported in a Table (as was shown here in Table 18). As already suggested in the LCA guidelines, priority should be assessed also based on the goal and scope of the LCA study. This means that the impact categories that are currently ranked as medium or low priority could be considered having a high priority (together with the already selected high priority impact categories) depending also on the study and geothermal context.

c. The impact categories results could be further weighted to ease the communication of LCA results. Such weighting is an optional step in the LCA framework and follows normalization, done using the normalisation set recommended in the chosen impact assessment method. The weighting could be tailored to reflect the uncertainty of the impact assessment method as well as the importance of the impact category within the geothermal sector. In addition, while LCA focuses on the potential environmental impacts of geothermal energy, the potential of geothermal energy to support achieving sustainability goals also requires including other considerations such as policy, cultural as well as other value choices.

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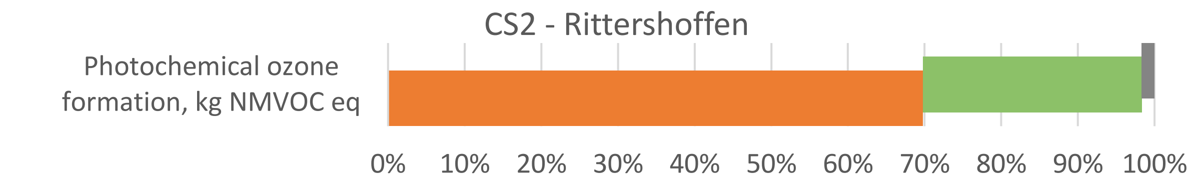
ANNEX I

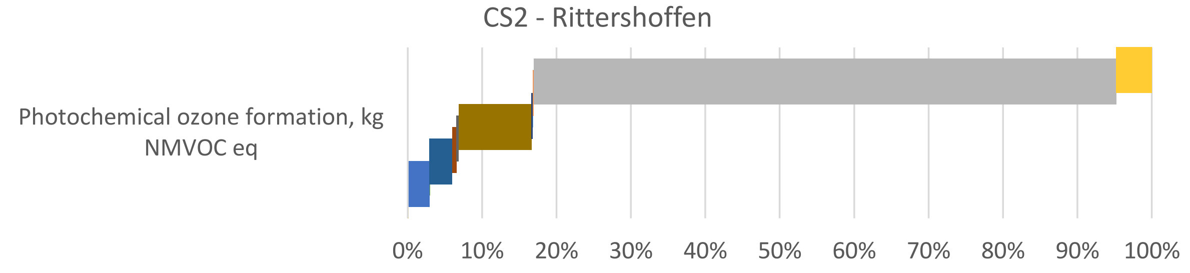
Impact categories with a low priority for CS2

Photochemical ozone formation



	Photochemical ozone formation, kg NMVOC eq
Construction	1.52E-05
Operation and Maintenance	6.20E-06
End of Life	3.66E-07

Figure 29 Contribution of the three main phases on the total impact on the Photochemical ozone formation category.



	Photochemical ozone formation, kg NMVOC eq
Power plant - Air cooler	1.55E-08
Power plant - Building	4.27E-07
Power plant - Filters	9.19E-10
Power plant - Heat exchanger	4.62E-07
Power plant - Injection pumps	8.44E-08
Power plant - Pipes	4.24E-08
Power plant - Production pumps	1.48E-06
Power plant - Valves	2.65E-08
Well drilling - Chemical stimulation	8.44E-09
Well drilling - Hydraulic stimulation	1.38E-08
Well drilling - Deep well drilling	1.18E-05
Well drilling - Drilling platform	7.27E-07

Figure 30 Contribution of processes to the total impact of the commissioning phase on the Photochemical ozone formation category.

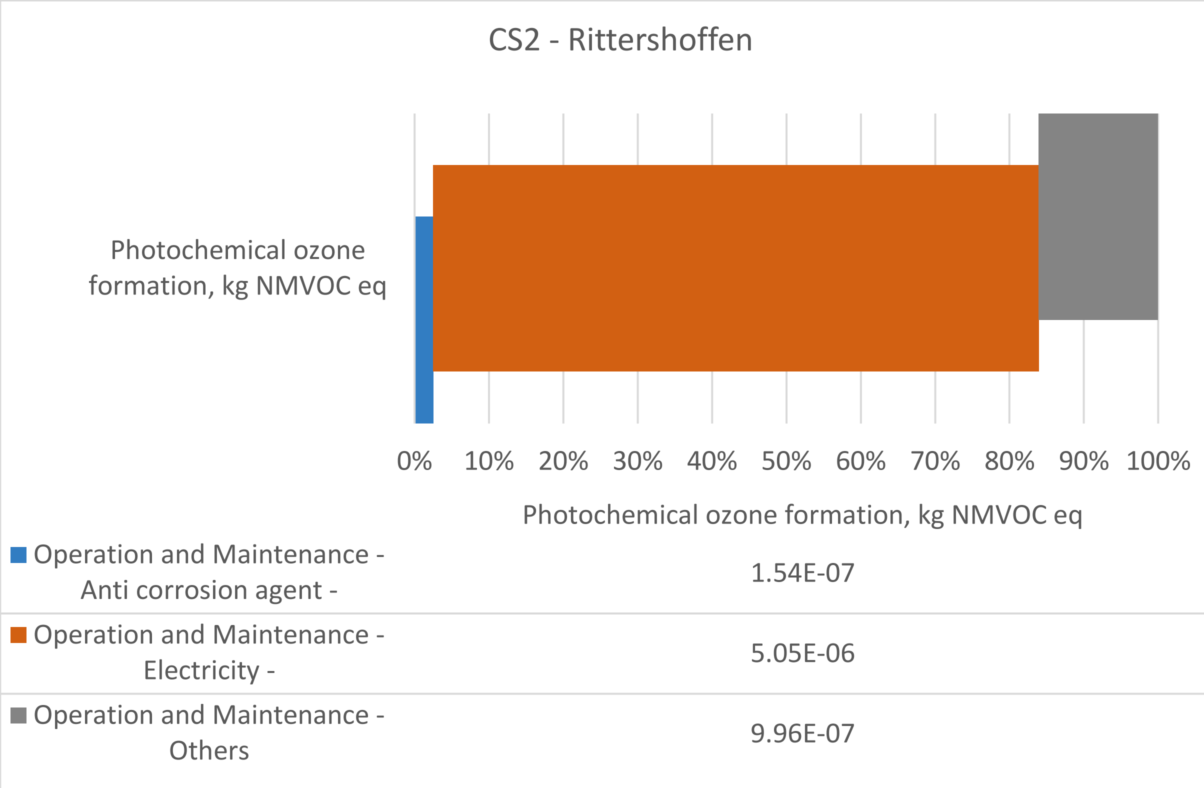


Figure 31 Contribution of processes on the total impact of the operation and maintenance phase on the Photochemical ozone formation category.

Eutrophication marine

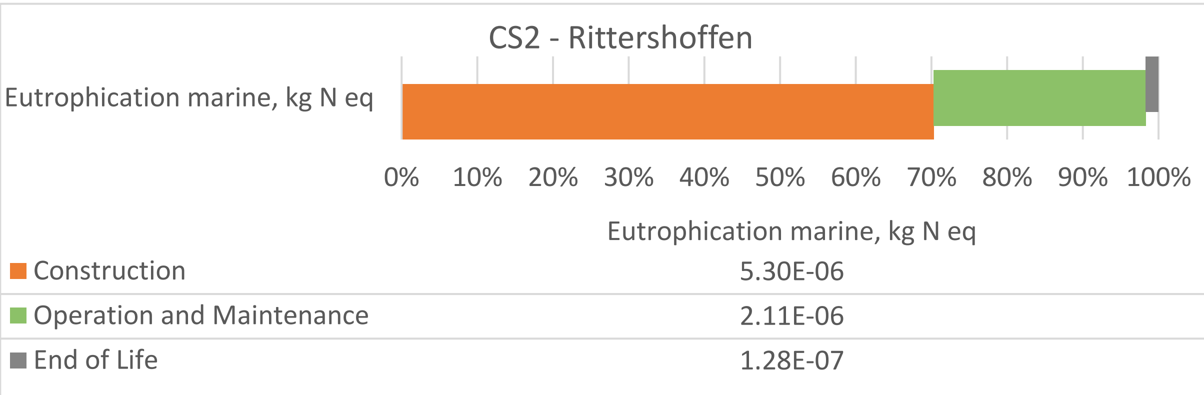
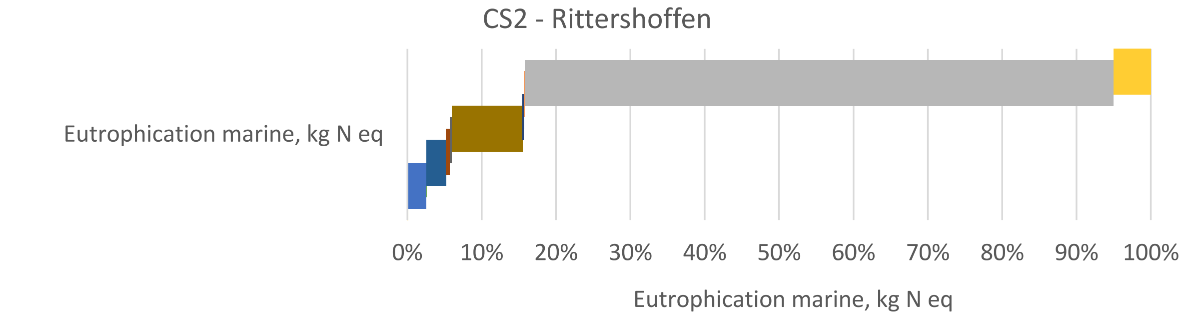
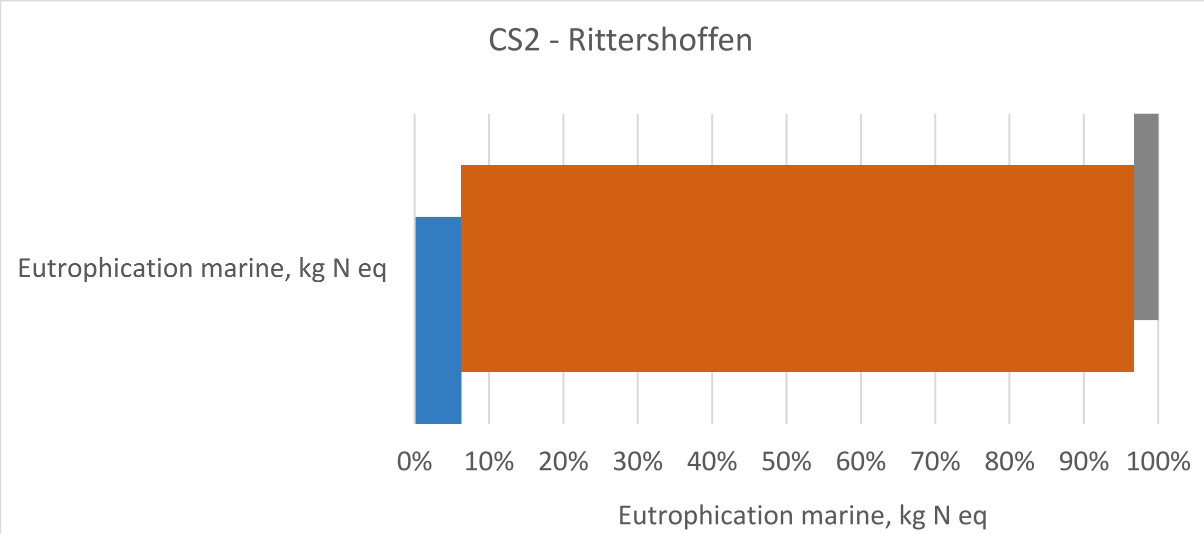


Figure 32 Contribution of the three main phases on the total impact on the Eutrophication marine category.



	Eutrophication marine, kg N eq
Power plant - Air cooler	4.46E-09
Power plant - Building	1.29E-07
Power plant - Filters	2.63E-10
Power plant - Heat exchanger	1.42E-07
Power plant - Injection pumps	2.71E-08
Power plant - Pipes	1.31E-08
Power plant - Production pumps	5.01E-07
Power plant - Valves	8.01E-09
Well drilling - Chemical stimulation	3.13E-09
Well drilling - Hydraulic stimulation	4.82E-09
Well drilling - Deep well drilling	4.17E-06
Well drilling - Drilling platform	2.65E-07

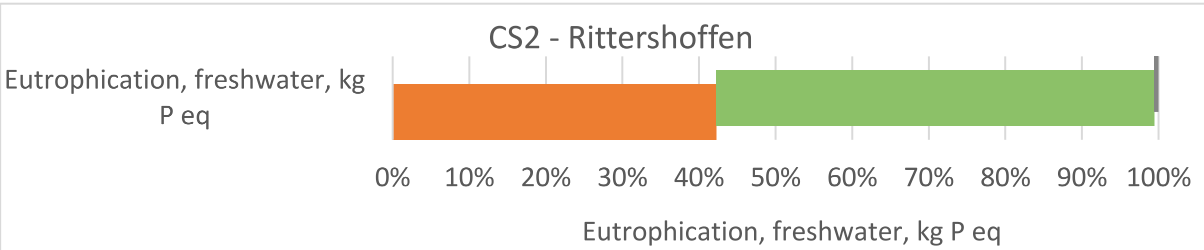
Figure 33 Contribution of processes to the total impact of the commissioning phase on the Eutrophication marine category.



	Eutrophication marine, kg N eq
Operation and Maintenance - Anti corrosion agent -	1.32E-07
Operation and Maintenance - Electricity -	1.91E-06
Operation and Maintenance - Others	6.88E-08

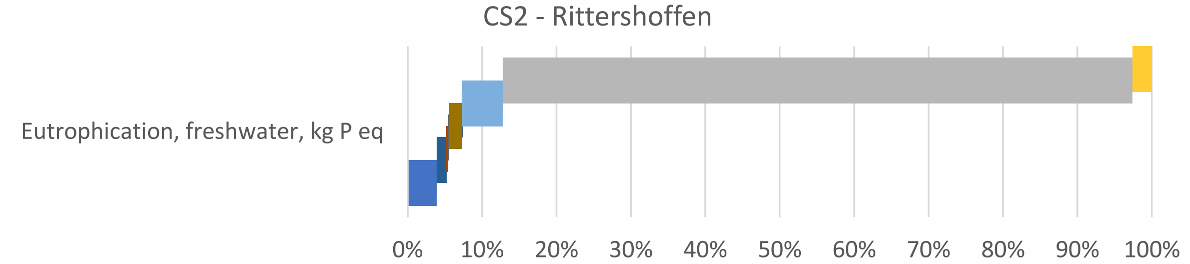
Figure 34 Contribution of processes on the total impact of the operation and maintenance phase on the Eutrophication marine category.

Eutrophication, freshwater



	Eutrophication, freshwater, kg P eq
Construction	1.40E-08
Operation and Maintenance	1.89E-08
End of Life	1.78E-10

Figure 35 Contribution of the three main phases on the total impact on the Eutrophication freshwater category.



	Eutrophication, freshwater, kg P eq
Power plant - Air cooler	6.81E-12
Power plant - Building	5.39E-10
Power plant - Filters	4.02E-13
Power plant - Heat exchanger	1.81E-10
Power plant - Injection pumps	3.54E-11
Power plant - Pipes	1.82E-11
Power plant - Production pumps	2.37E-10
Power plant - Valves	1.06E-11
Well drilling - Chemical stimulation	7.53E-10
Well drilling - Hydraulic stimulation	5.19E-12
Well drilling - Deep well drilling	1.18E-08
Well drilling - Drilling platform	3.62E-10

Figure 36 Contribution of processes to the total impact of the commissioning phase on the Eutrophication freshwater category.

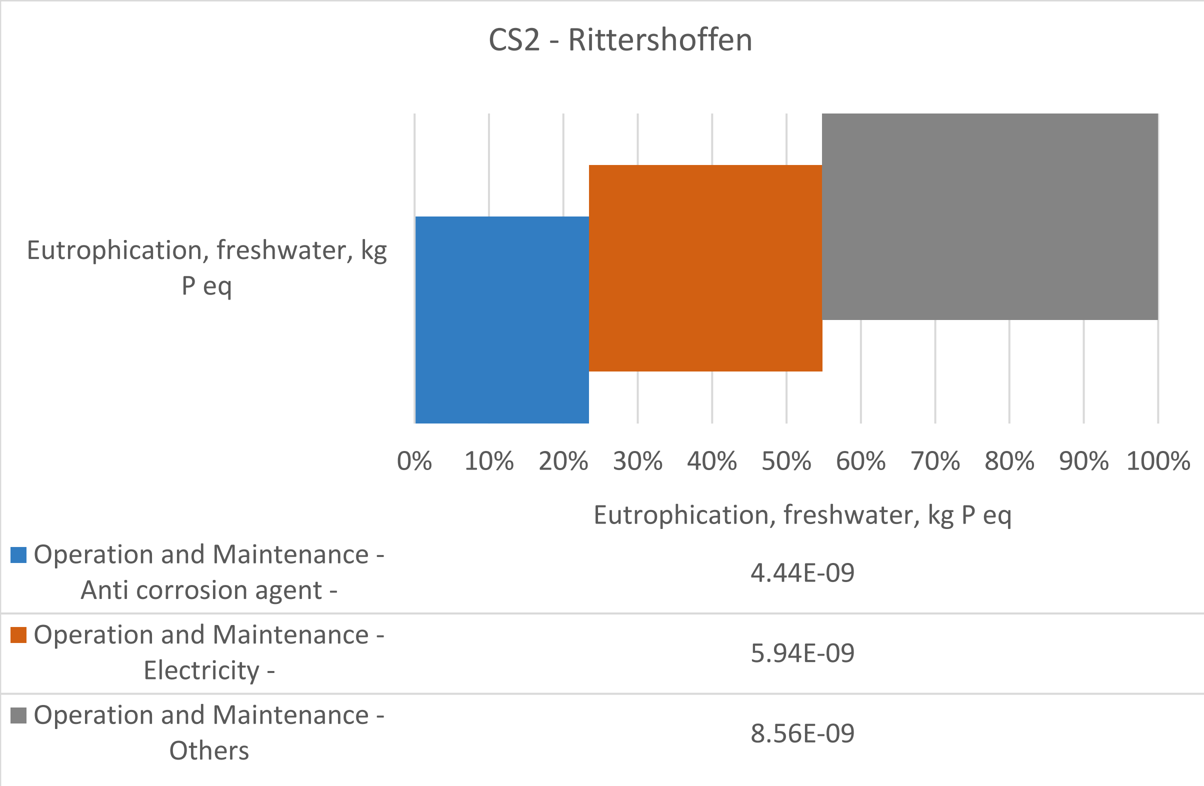


Figure 37 Contribution of processes on the total impact of the operation and maintenance phase on the Eutrophication freshwater category.

Eutrophication, terrestrial

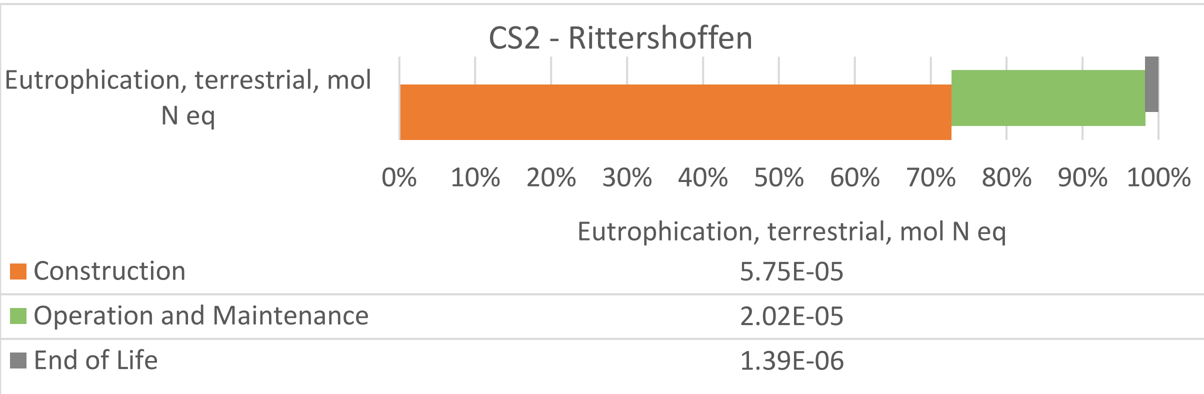
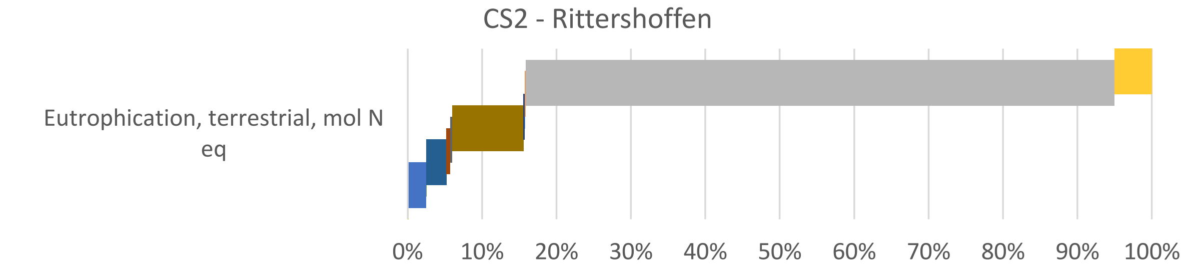
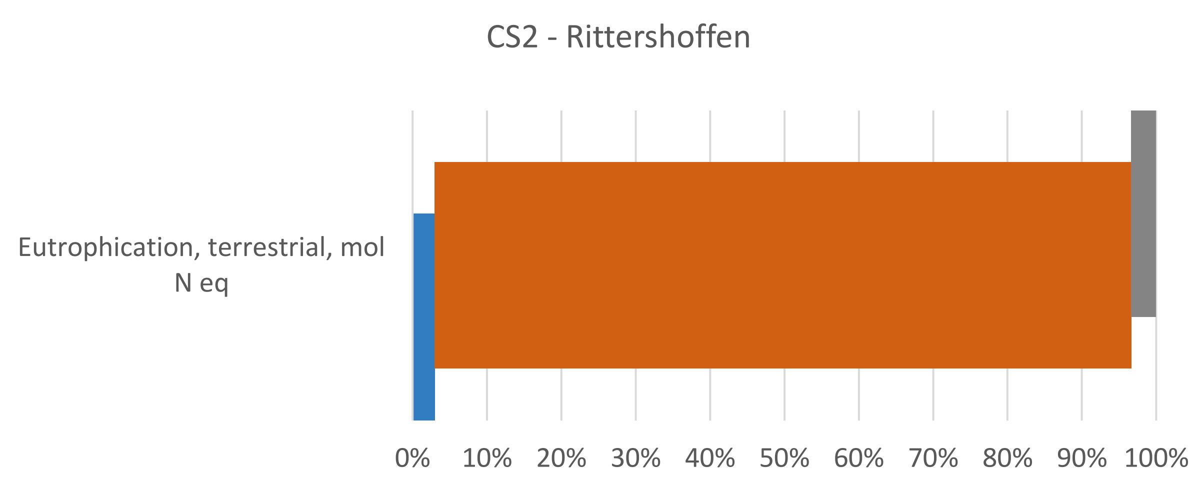


Figure 38 Contribution of the three main phases on the total impact on the Eutrophication terrestrial category.



	Eutrophication, terrestrial, mol N eq
Power plant - Air cooler	4.92E-08
Power plant - Building	1.38E-06
Power plant - Filters	2.85E-09
Power plant - Heat exchanger	1.55E-06
Power plant - Injection pumps	2.92E-07
Power plant - Pipes	1.60E-07
Power plant - Production pumps	5.47E-06
Power plant - Valves	8.68E-08
Well drilling - Chemical stimulation	3.23E-08
Well drilling - Hydraulic stimulation	5.24E-08
Well drilling - Deep well drilling	4.53E-05
Well drilling - Drilling platform	2.87E-06

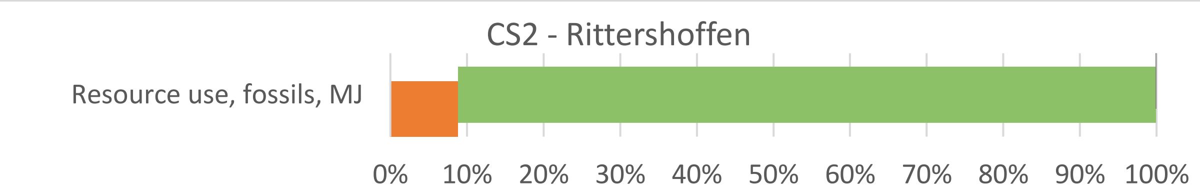
Figure 39 Contribution of processes to the total impact of the commissioning phase on the Eutrophication terrestrial category.



	Eutrophication, terrestrial, mol N eq
Operation and Maintenance - Anti corrosion agent -	5.99E-07
Operation and Maintenance - Electricity -	1.89E-05
Operation and Maintenance - Others	6.77E-07

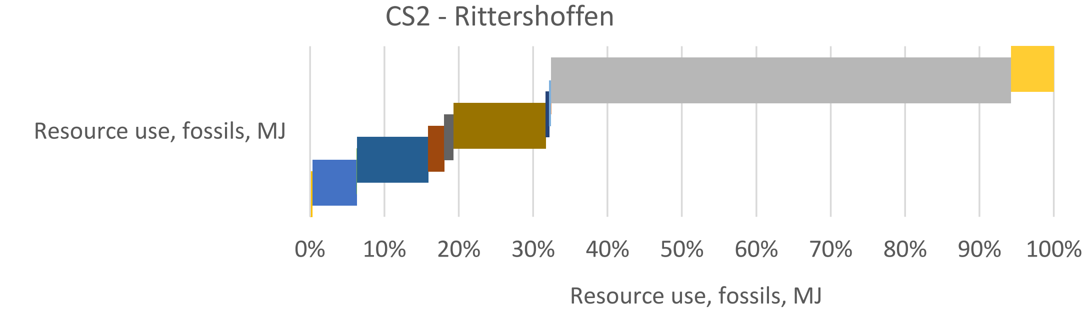
Figure 40 Contribution of processes on the total impact of the operation and maintenance phase on the Eutrophication terrestrial category.

Resource use, fossils



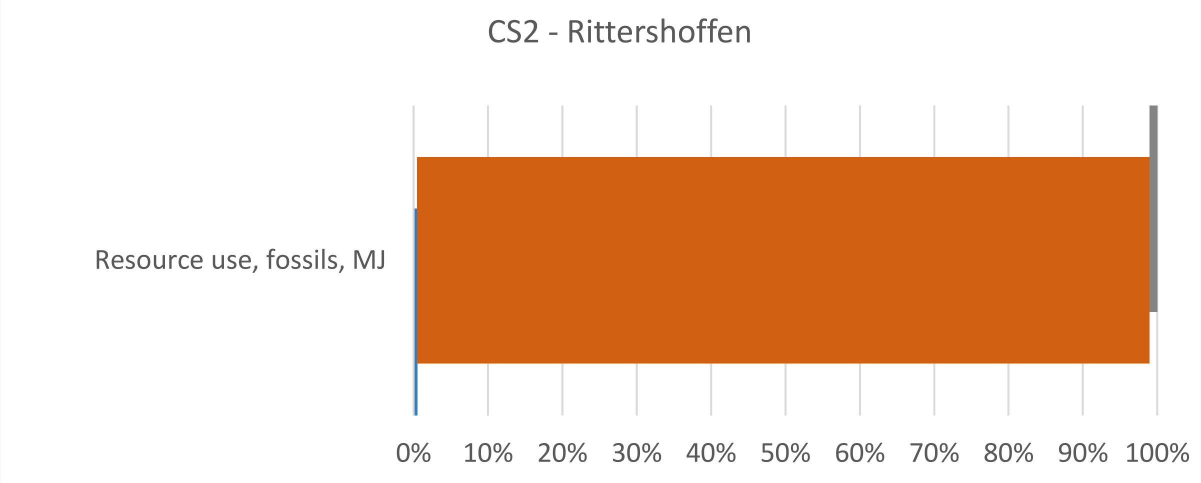
	Resource use, fossils, MJ
Construction	2.19E-02
Operation and Maintenance	2.26E-01
End of Life	3.16E-04

Figure 41 Contribution of the three main phases on the total impact on the Resource use, fossil category.



	Resource use, fossils, MJ
Power plant - Air cooler	7.01E-05
Power plant - Building	1.31E-03
Power plant - Filters	4.15E-06
Power plant - Heat exchanger	2.10E-03
Power plant - Injection pumps	4.68E-04
Power plant - Pipes	2.65E-04
Power plant - Production pumps	2.71E-03
Power plant - Valves	1.13E-04
Well drilling - Chemical stimulation	5.05E-05
Well drilling - Hydraulic stimulation	1.13E-05
Well drilling - Deep well drilling	1.35E-02
Well drilling - Drilling platform	1.26E-03

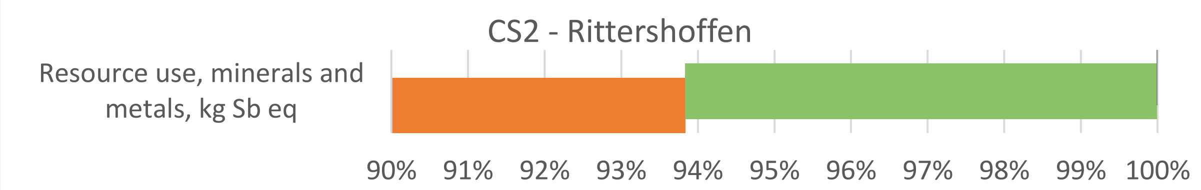
Figure 42 Contribution of processes to the total impact of the commissioning phase on the Resource use, fossil category.



	Resource use, fossils, MJ
Operation and Maintenance - Anti corrosion agent -	1.10E-03
Operation and Maintenance - Electricity -	2.23E-01
Operation and Maintenance - Others	2.34E-03

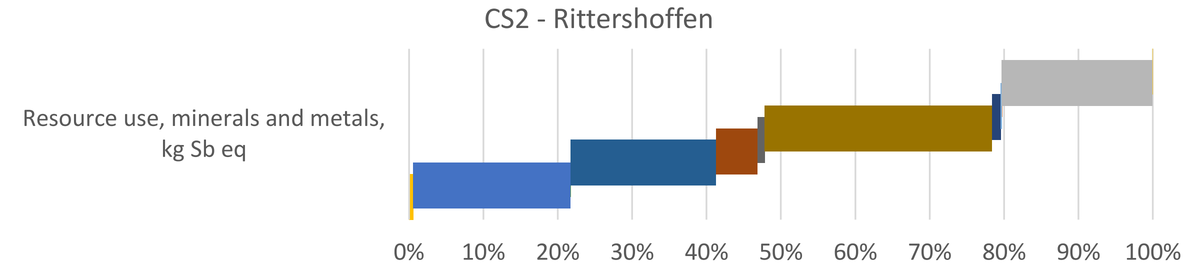
Figure 43 Contribution of processes on the total impact of the operation and maintenance phase on the Resource use, fossil category.

Resource use, minerals and metals



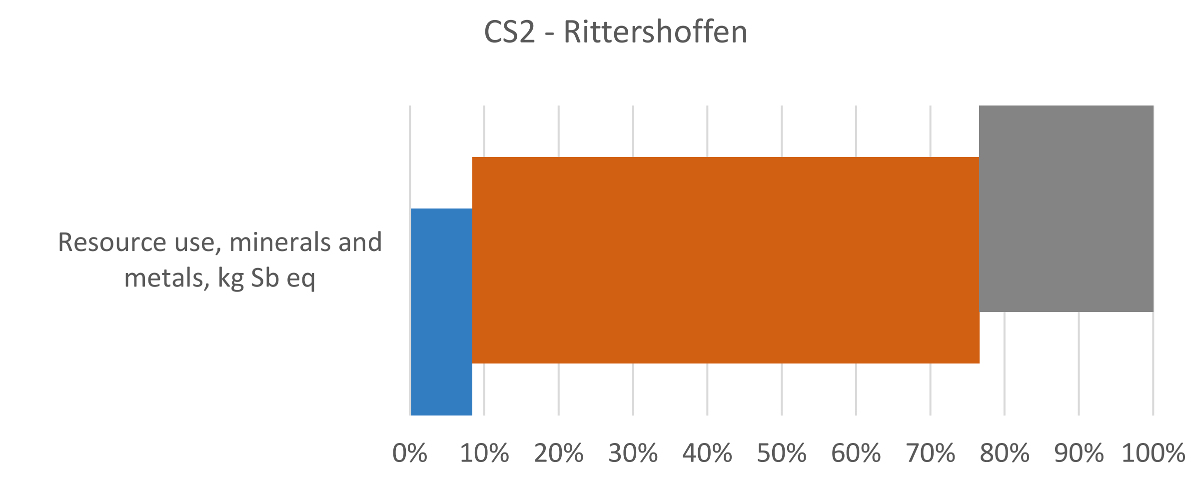
	Resource use, minerals and metals, kg Sb eq
Construction	3.90E-08
Operation and Maintenance	2.56E-09
End of Life	3.59E-12

Figure 44 Contribution of the three main phases on the total impact on the Resource use, minerals and metals category.



	Resource use, minerals and metals, kg Sb eq
Power plant - Air cooler	2.27E-10
Power plant - Building	8.24E-09
Power plant - Filters	1.36E-11
Power plant - Heat exchanger	7.61E-09
Power plant - Injection pumps	2.17E-09
Power plant - Pipes	3.92E-10
Power plant - Production pumps	1.19E-08
Power plant - Valves	4.53E-10
Well drilling - Chemical stimulation	5.10E-11
Well drilling - Hydraulic stimulation	5.45E-14
Well drilling - Deep well drilling	7.90E-09
Well drilling - Drilling platform	1.49E-11

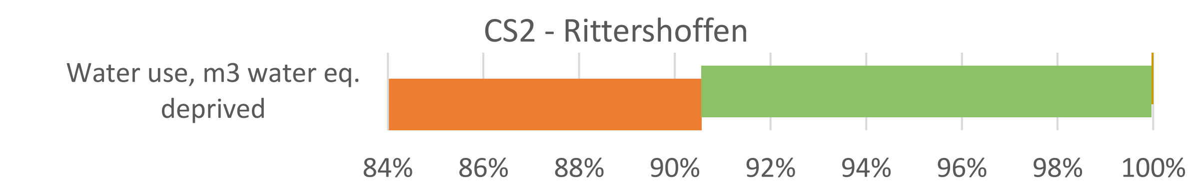
Figure 45 Contribution of processes to the total impact of the commissioning phase on the Resource use, minerals and metals category.



	Resource use, minerals and metals, kg Sb eq
Operation and Maintenance - Anti corrosion agent -	2.15E-10
Operation and Maintenance - Electricity -	1.75E-09
Operation and Maintenance - Others	5.99E-10

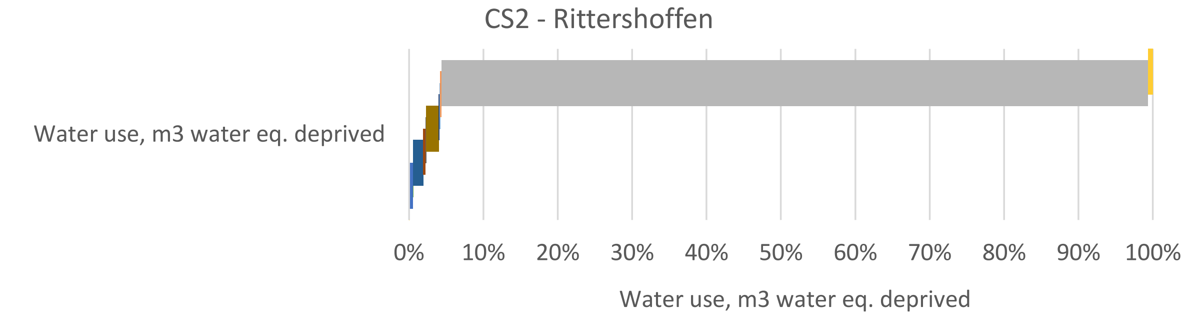
Figure 46 Contribution of processes on the total impact of the operation and maintenance phase on the Resource use, minerals and metals category.

Water use



	Water use, m3 water eq. deprived
Construction	3.04E-03
Operation and Maintenance	3.16E-04
End of Life	1.12E-06

Figure 47 Contribution of the three main phases on the total impact on the Water use category



	Water use, m3 water eq. deprived
Power plant - Air cooler	1.11E-06
Power plant - Building	1.45E-05
Power plant - Filters	6.57E-08
Power plant - Heat exchanger	4.27E-05
Power plant - Injection pumps	9.03E-06
Power plant - Pipes	2.71E-06
Power plant - Production pumps	5.24E-05
Power plant - Valves	2.42E-06
Well drilling - Chemical stimulation	2.16E-06
Well drilling - Hydraulic stimulation	5.60E-06
Well drilling - Deep well drilling	2.88E-03
Well drilling - Drilling platform	2.02E-05

Figure 48 Contribution of processes to the total impact of the commissioning phase on the total impact on the Water use category.

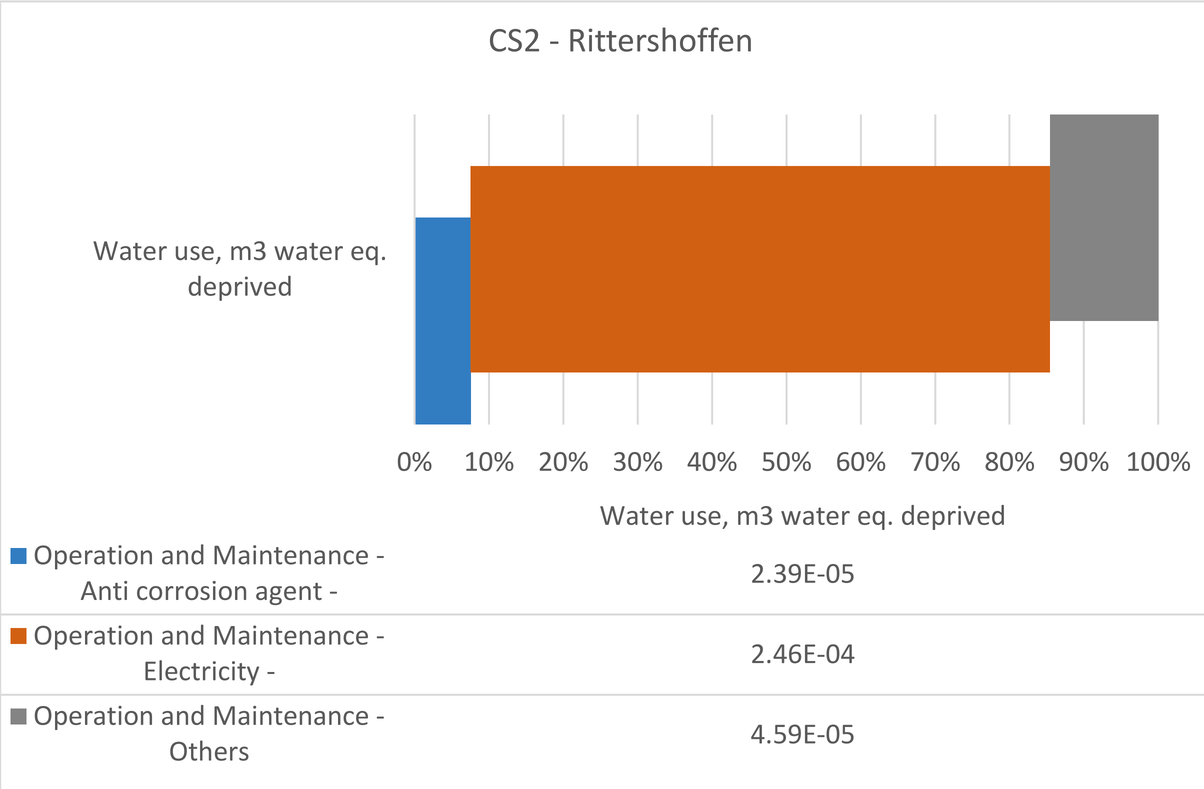


Figure 49 Contribution of processes on the total impact of the operation and maintenance phase on the total impact on the Water use category.

ANNEX II

Main differences between ILCD and EF

In this Annex we report the summarized difference between the Life cycle impact assessment method recommended in the framework of the Environmental Footprint (EF) and the ILCD 2011 method. These differences are extensively discussed in the document “Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment method” (Fazio et al. 2018).

Climate change

The reference model for climate change, midpoint, in ILCD was the one proposed by IPCC 2007, while in the EF scheme IPCC 2013 is adopted. Furthermore, the values adopted for the Global Warming Potentials with time horizon 100 years (GWP-100) includes the carbon feedbacks for different substances, while the GWP-100 adopted in ILCD was accounting only for the effect of single substances. Several new substances have been characterised in the new model, compared to ILCD. Beyond the main method containing all the characterised substances in this category, three sub-methods for fossil, biogenic, and land use emissions are available in EF 3.0.

Ozone depletion potential

The reference model for ozone depletion, midpoint, in ILCD was developed by the World Meteorological Organisation (WMO) in 1999, while in the EF scheme the WMO 2014 is adopted as reference model.

Human and Eco Toxicity

The most recent version of the USEtox® model (2.1) has been used. Overall, CFs have been provided for more than 6700 substances. The list of chemicals has been enlarged: new added chemicals’ CF have been calculated on the basis of data collected from REACHIUCLID database, EFSA’s OpenFoodTox database and PPDB database. Last, for data gap filling purposes, EPISuite and OECD QSAR toolbox have been investigated. For Ecotoxicity the Effect Factor is derived from log(HC20) instead from avlogEC50, in order to be in line with the most recent recommendations from UNEP – Pellston Workshop 2018. As consequence, the Effect Factor is calculated as follows: EF = 0.2/HC20. USEtox® 2.1 model has been run for organics, inorganics, and metals. However, being USEtox® built only for organic chemicals, some factors have been applied for cover uncertainty associated to inorganics and metals

Respiratory inorganics

The model adopted in ILCD characterized the impacts in kg of PM2.5 equivalents and was based on three different references (Rosenbaum et al. 2008; Greco et al. 2007; Rabl et al. 2014), combined as proposed in (Humbert 2010). The new model is characterising the emissions as deaths due to the emission of PM, as defined by (Unep/Setac 2016; Fantke et al. 2015).

Ionising radiation

The model adopted in ILCD for ionising radiation is not changed. Proxy CFs have been adopted for some emissions to specific sub-compartment. The reference unit was adapted from kg to kBq, according to ILCD unit group for radioactivity.

Photochemical ozone formation

The model adopted in ILCD for Photochemical Ozone Formation is not changed. CFs for specific flows, not available in the original model, but listed in the elementary flow list, both forILCD and EF, have been calculated

Acidification

The model adopted in ILCD for Acidification is not changed. CFs for specific flows, not available in the original model, but contained in the elementary flow list, both for ILCD and EF, have been calculated. For the most relevant flows in the specific category, country-specific CFs have been calculated.

Eutrophication

The models adopted in ILCD for the three impacts related to Eutrophication are not changed. CFs for specific flows, not available in the original models, have been calculated. For terrestrial eutrophication, country-specific CFs have been calculated for ammonia, nitrogen oxides and nitrogen dioxide.

Land use

The model for land use impact assessment is completely changed. In ILCD the model evaluating Soil Organic Matter (SOM) loss, developed by (Milà I Canals et al. 2007) was adopted, in EF the model LANCA (Bos et al. 2016) is implemented. LANCA model is taking into account different indicators for different soil properties, as explained below. Those indicators have been pooled and re-scaled, in order to obtain a dimensionless soil quality index, accounting for the different properties evaluated by the model. The model assigns both global and spatially differentiated CFs at country level.

Resource use

The overall approach (abiotic resource depletion – ADP, (de Bruijn, van Duin, and Huijbregts 2002) is not changed. However, the reference model for resource depletion of minerals and metals has changed from reserve base to ultimate reserves. A more recent version of CFs (corresponding to CML v. 4.8) is recommended. Energy carriers are now considered separately, and characterised as MJ equivalents, while mineral and metal resources are characterised in Sb-equivalents.

Water scarcity

The model for water use impact assessment is new. In ILCD, the model characterized the water depletion according to scarcity adjusted mass of water used (Frischknecht et al. 2006; FOEN 2009), in EF the model AWARE (Boulay et al. 2018; Unep/Setac 2016) is implemented, and evaluates the impact in quantity of water deprived.

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