Report on the environmental impact of the underground H2 storage

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Revision History

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Darío CORTÉS	Aragon Hydrogen Foundation	2 February 2023
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List of Acronyms

CAT	Category
CCS	Carbon Capture Storage
CEM	Cement
CO_2	Carbon dioxide
EC	European Commission
EF	Environmental Footprint
EEA	European Environment Agency
E-LCA	Environmental Life Cycle Assessment
EN	European Normative
eq.	equivalent
EU	European Union
FR	France
FU	Functional Unit
GLO	Global
H_2	Hydrogen
H+	Hydrogen ion
HDPE	High density Polyethylene
ISO	International Standard Organization
LCA	Life Cycle Assessment
MSm^3	Million of Standard Cubic meter
N	Nitrogen
na	not available
NMVOC	Non-Methane Volatile Organic Compounds
P	Phosphorus
PM	Porous Media
RED	Renewable Energy Directive
RFNBO	Renewable transport Fuels of Non-Biological Origin
Sb	Antimony
SC	Salt Cavern
S-LCA	Social Life Cycle Assessment

SMR	Steam Methane Reforming
WP	Work Package

1. Introduction

The Hystories project aims to address the main technical feasibility issues of large-scale underground storage of pure hydrogen in aquifers or depleted fields, and will provide market, societal, economic and environmental information on the deployment and exploitation of underground hydrogen storage in Europe, considering the three main types of underground hydrogen techniques (the mature salt caverns as well as aquifers and depleted fields). The Work Package 6 (WP6) assesses the economic feasibility, environmental and social performance of several future aquifer or depleted field sites for pure hydrogen storage. In particular, task 6.2 focuses on the Environmental-Life Cycle Assessment (E-LCA) results of potential large-scale underground hydrogen storages. The findings will be a key input for defining the implementation plan for underground renewable hydrogen storage in the EU by 2050 (WP9).

The objective of this report is to present the final results of the E-LCA of two large-scale hydrogen underground storages (salt cavern and porous media, which includes both aquifer and depleted field techniques), including the hotspot analysis for each storage site, a sensitivity analysis and the comparison between the two theoretical sites from an E-LCA perspective. This report was agreed upon after in-depth discussions between the consortium and industrial parties from the Advisory Board and is based on data provided by Geostock, consortium partner and Hystories project's coordinator.

This report is structured in 9 chapters. The first one presents the introduction of this report. Chapter 2 includes the main characteristics of large-scale underground storages of H_2 selected, Chapter 3 indicates the LCA methodology applied, Chapter 4 defines the goal and scope of H_2 storage systems, Chapter 5 comprises the inventory analysis, Chapter 6 presents the final impact assessment results, Chapter 7 addresses the comparative assessment of different storage techniques and discusses the inclusion of the H_2 production stage, and Chapter 8 gives the main E-LCA conclusions. Finally, Chapter 9 lists the literature referred to in the report.

2. Underground hydrogen storage systems description

The large-scale hydrogen underground storage systems selected to carry out the E-LCA are a salt cavern storage site and a porous media storage site. The main features of each theoretical storage site are shown in Table 1 and were provided by Geostock. Both future underground storages are assumed to be located in France and guarantee a quality of H_2 stored of 99.93%.

Concerning the salt cavern storage site, the site embraces 8 caverns, the free gas volume is 380,000 m³ per cavern (250 MSm³ of working gas volume in total), with a casing shoe depth of 1,000 m, a pressure range of 55-180 bar and 1 well/cavern per site, resulting in a working gas capacity of 250 MSm³, maximum injection and withdrawal rates of 2.17 MSm³/d and performing 1.1 annual gas injection/withdrawal cycles.

Regarding the porous media, it operates in a pressure range of 55-130 bar with 550 MSm³ of working gas, has an injection and withdrawal rate of up to 4.78 MSm³/d of H_2 and 1.1 gas turnover can be performed per year. 24 wells are drilled for production and 6 additional wells for monitoring of the storage. More details about the development and operation of these underground storage technologies can be found in Hystories report *D7.1-1 - Conceptual Design of salt cavern and porous media underground storage site*. Cycle that was selected corresponds to the one defined as “OC1” in the deliverable *D7.3 – Ranking and Selection of Geological Stores*. It corresponds to a relatively smooth seasonal cycle.

Table 1: Main features considered of the theoretical underground hydrogen storages. From Hystories reports D7.1-1 and D7.3

Feature	Salt cavern	Porous media
Number of salt cavern/porous reservoir per storage site	8	1
Free gas volume per cavern (m³)	380,000	-
Storage site working gas (MSm³)	250	550
Maximum site withdrawal flowrate (MSm³/d [a])	2.17	4.78
Withdrawal-to-injection flowrate ratio	1	1
Number of wells	8	24 + 6
Cycles per year [b]	1.1	1.1
Cavern height (m)	155	-
Quality of H_2 (%)	99.93	99.93
Pressure range (bar)	55-180	55-130
Temperature range (ºC)	40-60	40-60
Total H_2 stored [c] (ton/year)	25,000	55,000

[a] MSm³/day: Million standard cubic metre (at 15 ºC, 1.01325 bara) per day.

[b] Gas injection/withdrawal cycles based on business needs and storage operating strategy.

[c] Considering a H_2 standard volume per kilogram of 11 MSm³/kg.

3. Methodology: LCA

The methodology to perform the E-LCA is based on the ISO 14040 framework (ISO, 2006a, 2006b) and is structured in the following four phases: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment and (4) interpretation (see Figure 1). More details can be found in Hystories report *D6.2-1-Final definition of impact categories and indicators for E-LCA and S-LCA*.

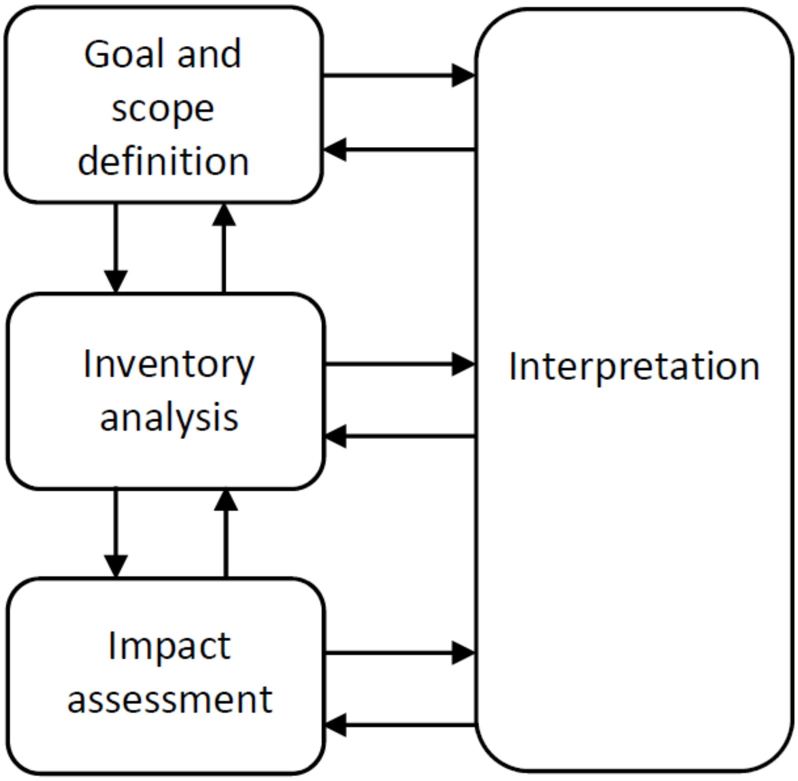

Figure 1: LCA structure.

4. Goal and scope definition of underground hydrogen storages

The first stage of E-LCA consists in defining a goal and the scope of the study. This stage determines what functional unit (FU) will be considered to evaluate environmental impacts, the impact assessment categories and the extent of the system boundary.

4.1. Goal

The main objective of the study is to evaluate the environmental performance of two underground hydrogen storage systems: salt cavern and porous media, for a better understanding and implementation of the impact associated with large-scale underground hydrogen storage, as well as those associated with the auxiliary systems that are needed to perform these types of storages, using specific data provided by Geostock.

The principal purpose is to quantify the potential environmental life cycle impacts of the underground hydrogen storage systems and to identify the processes with the largest impacts (hotspots), as well as to compare both storage systems from a LCA perspective. The intended audience are the partners of the Hystories project and other parties interested in the topic.

4.2. Functional unit

The FU is the underground storage of 1 kg of H_2 produced through an electrolyser, stored for an annual cycle for both storage sites with a quality of 99.93%, a pressure of 55-180 bar for salt cavern or 55-130 bar for porous media and a temperature of 40-60 °C. The lifetime of both theoretical underground H_2 storages considered (salt cavern and porous media) is estimated to be 50 years.

4.3. Software tool and data sources

E-LCA estimations were performed with GaBi Professional software. Inventory data (primary data) was provided by Geostock and complemented (secondary data) by GaBi 2022 database (Kupfer et al., 2020) and literature data.

4.4. Impact assessment categories

The impact assessment categories employed for the environmental assessment of underground H_2 systems are selected according to the latest development of the European

Commission on the recommended Environmental Footprint (EF) life cycle impact assessment methods (EC-JRC, 2018). Therefore, the environmental impact categories selected from EF 3.0 method for the E-LCA are: climate change, acidification, freshwater eutrophication, marine eutrophication, photochemical ozone formation, minerals and metals resources use, and fossils resources use. More details can be found in Hystories report D6.2-1 (Final definition of impact categories and indicators for E-LCA and S-LCA).

4.5. System boundaries

The system boundaries for both underground H_2 storage sites (salt cavern and porous media) include the stages of construction, use or operation (H_2 storage) over 50 years, and abandonment or end-of-life of the storage (see Figure 2). In both theoretical storage sites, the production of capital goods (buildings, machinery, and equipment), energy, fuels, staff travels, and materials consumed in all the stages is also considered.

The stages of H_2 production (water electrolysis, compression, etc…) and the H_2 final use are excluded in both storage sites because they are out of the scope of the present study, focused and using detailed data only for storage. Therefore, the consistency and precision of the set information used would be lost if data from literature are utilised for those other stages.

The construction stage encompasses the components or sub-stages of (1) investigation phase, (2) drilling & completion, (3) leaching (only for salt cavern), (4) surface facilities and (5) buildings.

Investigation phase requires the consumption of industrial water and cement, the use of different machinery (drilling rigs, electrical mobile crane, vibrators run by diesel, construction pump) and cargo and transport vehicles (trucks, semi-trailer and van). During this first phase of construction stage, the staff travel is done by plane.

The drilling & completion involves the consumption of materials (cement, bentonite, barite, potassium chloride, sodium chloride, steel for casing) and other chemicals for drilling, as well as nitrogen and steel piping for leaching completion installation, and the use of different machinery (drilling rigs run by diesel, electrical mobile crane, excavator, forklift, construction pump) and cargo and transport vehicles (trucks and boat) during this second phase of construction stage. For wastes generated, the wastewater is discharged into a wastewater treatment plant, whereas the solid waste is landfilled. During this phase, the staff travel is be done by plane.

Leaching requires the consumption of a large amount of seawater, and also flocculants (anionic polymer), coagulants (aluminium hydroxide chloride) and nitrogen (for leaching process, tightness tests and gas completion installation), as well as concrete and steel for the temporary surface facilities, and the use of different machinery (electrical pumps, sonar, electrical mobile cranes run by diesel, drilling rig runs by diesel, construction pump) and cargo and transport vehicles (boat and trucks) during this phase. For wastes generated, the brine goes to the sea, and the solid waste is landfilled. The staff travel is done by plane during this construction stage.

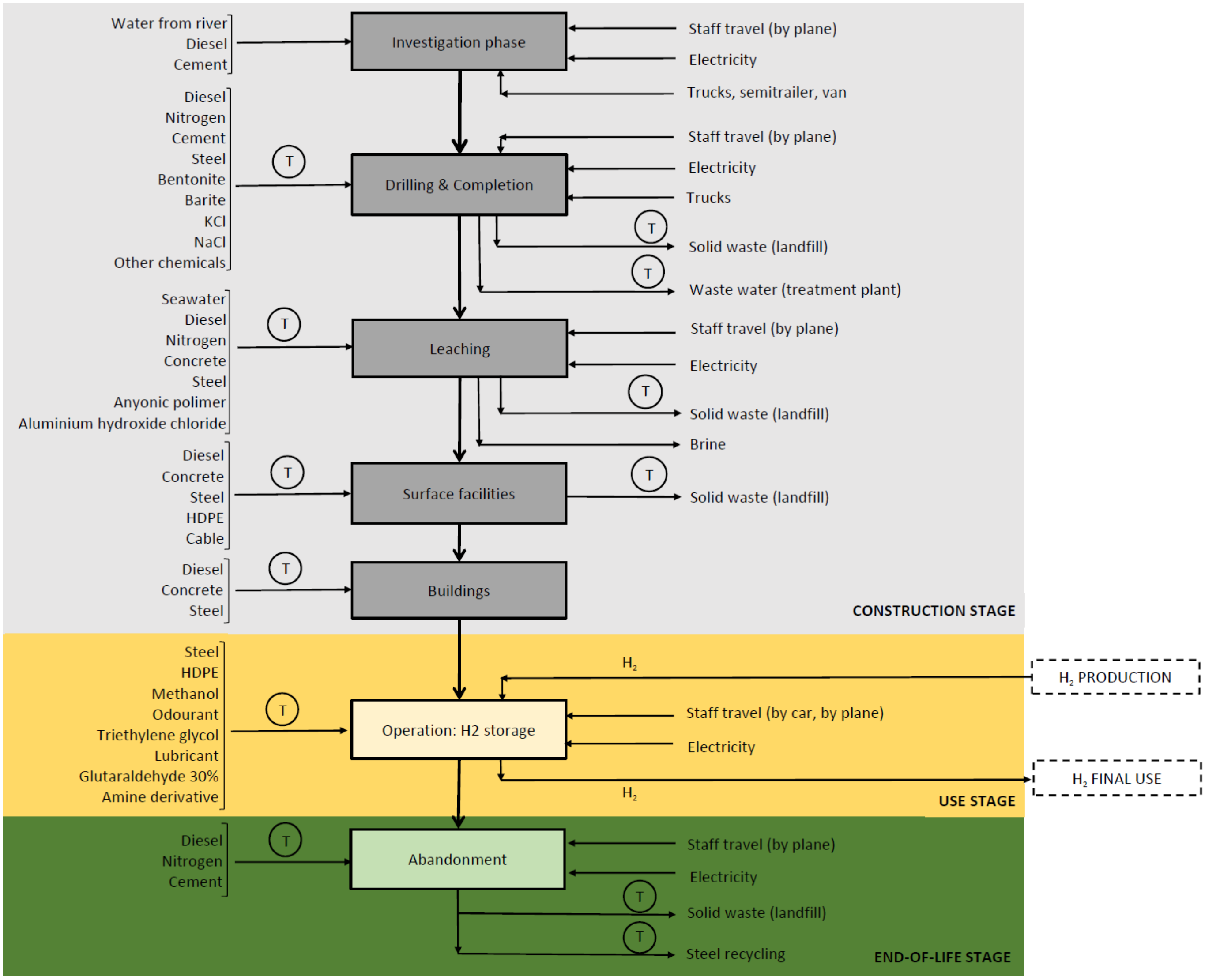

Figure 2: System boundaries in the life cycle of underground H_2 storage systems. Solid boxes represent stages considered (Leaching is only included for salt cavern) and dotted boxes represent stages excluded from assessment. T: transport by truck and/or boat.

The surface facilities entail the consumption of steel (for engineering construction and different units: compressor, separator, drying, odorization, aerial and buried pipings), concrete, cable and high-density polyethylene (for buried piping), as well as the use of different machinery (electrical mobile cranes run by diesel, excavator) and cargo and transport vehicles (boat and trucks). The solid waste generated is landfilled.

The buildings (adjoining and administrative buildings, Electrical & Instrumentation building, guard house and different shelters: electrical for product pump, instrumental air, chemical product, chemical product platform, fiscal metering, pump, firewater) require the consumption of steel and concrete, as well as the use of mobile cranes run by diesel and trucks.

The use or operation consists of the H_2 storage during 50 years for both types of underground storage sites. This stage consumes electricity for the annual cycles and different consumables:

methanol, odorant, triethylene glycol, lubricant (for compressor), glutaraldehyde 30% (biocide) and amine derivative (corrosion inhibitor) as well as the use of cargo and transport vehicles (boat and trucks). Piping (made of steel and high-density polyethylene) of the surface facilities needs to be renewed once over the 50-years lifetime due to the piping lifetime that is 30 years. Inspections of salt cavern volume evolution and casing part (for salt cavern and porous media, respectively) are compulsory during the operation, every 10 years for the former storage and for the latter, different wells are inspected every 2 years, but it is recommended to inspect the same well every 10 years. Salt caverns inspection consists of removing the piping and then introduction of a sonar logging tool or sampling to measure the volume at each angle of the cavern and lasts 20 days each cavern. The casing inspection (corrosion and cementation inspection) lasts 10 days and only 4 wells are inspected each time. The staff travel is done by car and plane during the operation stage.

The end-of-life or abandonment stage of the underground storages consists in (1) the on-site inertization with nitrogen of approximately 50% of buried pipes; (2) the removal of the aerial piping and steels units from surface facilities phase, the concrete and steel from buildings and steel piping from drilling & completion phase; (3) the well plugging (with cement) and (4) abandonment. It requires the use of different machinery (drilling rigs, mobile crane) run by diesel and trucks during this stage. The solid waste generated from the removal is landfilled, except the steel scrap, which is assumed that is recycled (65%) and the remaining (35%) is landfilled according to the EU requirements by 2020 for construction and demolition waste (EU directive 2008/98/EC). The staff travel is done by plane.

The D7.1-1 (Conceptual design of salt cavern and porous media underground storage site) and D7.2-1 (Life Cycle Cost Assessment of an underground storage site) include more detailed information about the development and operation of both underground storage technologies.

5. Inventory analysis

Life cycle inventory analysis includes data collection for all the inputs and outputs for considered stages within the system boundaries.

5.1. Construction stage

Table 2 shows the inventory table (inputs and outputs) for the different components of construction stage of both theoretical storage systems, information provided by Geostock, as well as the corresponding processes selected from GaBi database. No data are available in GaBi for the production of barite, other chemicals, the anionic polymer flocculant, and the coagulant aluminum hydroxide chloride. Thus, these processes are not accounted for. However, their contribution is not expected to be relevant for the total impacts. Air emissions from the burning of diesel for machinery and from the burning of kerosene for passenger aircraft are estimated (see Table A.I of Annex I) based on emission factors from EEA (2016).

Table 2: Inventory table for the different components of the construction stage of salt cavern and porous media, and processes selected from GaBi.

Construction stage	Salt cavern	Porous media	Processes from GaBi
1-Investigation phase			
Inputs			
Water from river	1,443 ton	1,443 ton	River water regionalized, FR
Electricity (low voltage)	63.6 MWh	63.6 MWh	FR: Electricity grid mix <1kV
Diesel for machinery	12.16 m^3	12.16 m^3	FR: Diesel mix at filling station + Fuel combustion for machinery [a]
Cement	6 ton	6 ton	Cement (CEM I 52.5) (burden free binders) (EU-28)
Van	1,200 km	1,200 km	Transport, van (up to 7.5 ton total capacity, 3.3 ton payload)
Trucks	900 km	900 km	EU-28: Transport, truck (26 ton total capacity, 17.3 ton payload)
Semi-trailer	400 km	400 km	EU-28: Transport, truck-trailer (40 ton total cap., 24.7 ton payload)
Staff travel (by plane)	1,600 km; 13 travels	1,600 km; 13 travels	FR: Kerosene / Jet A1 at refinery + Fuel combustion for passenger aircraft [a]
2-Drilling & Completion			
Inputs			
Electricity (low voltage)	827 MWh	1,296 MWh	FR: Electricity grid mix <1kV
Diesel for machinery	8,000 m^3	12,150 m^3	FR: Diesel mix at filling station + Fuel combustion for machinery [a]

Construction stage	Salt cavern	Porous media	Processes from GaBi
Nitrogen	80 ton	300 ton	EU-28: Nitrogen (gaseous)
Cement	480 m^3	1,800 m^3	Cement (CEM I 52.5) (burden free binders) (EU-28)
Steel	1,176 m^3	2,563 m^3	EU-28: Steel pipe
Bentonite	130 ton	486 ton	RER: Bentonite powder, sodium activated
Barite	108 ton	405 ton	na
Potassium chloride (KCl)	28 ton	105 ton	EU-28: Potassium chloride
Sodium chloride (NaCl)	80 ton	300 ton	EU-28: Sodium chloride
Other chemicals	84 ton	315 ton	na
Trucks (for different activities)	1,602 km; 100 trucks	1,602 km; 100 trucks	EU-28: Transport, truck (26 ton total capacity, 17.3 ton payload)
Transport by truck	5,200 km	5,200 km	GLO: Truck, Euro 0-6 mix, 7.5-12 ton gross weight / 5 ton payload capacity + FR: Diesel mix at filling station
Transport by boat	4,000 km	4,000 km	River freight ship, 4,000 ton payload capacity /downstream + FR: Diesel mix at filling station
Staff travel (by plane)	1,600 km; 20 travels	1,600 km; 60 travels	FR: Kerosene / Jet A1 at refinery + Fuel combustion for passenger aircraft [a]
Outputs			
Wastewater (for treatment)	3,016 m^3	9,050 m^3	EU-28: Municipal wastewater treatment
Solid waste (for landfill)	1,240 m^3	3,720 m^3	EU-28: Municipal waste landfill
Solid waste (to abandonment stage)	1,363 ton	2,261 ton	-
Steel (to abandonment stage)	2,531 ton	4,199 ton	-
3-Leaching			
Inputs			
Seawater	29,600,000 ton	-	-
Electricity (medium voltage)	115,675 MWh	-	FR: Electricity grid mix 1kV-60kV
Diesel for machinery	153.6 m^3	-	FR: Diesel mix at filling station + Fuel combustion for machinery [a]
Nitrogen	4,127,898 m^3	-	EU-28: Nitrogen (gaseous)
Concrete	193 m^3	-	GLO: Building, reinforced concrete frame construction
Steel	15,895 ton	-	EU-28: Steel pipe
Anionic polymer	40 m^3	-	na
Aluminium hydroxide chloride	4,000 m^3	-	na

Construction stage	Salt cavern	Porous media	Processes from GaBi
Transport by truck	5,100 km	-	GLO: Truck, Euro 0-6 mix, 20-26 ton gross weight / 17.3 ton payload capacity + FR: Diesel mix at filling station
	300 km	-	GLO: Truck, Euro 0-6 mix, 7.5-12 ton gross weight / 5 ton payload capacity + FR: Diesel mix at filling station
Transport by boat	4,000 km	-	River freight ship, 4,000 ton payload capacity /downstream + FR: Diesel mix at filling station
Staff travel (by plane)	1,600 km; 42 travels	-	FR: Kerosene / Jet A1 at refinery + Fuel combustion for passenger aircraft [a]
Outputs			
Brine (to the sea)	29,600,000 ton	-	-
Solid waste (for landfill)	8,000 m^3	-	EU-28: Municipal waste landfill (EN15804 C4)
4-Surface facilities			
Inputs			
Diesel for machinery	599.04 m^3	599.04 m^3	FR: Diesel mix at filling station + Fuel combustion for machinery [a]
Concrete	2,080 m^3	2,080 m^3	GLO: Building, reinforced concrete frame construction
Steel	1,351 ton	1,351 ton	EU-28: Steel sections
	2,536 ton	2,536 ton	EU-28: Steel pipe
High density polyethylene (HDPE)	40 ton	40 ton	EU-28: Polyethylene, HDPE
Cable	60 km	60 km	EU-28: Cable CAT 7
Transport by truck	5,100 km	5,100 km	GLO: Truck, Euro 0-6 mix, 20-26 ton gross weight / 17.3 ton payload capacity + FR: Diesel mix at filling station
Transport by boat	4,000 km	4,000 km	River freight ship, 4,000 ton payload capacity /downstream + FR: Diesel mix at filling station
Outputs			
Solid waste (to abandonment stage)	878 ton	878 ton	-
Steel (to abandonment stage)	1,630 ton	1,630 ton	-
5-Buildings			
Inputs			

Construction stage	Salt cavern	Porous media	Processes from GaBi
Diesel for machinery	69.12 m^3	69.12 m^3	FR: Diesel mix at filling station + Fuel combustion for machinery [a]
Concrete	2,661 m^3	2,661 m^3	GLO: Building, reinforced concrete frame construction
Steel	3,523 ton	3,523 ton	EU-28: Steel sections
Transport by truck	4,400 km	4,400 km	GLO: Truck, Euro 0-6 mix, 20-26 ton gross weight / 17.3 ton payload capacity + FR: Diesel mix at filling station
Outputs			
Solid waste (to abandonment stage)	4,160 ton	4,160 ton	-
Steel (to abandonment stage)	2,290 ton	2,290 ton	-

[a] Air emissions estimated based on emission factors from EEA (2016).

5.2. Operation stage

Data on the inputs and outputs for the operation stage over 50 years of both future underground H_2 storage systems, information supplied by Geostock, are shown in Table 3, as well as the corresponding processes chosen from GaBi database. Processes for the production of the lubricant for the compressor, the biocide glutaraldehyde 30% (biocide) and the amine derivative corrosion inhibitor are not accounted for due to no data available in GaBi. However, their contribution is not expected to be relevant for the total impacts. Air emissions from the kerosene combustion for passenger aircraft (see Table A.I) are estimated based on emission factors from EEA (2016).

Table 3: Inventory table for the operation stage of salt cavern and porous media over 50 years, and processes selected from GaBi.

Operation stage	Salt cavern	Porous media	Processes from GaBi
Inputs			
H_2 transiting through the storage	1,2500,000 ton	2,750,000 ton	-
Electricity (medium voltage)	1,459,132 MWh	5,467,702 MWh	FR: Electricity grid mix 1kV-60kV
Steel	2,536 ton	2,536 ton	EU-28: Steel pipe
High density polyethylene (HDPE)	40 ton	40 ton	EU-28: Polyethylene, HDPE
Odorant	400 m^3	1,200 m^3	EU-28: Ethyl acrylate
Triethylene glycol	400 m^3	1,200 m^3	EU-28: Triethylene glycol
Lubricant	2,000 m^3	6,000 m^3	na
Glutaraldehyde 30%	0.04 m^3	0.12 m^3	na

Operation stage	Salt cavern	Porous media	Processes from GaBi
Amine derivative	0.48 m^3	1.44 m^3	na
Transport by truck	1,200 km	1,200 km	GLO: Truck, Euro 0-6 mix, 20-26 ton gross weight / 17.3 ton payload capacity + FR: Diesel mix at filling station
	1,200 km	1,200 km	EU-28: Transport, truck (26 ton total capacity, 17.3 ton payload) + FR: Diesel mix at filling station
Transport by boat	4,000 km	4,000 km	River freight ship, 4,000 ton payload capacity /downstream + FR: Diesel mix at filling station
Staff travel (by car)	13,140,000 km	13,140,000 km	EU-28: Car, diesel EURO 4
Staff travel (by plane)	10,560,000 km; 20 travels/year	10,560,000 km; 20 travels/year	FR: Kerosene / Jet A1 at refinery + Fuel combustion for passenger aircraft [a]
Outputs			
H_2	1,250,000 ton	2,750,000 ton	-
Emissions of CO_2 equivalent (work over operation)	1,068 ton CO_2 eq.	2,503 ton CO_2 eq.	-

[a] Air emissions estimated based on emission factors from EEA (2016).

5.3. Abandonment stage

Table 4 presents data on the inputs and outputs (gathered from Geostock) of the end-of-life stage of both theoretical storage systems, and the corresponding processes selected from GaBi database. Air emissions from the combustion of diesel for machinery and from the combustion of kerosene for passenger aircraft (see Table A.I) are estimated based on emission factors from EEA (2016).

Table 4: Inventory table for the abandonment stage of salt cavern and porous media, and processes selected from GaBi.

Abandonment stage	Salt cavern	Porous media	Processes from GaBi
Inputs			
Electricity (low voltage)	2.56 MWh	2.56 MWh	FR: Electricity grid mix <1kV
Diesel for machinery	206.08 m^3	206.08 m^3	FR: Diesel mix at filling station + Fuel combustion for machinery [a]
Nitrogen	70 ton	70 ton	EU-28: Nitrogen (gaseous)
Cement	160 m^3	20 m^3	Cement (CEM I 52.5) (burden free binders) (EU-28)

Abandonment stage	Salt cavern	Porous media	Processes from GaBi
Transport by truck	1,200 km	1,200 km	GLO: Truck, Euro 0-6 mix, 20-26 ton gross weight / 17.3 ton payload capacity + FR: Diesel mix at filling station
	300 km	300 km	GLO: Truck, Euro 0-6 mix, 7.5-12 ton gross weight / 5 ton payload capacity + FR: Diesel mix at filling station
Staff travel (by plane)	1,600 km; 5 travels	1,600 km; 2 travels	FR: Kerosene / Jet A1 at refinery + Fuel combustion for passenger aircraft [a]
Solid waste [b]	6,401 ton	7,299 ton	-
Steel [b]	6,451 ton	8,119 ton	-
Outputs			
Solid waste (for landfill) [b]	6,401 ton	7,299 ton	EU-28: Municipal waste landfill
Steel (for recycling) [b]	6,451 ton	8,119 ton	GLO: Credit for recycling of steel scrap

[a] Air emissions estimated based on emission factors from EEA (2016).

[b] From construction stage: Drilling & Completion, Surface facilities and Buildings.

6. E-LCA results

This chapter involves presenting results for each system, drawing conclusions and distinguishing the stages and processes that have a greater contribution to the systems total impact under study.

6.1. Hotspot analysis

6.1.1. Salt cavern

Table 5 presents the total environmental impacts of the salt cavern over 50 years of lifetime and the contribution of each stage expressed per kg of hydrogen stored (considering 1,250,000 ton of total H_2 stored). In Figure 3, the relative contributions of each stage to the total impacts for salt cavern by impact category can be distinguished.

The construction stage presents the highest contribution to the impacts in five of the seven categories (climate change, acidification, both eutrophication categories and photochemical ozone formation), representing 59 to 81.5% of the total impacts, depending on the impact category. The operation stage has the largest contribution in both resources use categories (83-84%) and ranging from 14.5-41% in the remaining categories. The share of the abandonment stage is relatively small (less than 4%) in all categories, except in mineral and metal resources use (34%), contributing positively (negative shares) in five of the seven categories (climate change, acidification, photochemical ozone formation, and both resources use categories).

Table 5: Total environmental impacts of salt cavern over 50-years lifetime, per FU (kg of hydrogen stored).

Impact category	Construction	Operation	Abandonment	Total
Climate change (kg CO_2 eq./FU)	1.88E-01	9.59E-02	-2.79E-03	2.81E-01
Acidification (mol H+ eq./FU)	3.56E-04	2.46E-04	-1.25E-05	5.89E-04
Freshwater eutrophication (kg P eq./FU)	2.46E-06	4.41E-07	1.16E-07	3.02E-06
Marine eutrophication (kg N eq./FU)	1.33E-04	7.59E-05	1.92E-08	2.08E-04
Photochemical ozone formation (kg NMVOC eq./FU)	3.68E-04	1.87E-04	-5.34E-06	5.50E-04
Fossils resources use (MJ/FU)	1.65E+00	8.67E+00	-6.21E-02	1.03E+01
Minerals and metals resources use (kg Sb eq./FU)	1.11E-08	5.37E-08	-2.21E-08	4.26E-08

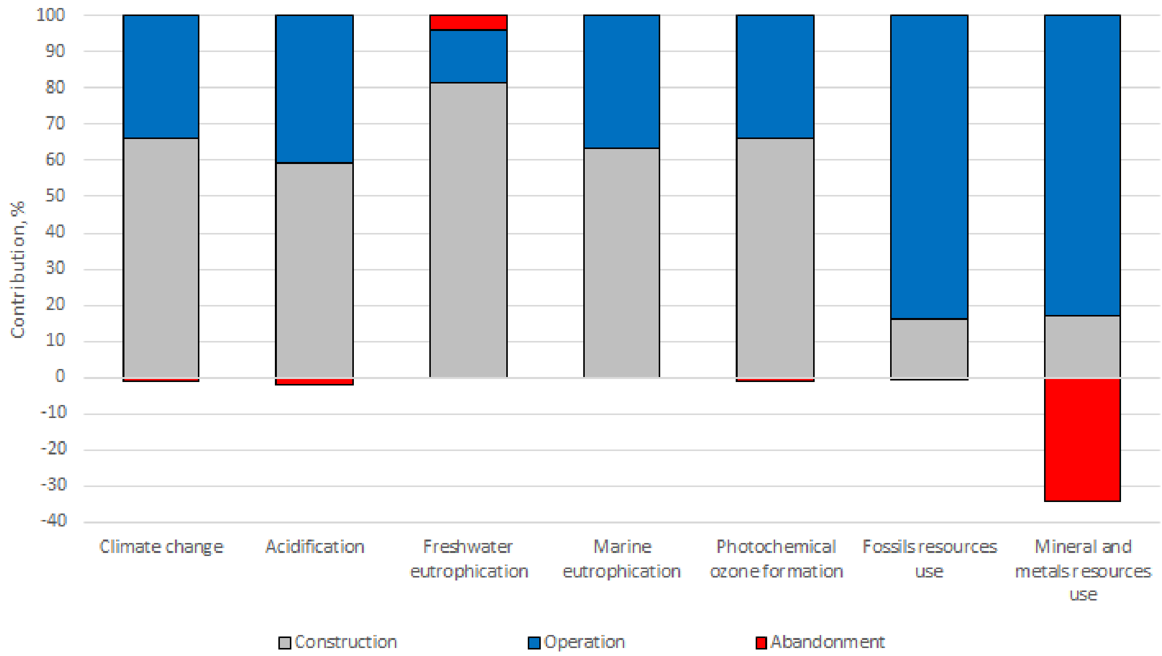

Figure 3: Relative contributions of the different life cycle stages to the total impacts for salt cavern storage by impact category.

The total scores for the climate change category (expressed in CO_2-equivalent emissions) for the construction stage, operation and abandonment stages of the salt cavern are, respectively: 235,000; 120,000 and -3,500 ton CO_2 eq., resulting in 351,500 ton CO_2 eq.; while the scores of CO_2-equivalent emissions per FU are: 1.88E-1, 9.59E-02 and -2.79E-3 kg CO_2 eq./kg H_2 stored for the construction, operation and abandonment stages, respectively, resulting in 2.81E-1 kg CO_2 eq./kg H_2 stored.

6.1.1.1 Construction stage

Figure 4 focuses on the components of construction stage (investigation phase, drilling & completion, leaching, surface facilities and buildings) for the future salt cavern. It shows that the surface facilities dominate the impacts of this stage in three of the seven impact categories (climate change, freshwater eutrophication and mineral and metals resources use), ranging from 43 to 73%. Drilling and completion causes the largest impact in acidification, marine eutrophication and photochemical ozone formation (reaching up to almost 49.5%), and leaching up to 60% in fossils resources use. The contribution of the buildings is small for all impact categories, not exceeding 4%, leading to a decrease of the impact (negative contribution of 34%) in mineral and metals resources use. The investigation phase has a negligible contribution in all impacts (<0.2%).

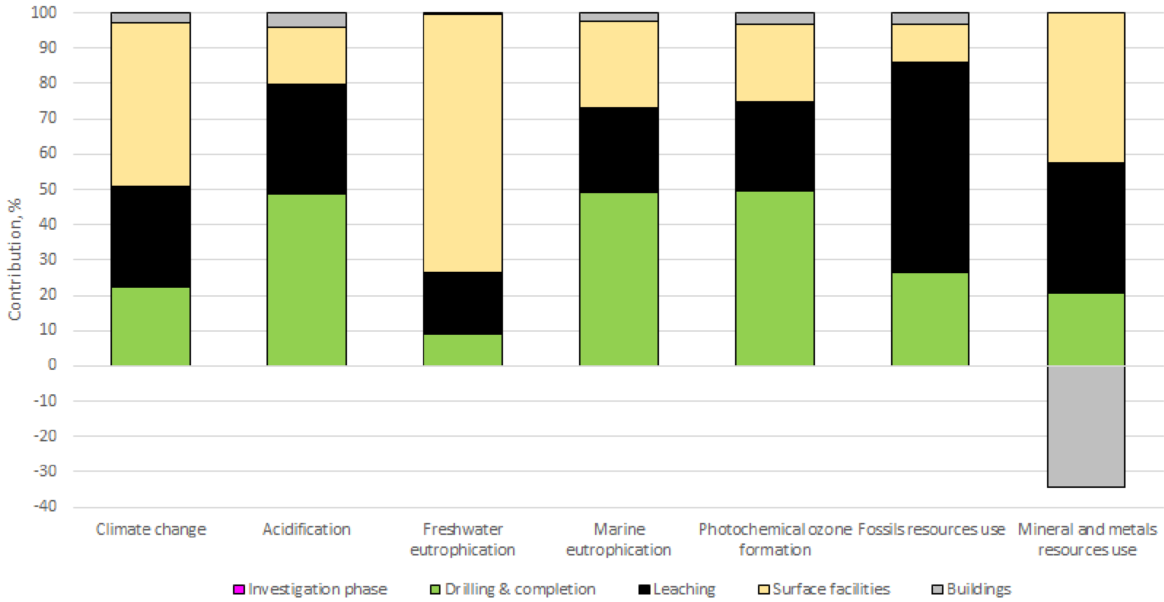

Figure 4: Relative contributions of the different components of the construction stage for the salt cavern by impact category.

A detailed contribution of the processes involved in the investigation phase is provided in Figure 5. The diesel use for machinery dominates the impacts of this phase in all categories (53-89%), except in fossils resources use, where the use of electricity has a contribution of 41% due to the French electricity mix of 2018 (see table A.II) is mainly dominated by the nuclear energy (uranium consumption). It should be noted that the electricity use represents 37.5% of the total impacts in mineral and metals resources use. The impacts of the staff travel by plane to the investigation phase contribute to 16-22% of the impacts, except in freshwater eutrophication and mineral and metals resources use for which it represents less than 5.5% of the total impacts. The remaining processes (cement and cargo and transport vehicles) contribute less than 7% of the impacts in all categories.

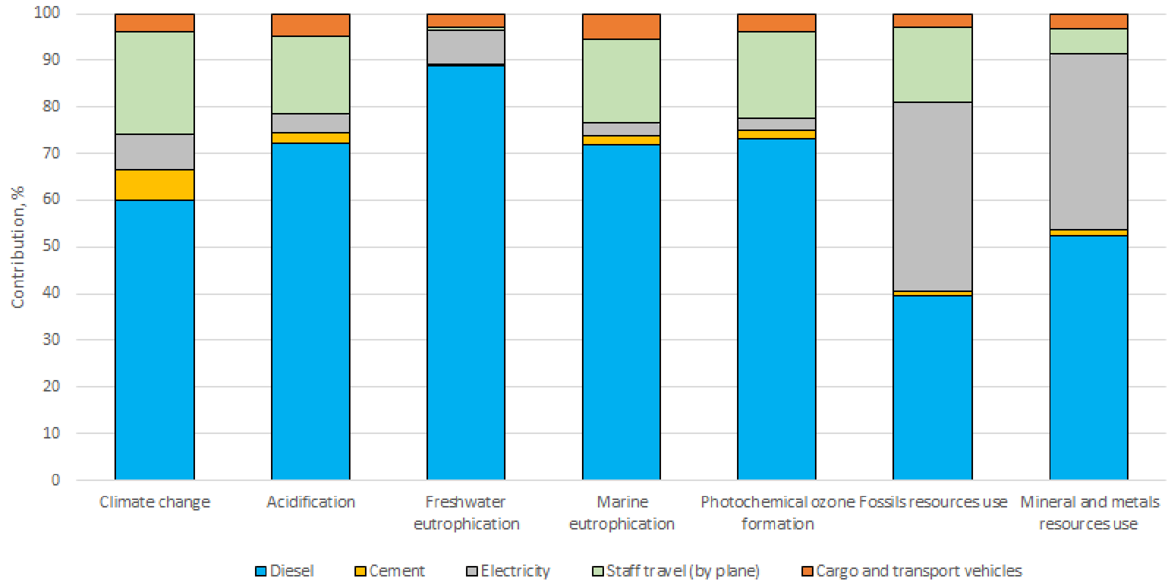

Figure 5: Relative contributions of the processes in the investigation phase (construction stage) for the salt cavern by impact category.

Figure 6 shows that the impacts of the drilling & completion are dominated by diesel use for machinery in all impacts categories, ranging from 49 to almost 76% of the total impacts. Steel pipe represents 15-40% of impacts in climate change, marine eutrophication, photochemical ozone formation and both resources use categories. The solid waste treatment (landfill) contributes to almost 24% of impacts in freshwater eutrophication and generates environmental a slight benefit (negative contribution less than 0.5%) in mineral and metals resources use because the landfill includes electricity generated from landfill gas utilisation and avoids the consumption of virgin material (mainly lead). The share of cargo and transport vehicles (trucks, boat) ranges from 3.5-6% in all categories. The contribution of the remaining processes (cement, nitrogen, potassium chloride, sodium chloride, bentonite, electricity, staff travel by plane and wastewater treatment) to this component is relatively small, lower than 1.5% in all impacts.

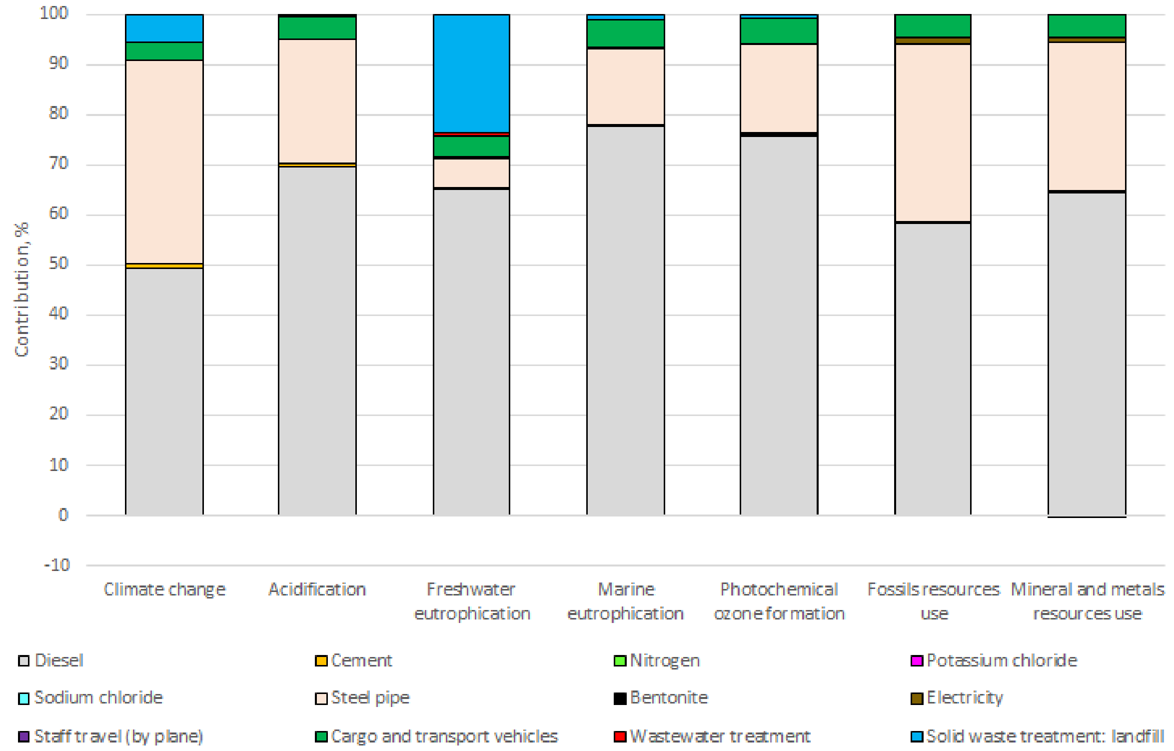

Figure 6: Relative contributions of the processes in the drilling & completion (construction stage) for the salt cavern by impact category.

Figure 7 shows the processes breakdown of the leaching. Steel pipe causes the largest impacts in four of the seven impact categories (climate change, acidification, marine eutrophication and photochemical ozone formation), ranging from 53 to 68% of the total impacts, mainly due to the CO_2 (climate change) and nitrogen oxides emissions. Electricity use contributes to 66-69% in both resources categories use due to the uranium consumption by the nuclear energy (French electricity mix). The contribution of solid waste treatment in freshwater eutrophication reaches almost 82% due to phosphorous emissions to water, and it also generated (as in drilling & completion phase) a small environmental benefit (negative contribution less than 1.5%) in mineral and metals resources use. The share of cargo and transport vehicles represents 10-16% of total impacts in acidification, marine eutrophication and photochemical ozone formation.

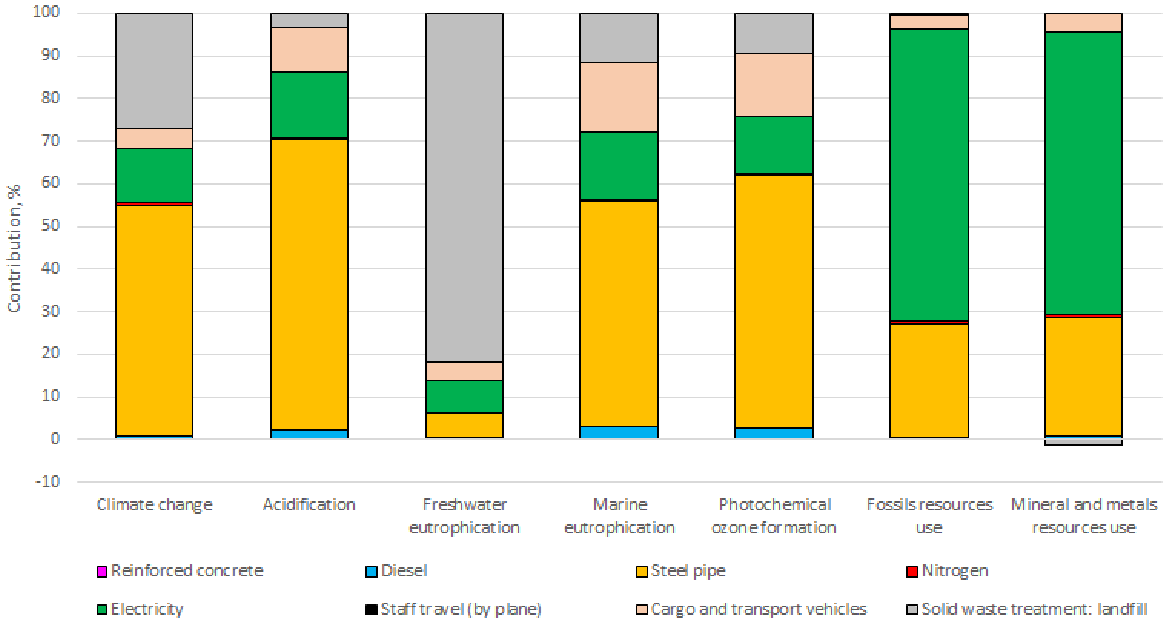

Figure 7: Relative contributions of the processes in the leaching (construction stage) for the salt cavern by impact category.

Figure 8 shows the processes breakdown of the surface facilities. The solid waste treatment has the highest contribution (30-97%) in climate change, acidification, both eutrophication, photochemical ozone formation, and as in drilling & completion and leaching, it also generated a slight environmental benefit (negative contribution less than 4%) in mineral and metals resources use. Steel pipe represents 20% in acidification and 24% in fossils resource use, mainly due to sulphur dioxide emissions to air and to crude oil consumption, respectively. The cargo and transport vehicles cause up to 43% of total impacts in fossils resource use mainly due to crude oil consumption. Cable represents almost 89% in mineral and metal resources use due to copper consumption. Steel generated an environmental benefit (negative contribution of 23%) in mineral and metals resources use due to the process from selected from GaBi uses steel scrap and avoids the use of virgin material (mainly zinc). The share of diesel use for machinery reaches 11-15% in acidification, marine eutrophication, photochemical ozone formation and fossils resources use. The contribution of remaining processes (reinforced concrete, HDPE) is less than 1.5% of total impacts.

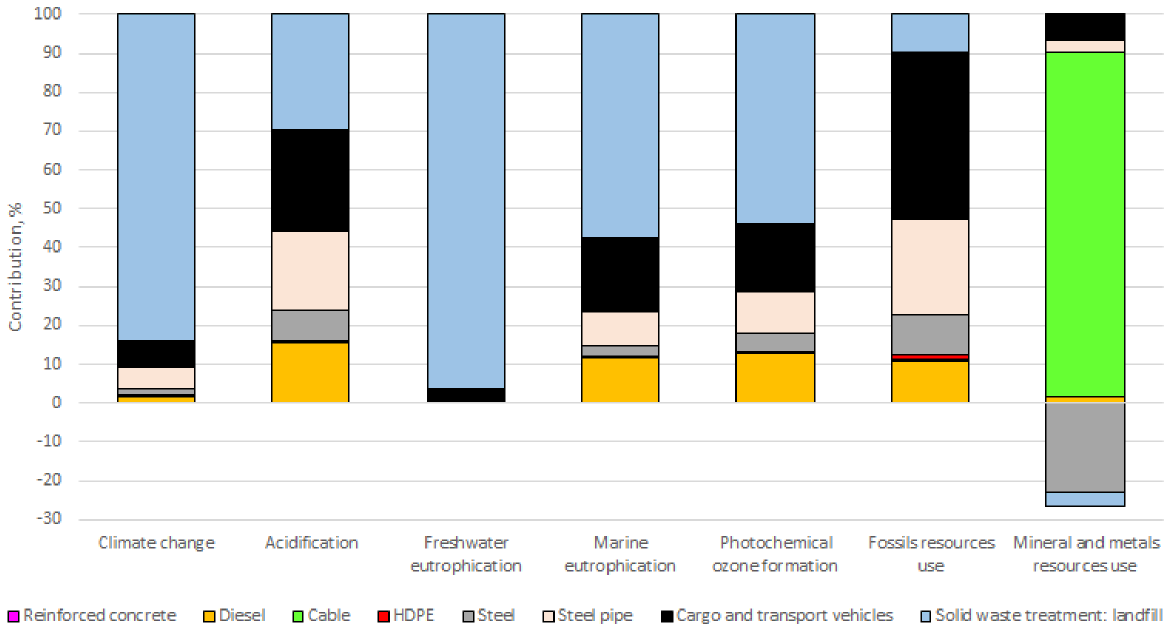

Figure 8: Relative contributions of the processes in the surface facilities (construction stage) for the salt cavern by impact category.

The processes breakdown of the building is shown in Figure 9. Steel is the main contributor in six of seven impacts (except in freshwater eutrophication), ranging from 75 to 84% of total impacts, and leading to positive impact (negative contribution) in mineral and metals resources use due to the production of steel uses steel scrap and avoids the consumption of virgin material (mostly zinc). Cargo and transport vehicles are the largest contributor (41%) in freshwater eutrophication mainly due to phosphate emissions to water. The contribution of diesel use for machinery reaches 10-15% in both eutrophication and photochemical ozone formation. The share of reinforced concrete is less than 6% of total impacts in all categories.

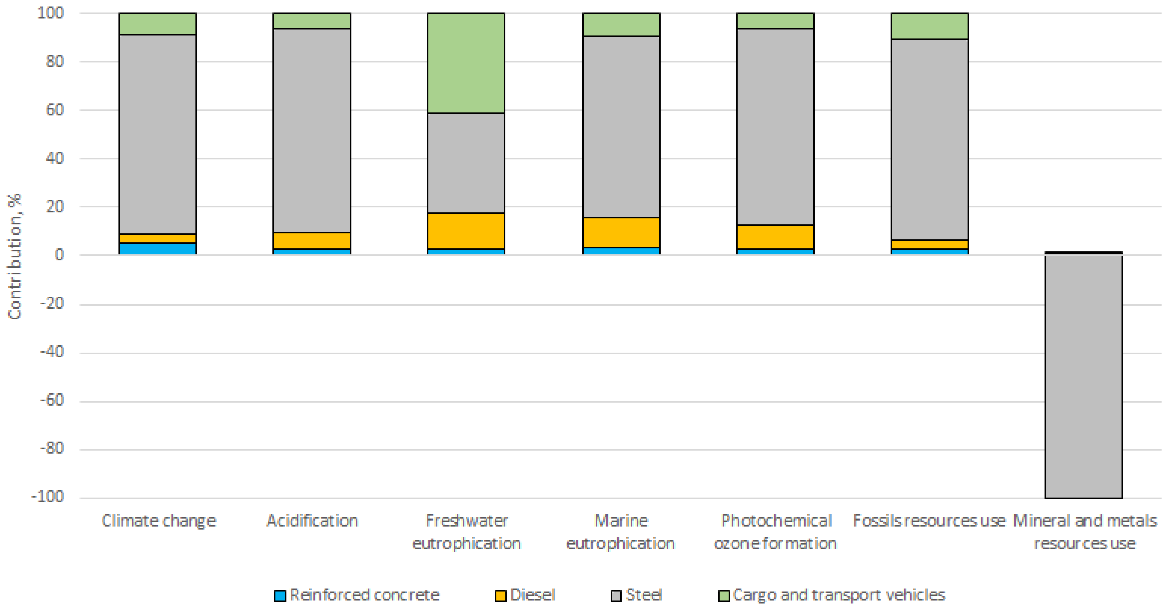

Figure 9: Relative contributions of the processes in the buildings (construction stage) for the salt cavern by impact category.

6.1.1.2 Operation stage

Concerning the relative contributions of the processes involved in the operation stage over 50 years for the theoretical salt cavern, Figure 10 shows that the impacts of this stage are clearly dominated by electricity use, ranging from 85% to 98.5% of the total impacts. The remaining processes represent less than 5% of the total impacts in all categories.

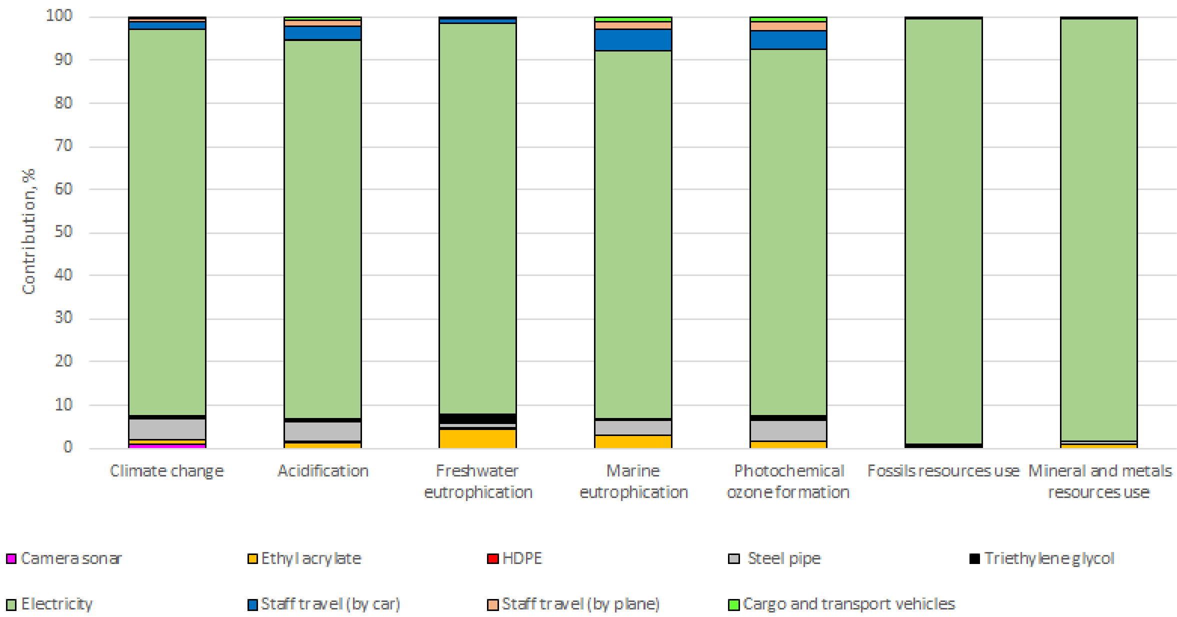

Figure 10: Relative contributions of the processes in the operation stage over 50 years for the salt cavern by impact category.

6.1.1.3 Abandonment stage

Regarding the processes involved in the abandonment stage for the salt cavern, Figure 11 shows that the steel recycling dominates the impacts of the abandonment stage for the salt caverns in all categories (except in freshwater eutrophication) and generates environmental benefits (negative contributions) in all impact categories because the recycling of steel scrap avoids the consumption of virgin material (mainly zinc) and fossils (mainly hard coal) and mitigating both resources use categories, and avoids the polluting emissions to soil (mainly ammonia, mitigating acidification), air (mainly carbon dioxide and nitrogen oxides, mitigating climate change and photochemical ozone formation, respectively), and water (mainly phosphorous and nitrogen, mitigating both eutrophication categories). In marine eutrophication, the negative emissions resulting from the steel recycling almost equals the positive emissions from the rest of the processes. Solid waste treatment causes the largest impacts in freshwater eutrophication (91%) and contributes up to 50% in climate change due to the emissions of phosphorous to fresh water and methane to air, respectively.

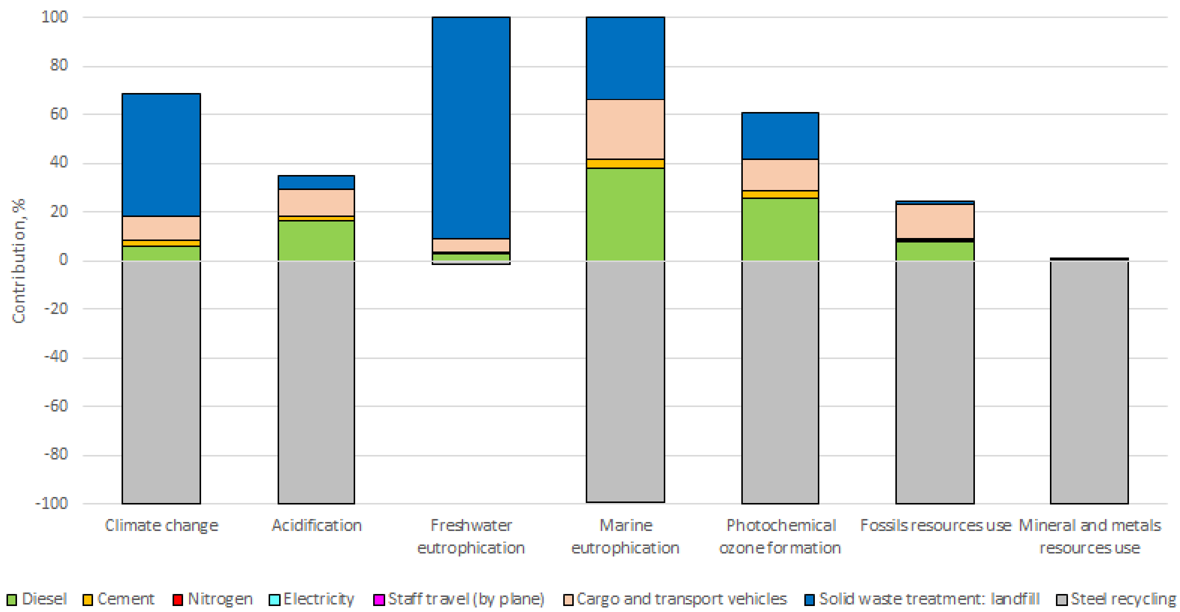

Figure 11: Relative contributions of the processes in the abandonment stage for the salt cavern by impact category.

6.1.1.4 Hotspots of processes

The relative contributions of the main processes of the salt caverns to the total environmental impact are included in Figure 12. The use of electricity during the operation stage has the highest environmental impacts for all categories, except freshwater eutrophication, ranging from 31 to 83%. The contribution of solid waste treatment (landfill) in the surface facilities of construction stage is particularly significant for freshwater eutrophication (58%) and climate change (26%). The use of diesel in drilling & completion of construction stage is also important in acidification (20%), marine eutrophication (24%) and photochemical ozone formation (25%). The recycling steel in abandonment stage has a negative share (positive impact) in mineral and metals resources use of up to 13%. The remaining processes of the different stages present a contribution from 7 to 23%.

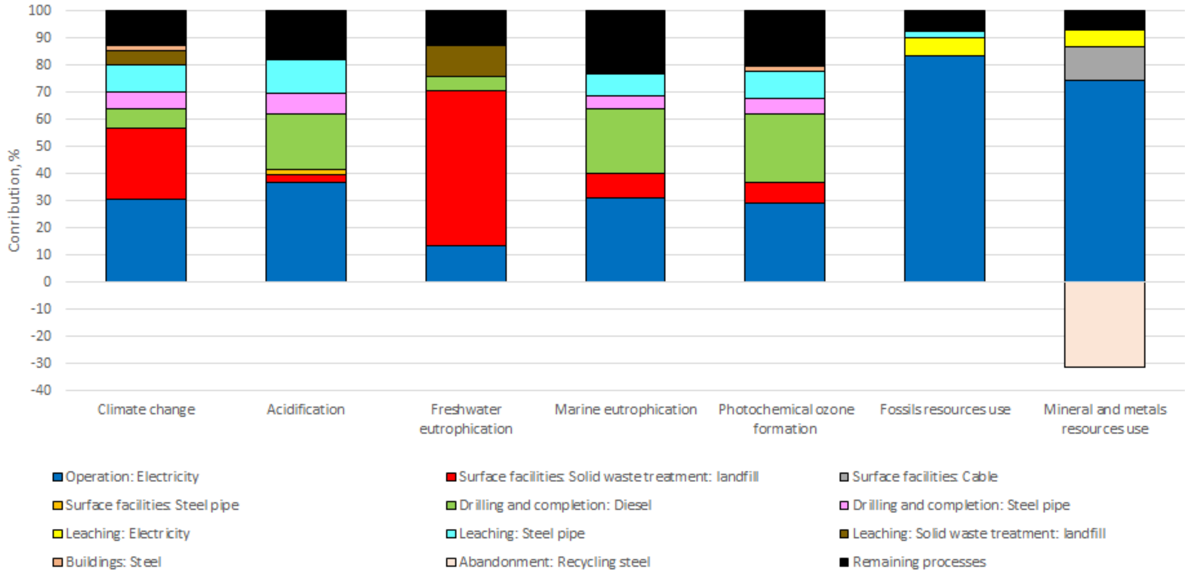

Figure 12: Contributions of the main processes of the salt caverns to the total environmental impact by impact category.

6.1.2. Porous media

The total environmental impact scores of the theoretical porous media over 50 years of lifetime and the contribution of each stage expressed per FU (kg of hydrogen stored) (considering 2,750,000 ton of total H_2 stored) are shown in Table 6. Figure 13 presents the relative contributions of each stage to the total impacts for the porous media by impact category.

The operation stage has the highest impacts in all categories, except in freshwater eutrophication, representing 61 to almost 97% of the total impacts, depending on the impact category. The construction stage has the largest contribution in freshwater eutrophication (56.5%) and ranges from 30-39% in climate change, acidification, marine eutrophication and photochemical ozone formation, and less 4% in resources use categories. The contribution of the abandonment stage is relatively small (less than 3%) in all categories, except in mineral and metals resources use (13.5%), contributing positively (negative contributions) in all categories except freshwater eutrophication.

Table 6: Total environmental impacts of the porous media over 50-years lifetime, per kg of H_2 stored.

Impact category	Construction	Operation	Abandonment	Total
Climate change (kg CO_2 eq./FU)	7.84E-02	1.53E-01	-2.04E-03	2.29E-01
Acidification (mol H+ eq./FU)	1.69E-04	3.87E-04	-7.83E-06	5.48E-04
Freshwater eutrophication (kg P eq./FU)	1.03E-06	7.26E-07	5.99E-08	1.81E-06

Impact category	Construction	Operation	Abandonment	Total
Marine eutrophication (kg N eq./FU)	6.54E-04	1.18E-04	-2.92E-07	1.83E-04
Photochemical ozone formation (kg NMVOC eq./FU)	1.82E-04	2.88E-04	-3.86E-06	4.66E-04
Fossils resources use (MJ/FU)	4.57E-01	1.46E+01	-3.71E-02	1.51E+01
Minerals and metals resources use (kg Sb eq./FU)	3.39E-09	9.06E-08	-1.27E-08	8.13E-08

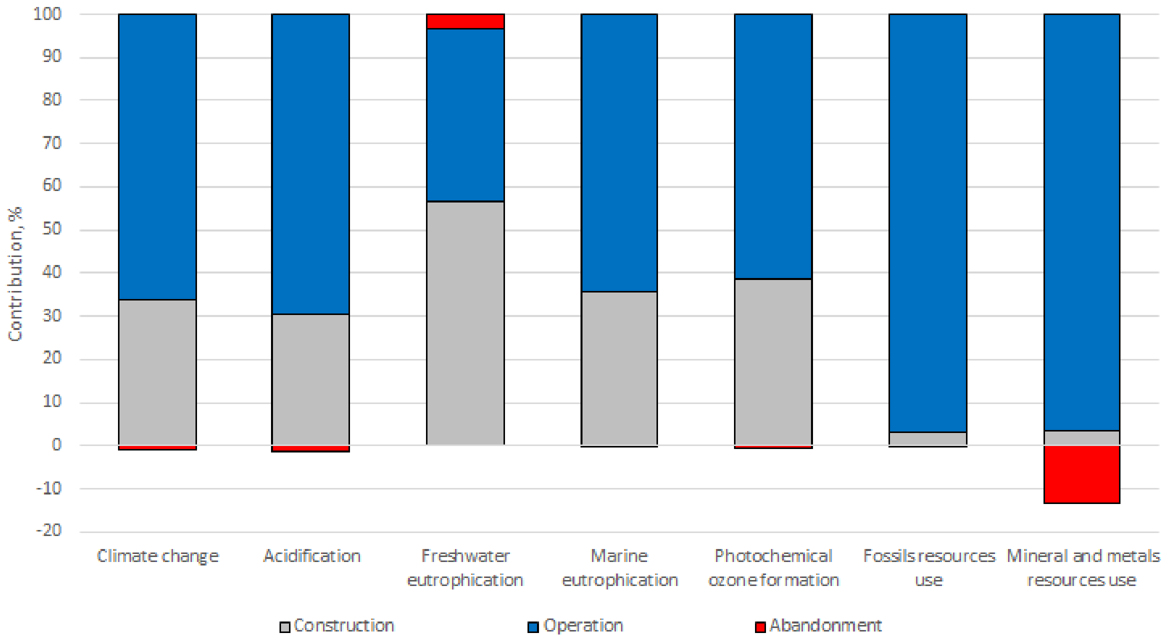

Figure 13: Relative contributions of the different life cycle stages to the total impacts for the porous media storage by impact category.

The total CO_2-equivalent emissions for the construction stage, operation and abandonment stages of the porous media are, respectively: 216,000; 420,000 and -5,600 ton CO_2 eq., resulting in 630,400 ton CO_2 eq.; while the CO_2-eq. emissions per FU are: 7.84E-2, 1.53E-01 and -2.04E-3 kg CO_2 eq./kg H_2 stored, for the construction, operation and abandonment stages, respectively, resulting in 2.29E-1 kg CO_2 eq./kg H_2 stored.

6.1.2.1 Construction stage

Figure 14 provides the relative contributions of the different components of the construction stage (investigation phase, drilling & completion, surface facilities and buildings) for the future porous media to the total impacts by impact category. Drilling and completion dominates the impacts of this stage in four of the seven impact categories (acidification, marine eutrophication and photochemical ozone formation and fossils resources use), ranging from 75 to 80%. Surface facilities causes the largest impact in climate change (50%), freshwater eutrophication (80%) and mineral and metals resources use (54%). The contribution of the buildings is irrelevant for all impact categories, not exceeding 6%, leading to a decrease of the impact (negative contribution of 43.5%) in mineral and metals resources use. The investigation phase has an insignificant share (<0.1%) in all impacts.

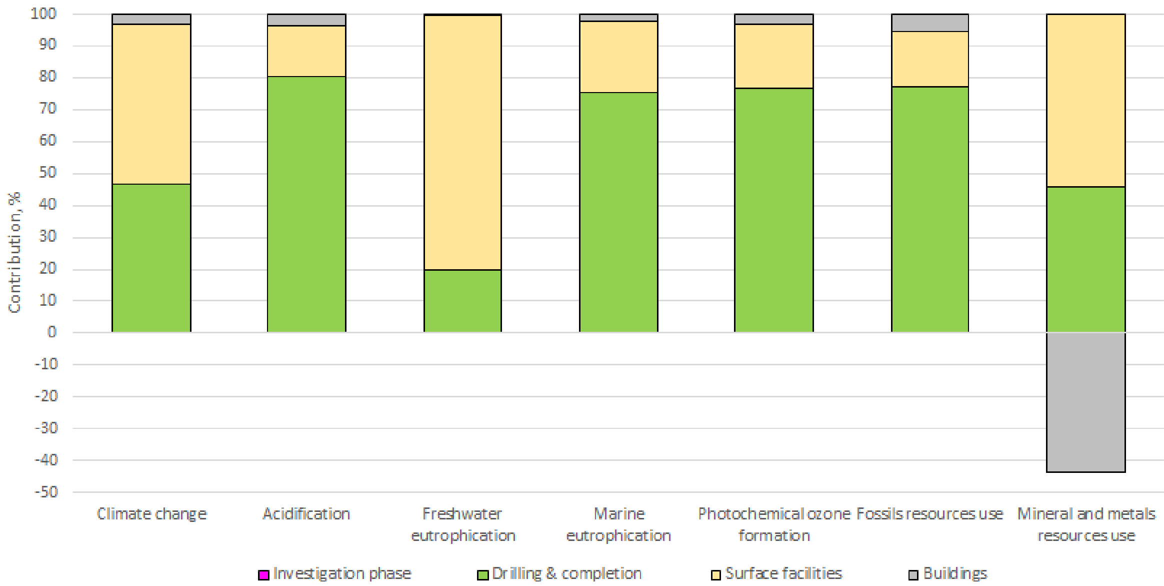

Figure 14: Relative contributions of the different contributions of the construction stage for the porous media by impact category.

The breakdown of processes involved in the investigation phase, surface facilities and buildings of construction stage for porous media are similar to those of the salt cavern (see Figures 5, 8, 9, respectively) since the inventory data for these components are the same for both storage sites (see table 2).

Figure 15 presents a detailed contribution of the processes involved in the drilling & completion. The impacts of this component are dominated by diesel use for machinery in all impact categories, except in climate change, ranging from 49 to 70.5% of the total impacts. Steel pipe is the main contributor to climate change (46%), contributing 20-43% of total impacts in marine eutrophication, photochemical ozone formation and both resources use categories. The solid waste treatment (landfill) contributes up to 36% of impacts in freshwater eutrophication and generates environmental a slight benefit (negative contribution less than 0.6%) in mineral and metals resources use because the landfill includes electricity generated from landfill gas utilisation and avoids the consumption of virgin material (mainly lead). The share of cargo and transport vehicles (trucks, boat) ranges from 4-7% in all categories. The contribution of the remaining processes (cement, nitrogen, potassium chloride, sodium chloride, bentonite, electricity, staff travel by plane and wastewater treatment) to this component is relatively small, lower than 2.5% in all impacts.

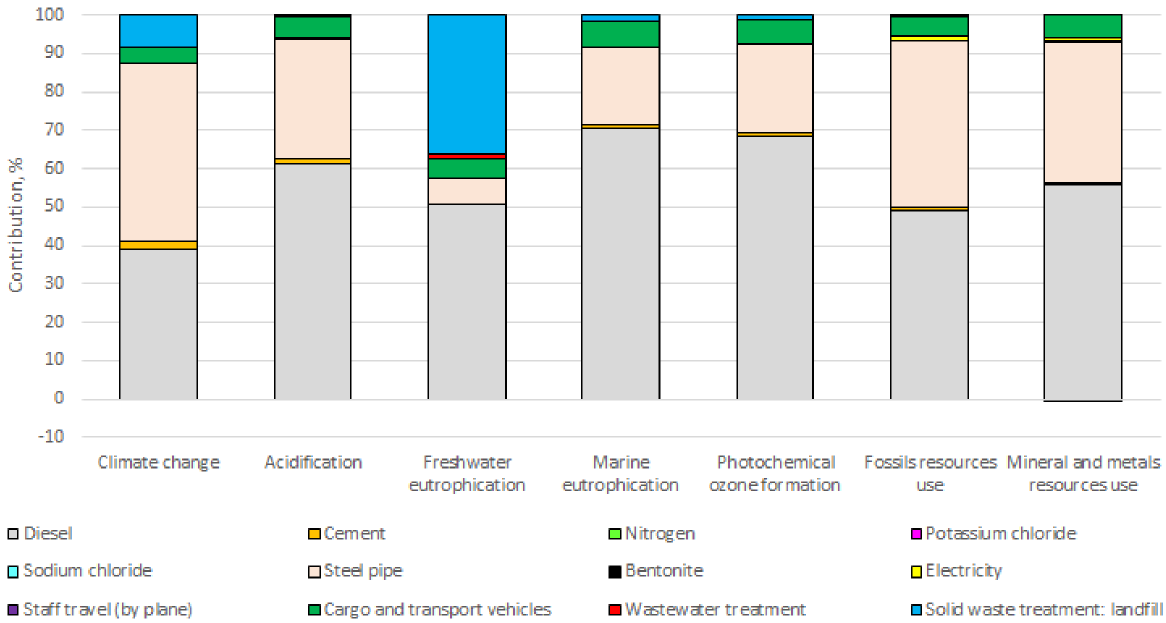

Figure 15: Relative contributions of the processes in the drilling & completion (construction stage) for the porous media by impact category.

6.1.2.2 Operation stage

The breakdown of processes involved in the operation stage over 50 years for the theoretical porous media is shown in Figure 16. The impacts of this stage are clearly dominated by electricity use, ranging from 93.5% to 99% of the total impacts. The remaining processes represent less than 4% of the total impacts in all categories.

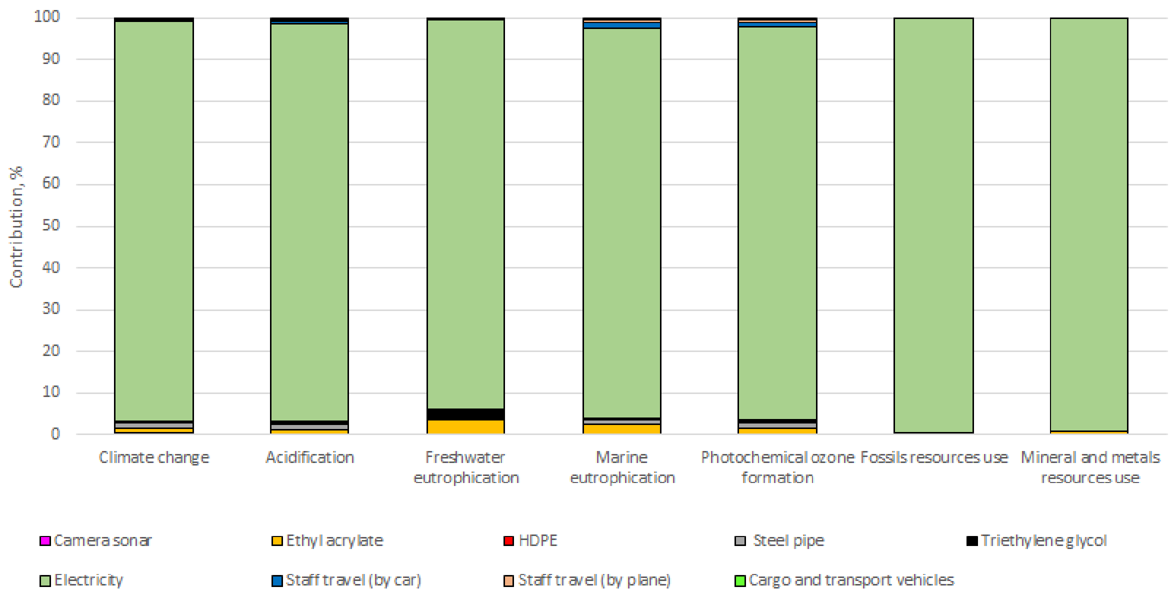

Figure 16: Relative contributions of the processes in the operation stage over 50 years for the porous media by impact category.

6.1.2.3 Abandonment stage

Figure 17 shows that the impacts of the processes involved in the abandonment stage for the porous media are dominated by the steel recycling in all categories (except in freshwater eutrophication) and generates environmental benefits (negative shares) in all impact categories because the recycling of steel scrap avoids the consumption of virgin material (mainly zinc) and fossils (mainly hard coal), and avoids the polluting emissions to soil (mainly ammonia), air (mainly carbon dioxide and nitrogen oxides), and water (mainly phosphorous and nitrogen). Solid waste treatment (landfill) causes the highest impacts in freshwater eutrophication (91%) due to phosphorous emissions to water and contributes up to 45% in climate change due to methane emissions to air.

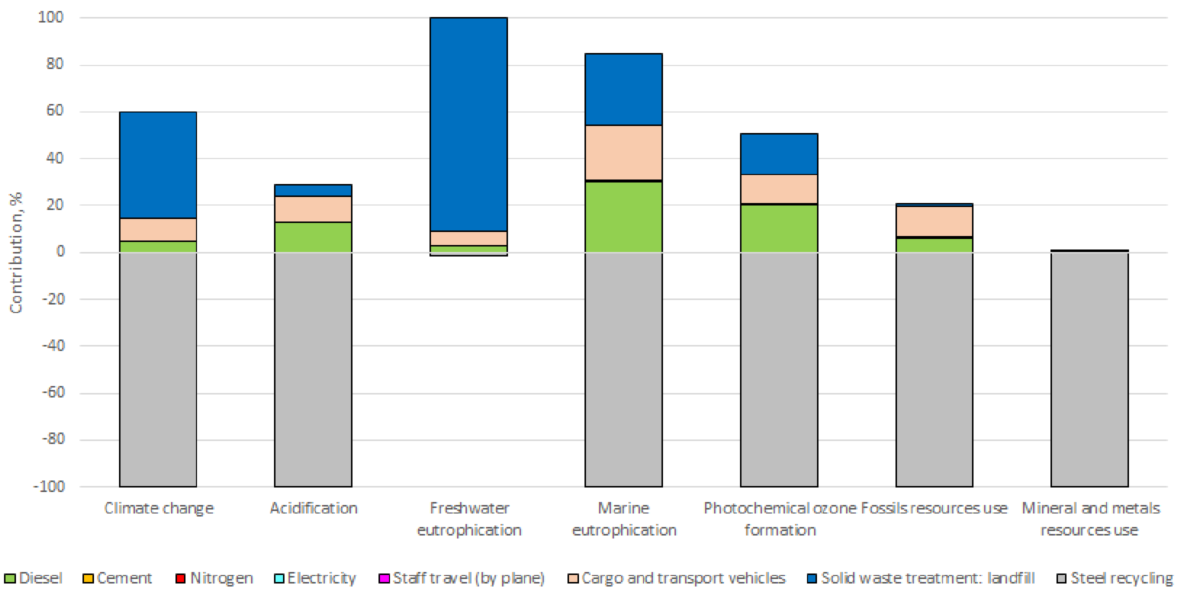

Figure 17: Relative contributions of the processes in the abandonment stage for the porous media by impact category.

6.1.2.4 Hotspots of processes

Figure 18 shows the relative contributions of the main processes of the porous media to the total impact. The use of electricity during operation stage has the largest environmental burdens for all impact categories, except in freshwater eutrophication, ranging from 58 to 97%. The contribution of solid waste treatment (landfill) in the surface facilities of construction stage is particularly relevant for freshwater eutrophication (44%). The use of diesel for machinery in drilling & completion of construction stage is also important in acidification (15%), marine eutrophication (19%) and photochemical ozone formation (20.5%). The recycling steel in abandonment stage has a negative contribution (positive impact) in mineral and metals resources use of up to 32%. The remaining processes of the different stages have a contribution of less than 14.5%.

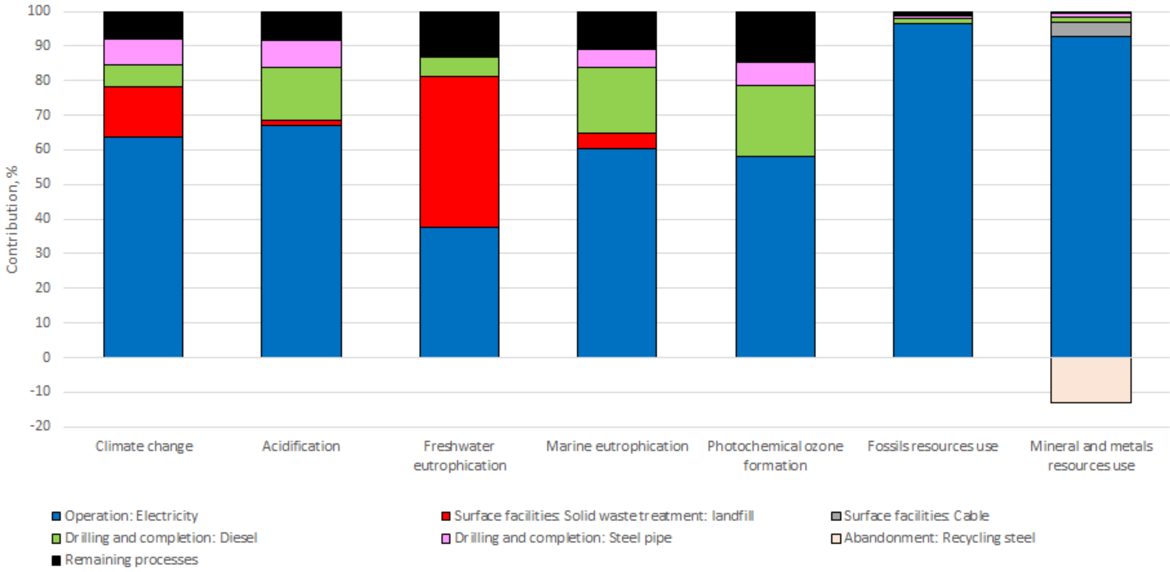

Figure 18: Contributions of main processes of the porous media to the environmental impact by impact category.

6.2. Sensitivity analysis

The results of this study highlight the relevance of the operation stage, more specifically consumption of electricity, to the total environmental impact of both theoretical storage sites; therefore, it is important to analyse the environmental burdens according to different scenarios of electricity production mix. In addition to the base case (French mix, mainly based on nuclear energy), different electricity origin scenarios were considered (see Table A.II of Annex I): Norwegian mix, predominantly based on hydropower (96%); Danish mix with up to 46% wind, 22% hard coal and 15% solid biomass; green Germany, a renewable origin scenario with a high presence of wind (52%), photovoltaic (20%) and biogas (14%); and green global, also of renewable origin, with a high presence of wind (55%), photovoltaic (26%) and hydropower (16%).

Figure 19 and Figure 20 show, for each impact category, and for salt cavern and porous media, respectively, the relative contribution of the total impacts obtained for different electricity origin, indicating that there are significant variations in all impact categories. Variation in degree of impact ranged from 41-55% (salt cavern) and 20-39% (porous media) for the worst case in climate change, 41-84.5% (salt cavern) and 18-80% (porous media) in acidification, 29-45% (salt cavern) and 10-33% (porous media) in freshwater eutrophication, 43.5-85% (salt cavern) and 20-80% (porous media) in marine eutrophication, 53-96.5% (salt cavern) and 26-95% (porous media) in photochemical ozone formation, 12-47.5% (salt cavern) and 6-44% (porous media) in fossils resources use, and 3-55% (salt cavern) and 3-56% (porous media) in mineral and metal resources use. Regardless the storage site, the German green scenario and the Norwegian scenario had, respectively, the greatest and lowest environmental impact in five of the seven categories considered: acidification, both eutrophication, photochemical ozone formation and mineral and metals resources use. It should be noted that the German green scenario presented an important difference with the others mixes in freshwater eutrophication and mineral and metal resources use. In the German green model, the main contributors are nitrogen emissions to the air from electricity derived from biogas and solid biomass in acidification, marine eutrophication and photochemical ozone formation; phosphate emissions to water from electricity derived from biomass in freshwater eutrophication, and lead consumption in mineral and fossil resource use. The Danish scenario was worse in climate change mainly due to the large share of power energy derived from hard coal. France, where nuclear energy contributed up to 71% of the electricity consumed, had the poorest environmental performance in fossils resources use due to the uranium consumed at nuclear plants. Green global had the best performance in climate change and fossils resources use. Table A.III of Annex I encompasses the total environmental impacts of both storage sites according to the electricity origin.

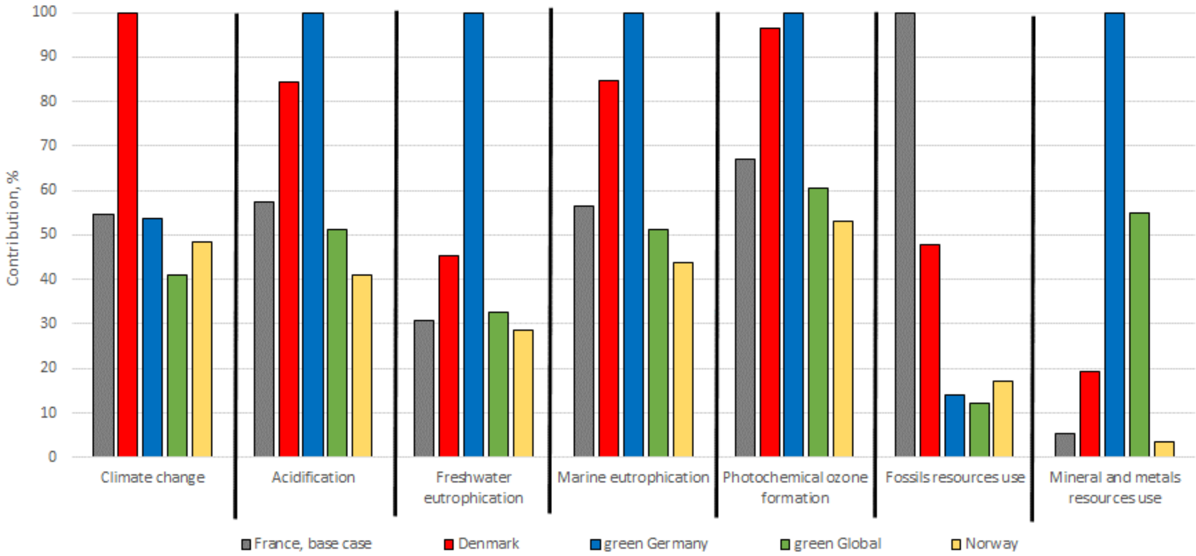

Figure 19: Relative contributions of total impacts according to the electricity production mix for salt cavern.

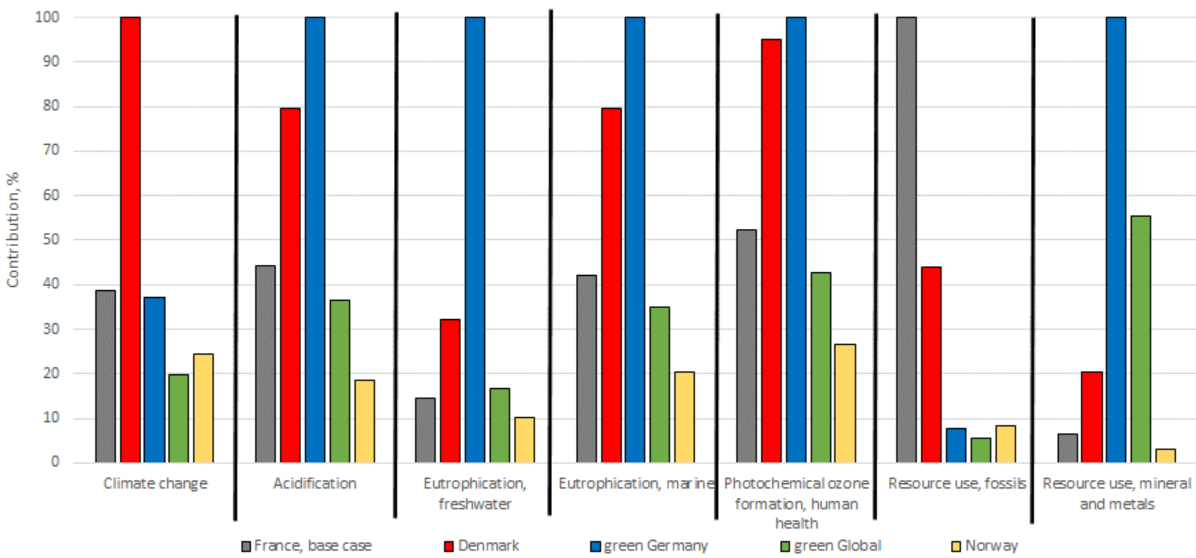

Figure 20: Relative contributions of total impacts according to the electricity production mix for porous media.

7. Comparison of large-scale underground storage systems

The benchmarking aims to compare E-LCA results of large-scale underground storage of hydrogen obtained in this study with other large-scale energy storage technologies or systems (e.g. pumped hydropower storage, compressed air energy storage, batteries). During the past five years, several public LCA studies evaluated different energy storage systems, whether focused on pumped hydropower storage (Guo et al., 2019), on compressed air (Li et al., 2021), on batteries (Carvalho et al., 2021), on both pumped hydropower storage and batteries (Immendoerfer et al., 2017; Kapila et al., 2019), and on both compressed air energy storage and batteries (AlShafi et al., 2021).

It is difficult to carry out a direct comparison among the technologies due to their inherent technical features, even though they are capable in principle of providing largely similar services. Pumped hydropower storage can supply the power grid with stable electricity, it drives the turbine in reserved mode using surplus electrical energy at low peak to store energy and back convert it into electricity when needed. Batteries can also provide the required balancing and ancillary services due to their capability to quickly absorb, hold, and then re-inject electricity into the grid; and compressed air energy storage smooths out energy demand through peak shaving and valley filling, it stores the heat generated by compressing air when there is less demand, which is then expanded through turbines to generate electricity to meet excess demand.

Hence, a comparable LCA-analysis was only undertaken between the two storage technologies analysed in this project (salt cavern and porous media) due to the limitations found in the other studies of the large-storage systems: difficulties in comparable functionality, different system boundaries, software and database, data accuracy, location, impact assessment methods and units, and difficulties in extracting numerical results.

7.1. Comparison of underground H_2 storage techniques

The comparative analysis of the total environmental impact of the theoretical underground H_2 storage sites expressed per kg of H_2 stored is shown in Figure 21 (for life cycle stages, assigning 100% to the storage site with the highest burden in each impact category) and Figure 22 (for main processes). The porous media analysed is clearly the best option from an environmental perspective in five of the seven impact categories (except in both resources use categories) due to the porous media stores 2.2 times more total kg of H_2 and consumes 1.7 times more electricity per kg of H_2 stored in operation stage (main hotspot process in both resources use categories) than the salt cavern analysed. For information, porous media consumes more electricity than salt cavern because a step of gas purification was added for porous media. On average, salt cavern analysed has an environmental impact of almost 1.4 times higher than porous media analysed.

It should be noted that in the salt cavern, although in some categories (climate change, acidification, marine eutrophication and photochemical ozone formation) the hotspot stage is the construction (Figure 21), the hotspot process is the electricity used during operation stage (Figure 22).

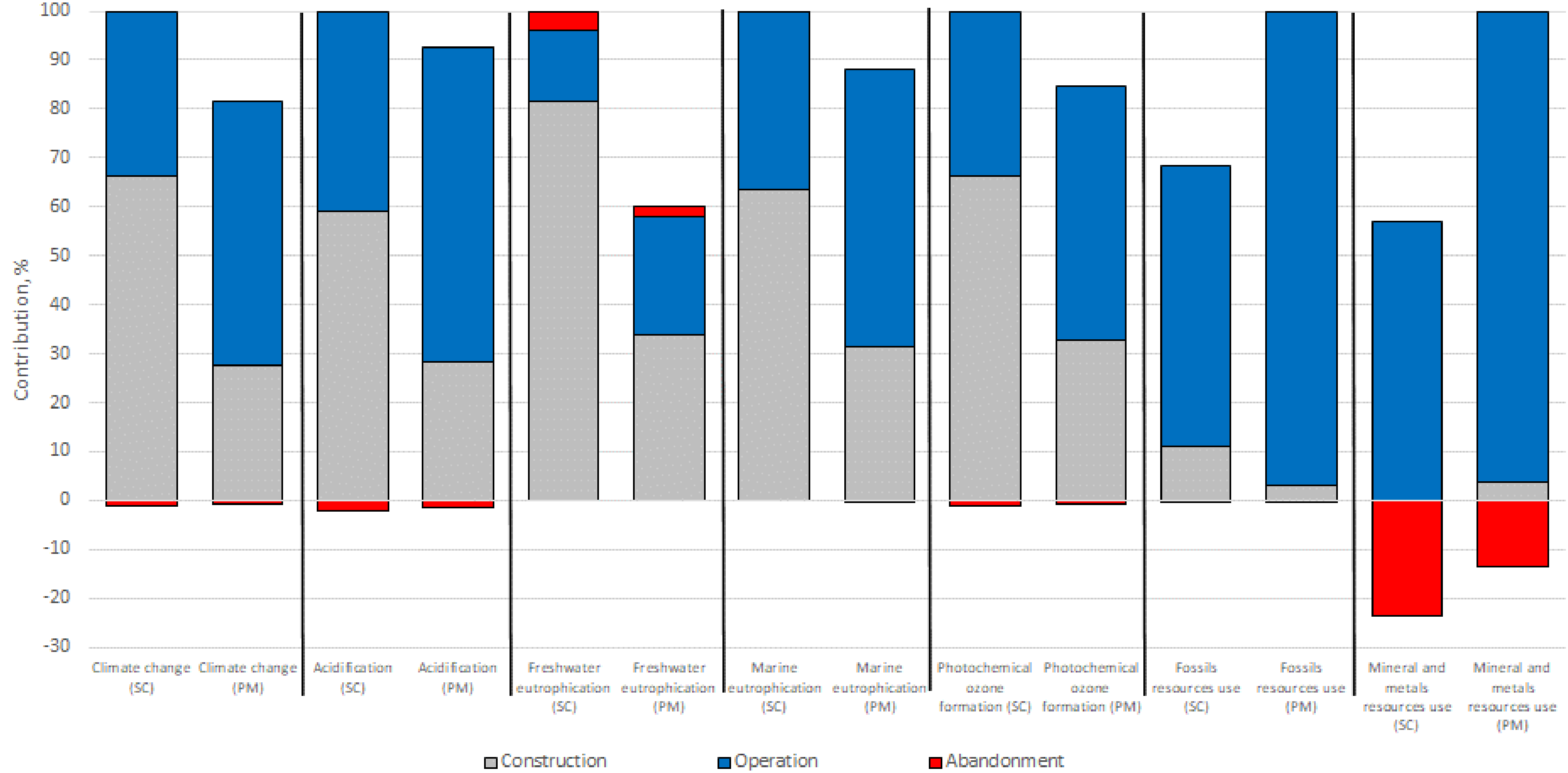

Figure 21: Contributions of life cycle stages for salt cavern (SC) and porous media (PM) by impact category, considering 100% for the storage site with the highest burden in each impact category.

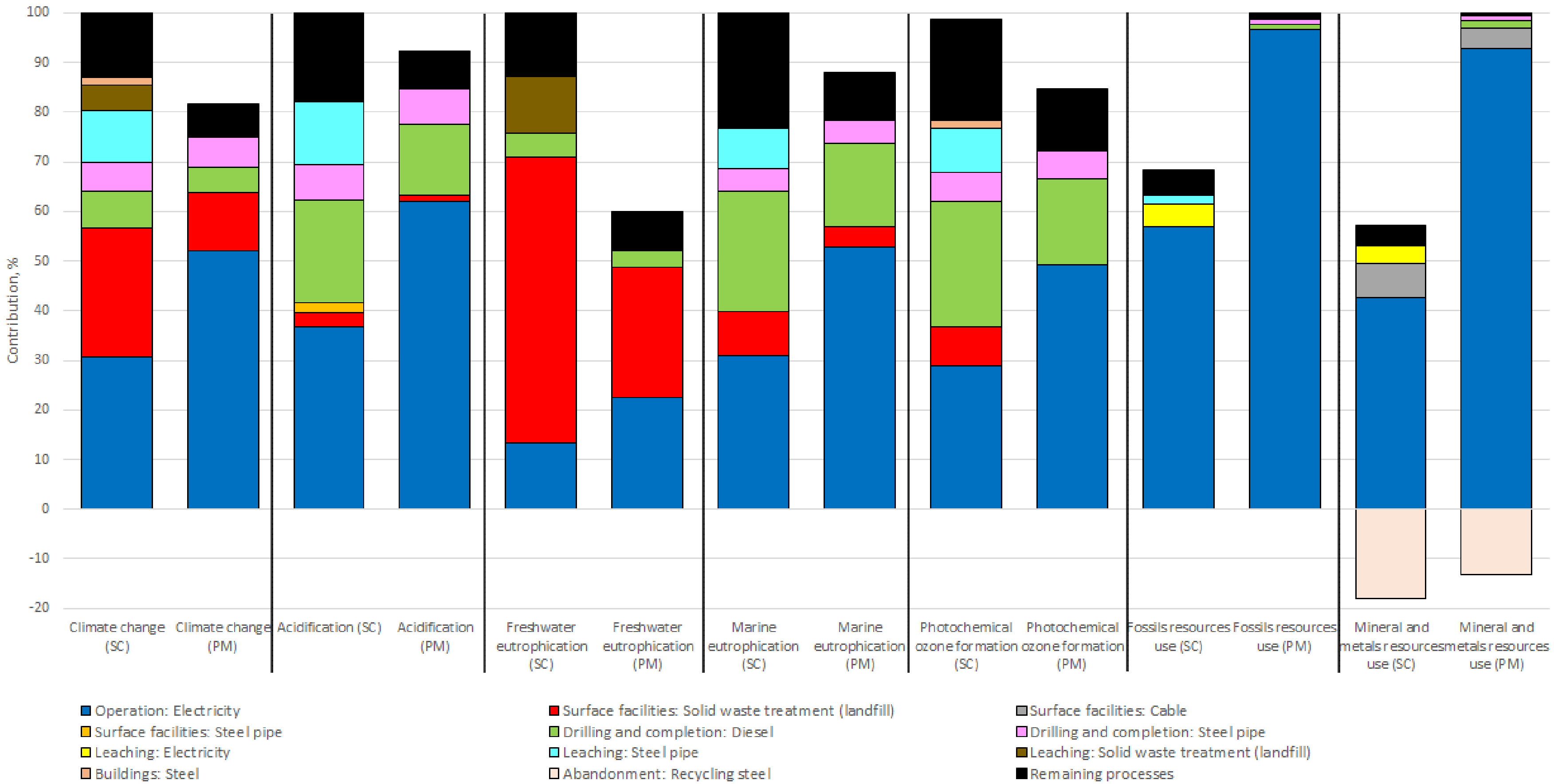

Figure 22: Contributions of main processes of salt cavern (SC) and porous media (PM) by impact category.

7.2. Underground storage perspective in relation to the H_2 production stage

Several emission factors and benchmarks for CO_2 emissions per kg of H_2 produced according to different H_2 production scenarios are collected in the second column of Table 7. If it is added to each of these emissions the CO_2-equivalent emissions from underground H_2 storage sites obtained in this study, the final values of CO_2 eq./kg H_2 produced and stored barely change due to the order of magnitude of the CO_2 eq. emissions per kg of H_2 produced (0-35.5 kg CO_2 eq./kg H_2 produced) is up to three orders higher than those got in this study (0.281-0.229 kg CO_2 eq./kg H_2 stored). It can be concluded that, from an E-LCA perspective, underground H_2 storage is not a H_2 value chain component with a high environmental burden compared to the H_2 production stage.

Table 7: Emission factors and benchmarks for CO_2 emissions related to H_2 according to the stages considered. RFNBO: Renewable transport Fuels of Non-Biological Origin; SMR: Steam Methane Reforming; CCS: Carbon Capture Storage; SC: salt cavern; PM: porous media.

Origin of H_2	Production (kg CO_2/kg H_2 produced) [a]	Production + storage in SC (kg CO_2 eq./kg H_2 produced and stored)	Production + storage in PM (kg CO_2 eq./kg H_2 produced and stored)
Electrolysis: Iceland mix electricity	0.0	0.281	0.229
Electrolysis: France mix electricity	2.8	3.081	3.029
EU Taxonomy [b]	3.0	3.281	3.229
RED II (threshold from RFNBO) [c]	3.384	3.665	3.613
SMR with CCS capture rate of 60%	4.4	4.681	4.629
SMR without CCS	9.0	9.281	9.229
Electrolysis: EU-27 mix electricity	11.5	11.781	11.729
Electrolysis: Poland mix electricity	35.5	35.781	35.729

[a] Values from Hydrogen Europe (2022), based on EEA data for 2020.
[b] EU Taxonomy threshold for sustainable H_2 manufacturing.
[c] RED II: Renewable Energy Directive from July 2021.

8. Conclusions

This report presents the final E-LCA findings of a future salt cavern and a future porous media for pure hydrogen storage, based on primary data provided by Geostock. The results shows that the main environmental hotspots in both underground H_2 storage sites analysed derive from the use of electricity in the operation stage. The impacts from construction stage are almost exclusively associated with the solid waste treatment in landfill (in the surface facilities) and the use of diesel for machinery (in the drilling and completion), whereas the abandonment stage has a small positive impact due to the steel recycling in both theoretical underground H_2 storage sites.

The sensitivity analysis according to different electricity production mixes indicates that the environmental burdens could change substantially depending on the electricity origin. Comparison between both H_2 storages sites showed the porous media analysed presents a better environmental performance per kg of H_2 stored than the salt cavern in all impact categories except in fossils resources use and mineral and metals resources use.

The detailed description of the impacts generated by the different stages of the theoretical storage sites analysed enables to understand the environmental footprint breakdown and develop solutions and alternatives to try to mitigate it. Thus, as mentioned before and based on these conclusions, the electricity consumption during operation is the main environmental hotspots, and consequently, the energy efficiency and optimization will be key factors to improve the global environmental performance of the future storage sites assessed.

The relatively low environmental impact of underground H_2 storage compared to H_2 production could encourage the implementation of renewable H_2, which needs to be stored due to its intermittent characteristics, in comparison to grey H_2 or grid connected electrolytic H_2 production, which do not need large storages because their production can be directly coupled to consumption point depending on its needs. Preference for any H_2 storage technology will have to weigh up preferences based on inherent technical characteristics on one hand against grid requirements and related economic, environmental and social impacts on the other.

9. References

AlShafi M., Bicer Y., 2021. Life cycle assessment of compressed air, vanadium redox flow battery, and molten salt systems for renewable energy storage. Energy Reports 7:7090-7105. doi: 10.1016/j.egyr.2021.09.161

Carvalho, M.L., Temporelli, A., Girardi, P., 2021. Life Cycle Assessment of Stationary Storage Systems within the Italian Electric Network. Energies 14, 2047. doi:10.3390/en14082047

EC-JRC, 2018. Fazio, S., Castellani, V., Sala, S., Schau, E.M., Secchi, M., Zampori, L., Diaconu E. Supporting Information to the Characterisation Factors of Recommended EF Life Cycle Impact Assessment methods. EUR 28888 EN, European Commission, Ispra, 2018, ISBN 978-92-79-76742-5, doi:10.2760/671368, JRC109369.

EEA, 2016. EMEP/EEA Air Pollutant Emission Inventory Guidebook 2016 - Technical Guidance to Prepare National Emission Inventories. European Environment Agency, Luxembourg. ISBN 978-92-9213-806-6

Guo Z., Ge S., Yao, X., Li H., Li, S., 2019. Life cycle sustainability assessment of pumped hydro energy storage. International Journal of Energy Research 1-13. doi:10.1002/er.4890

Horizon Europe, 2022. Clean H2 Monitor 2022. https://hydrogeneurope.eu/clean-hydrogen-monitor-2022/

Immendoerfer, A., Tietze I., Hottenroth H. Viere T., 2017. Life-cycle impacts of pumped hydropower storage and battery storage. International Journal of Energy Environmental Engineering 8:231-245. doi:10.1007/s40095-017-0237-5

ISO, 2006a. Environmental Management - Life Cycle Assessment - Principles and Framework. International Organization for Standardization, Geneva, Switzerland.

ISO, 2006b. Environmental management - Life cycle assessment - Requirements and guidelines. International Organization for Standardization, Geneva, Switzerland.

Kapila S., Oni A.O., Gemechu E.D., Kumar A., 2019. Development of net energy ratios and life cycle greenhouse gas emissions of large-scale mechanical energy storage systems. Energy 170:592-603. doi:10.1016/j.energy.2018.12.183

Kupfer, T., Baitz, M., Makishi-Colodel, C., Kokborg, M., Schöll, S., et al., 2020. GaBi Databases & Modeling Principles 2020. Sphera Solutions GmbH, Leinfelden-Echterdingen Germany. https://gabi.sphera.com/support/gabi/gabi-6-lci-documentation/

Li R., Zhang H., Chen H., Zhang, Y., Li Z., et al., 2021. Hybrid techno-economic and environmental assessment of adiabatic compressed air energy storage system in China-Situation. Applied Thermal Engineering 186:116443. doi:10.1016/j.applthermaleng.2020.116443

Annex I

This section presents the air emissions for the combustion of diesel for machinery and kerosene for passenger aircraft (Table A.I), the different scenarios of electricity production mix (Table A.II), and the total environmental impacts per kg of hydrogen stored for salt cavern and porous media according to the scenarios of electricity production mix (Table A.III).

Table A.I. Emissions to air for the fuel combustion for machinery and passenger aircraft based on emission factors from EEA (2016).

Air emission	Diesel	Kerosene
g CO_2/kg fuel	3,160	3,150
g CH_4/kg fuel	0.083	0.214
g N_2O/kg fuel	0.135	0.086
g NO_x/kg fuel	22.059	14.863
g NMOC/kg fuel	1.075	0.391
g CO/kg fuel	2.838	2.828
g SO_x/kg fuel	2.021	-
g SO_2/kg fuel	-	0.840

Table A.II. Different models of electricity production mix of 2018 from GaBi database (Kupfer et al., 2020).

Origin	France	Denmark	green Germany	green global	Norway
Electricity from nuclear (%)	70.96	-	-	-	-
Electricity from hydropower (%)	12.21	0.05	7.41	16.24	95.19
Electricity from natural gas (%)	5.26	6.82	-	-	1.76
Electricity from wind (%)	4.91	45.75	52.19	55.50	2.64
Electricity from hard coal (%)	1.45	21.63	-	-	0.03
Electricity from photovoltaics (%)	1.82	3.14	20.16	25.99	-
Electricity from fuel oil (%)	1.03	0.87	-	-	0.02
Electricity from biomass (solid) (%)	0.65	14.54	4.33	1.51	0.01
Electricity from waste (waste-to-energy) (%)	0.79	5.15	2.27	0.03	0.23
Electricity from coal gases (%)	0.49	-	-	-	0.09
Electricity from biogas (%)	0.41	2.05	13.56	0.36	0.01
Electricity from geothermal (%)	0.02	-	0.08	0.33	-
Electricity from solar thermal (%)	-	-	-	0.04	-

Table A.III. Total environmental impacts of salt cavern and porous media over 50-years lifetime per FU (kg of hydrogen stored) according to the electricity origin.

Salt cavern	Denmark	green Germany	green global	Norway
Climate change (kg CO_2 eq./FU)	5.13E-01	2.75E-01	2.11E-01	2.49E-01
Acidification (mol H+ eq./FU)	8.67E-04	1.03E-03	5.27E-04	4.21E-04
Freshwater eutrophication (kg P eq./FU)	4.42E-06	9.77E-06	3.18E-06	2.80E-06
Marine eutrophication (kg N eq./FU)	3.12E-04	3.68E-04	1.89E-04	1.61E-04
Photochemical ozone formation (kg NMVOC eq./FU)	7.91E-04	8.19E-04	4.95E-04	4.33E-04
Fossils resources use (MJ/FU)	4.89E+00	1.44E+00	1.24E+00	1.75E+00
Minerals and metals resources use (kg Sb eq./FU)	1.57E-07	8.06E-07	4.43E-07	2.73E-08
Porous media	**Denmark**	**green Germany**	**green global**	**Norway**
Climate change (kg CO_2 eq./FU)	5.95E-01	2.21E-01	1.18E-01	1.46E-01
Acidification (mol H+ eq./FU)	9.87E-04	1.24E-03	4.51E-04	2.28E-04
Freshwater eutrophication (kg P eq./FU)	4.02E-06	1.25E-05	2.06E-06	1.27E-06
Marine eutrophication (kg N eq./FU)	3.47E-04	4.35E-04	1.51E-04	8.88E-05
Photochemical ozone formation (kg NMVOC eq./FU)	8.47E-04	8.91E-04	3.80E-04	2.36E-04
Fossils resources use (MJ/FU)	6.60E+00	1.17E+00	8.51E-01	1.26E+00
Minerals and metals resources use (kg Sb eq./FU)	2.62E-07	1.29E-06	7.13E-07	4.09E-08

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