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State of the art review of the environmental assessment and risks of underground geo-energy resources exploitation

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ABSTRACT

Geo-resources play an increasing significant role in achieving a sustainable energy future. However, their exploitation is not free of environmental impacts. This paper aims to identify the lessons and knowledge gaps on understanding of the sources, mechanisms and scope of environmental consequences of underground geo-energy resources exploitation. The paper examines four underground exploitation activities: CO_2 geological storage, exploitation of shale gas, geothermal power and compressed air energy storage (CAES). Selected studies carrying out life cycle assessment (LCA) and environmental risk assessment (ERA) are structurally reviewed by applying a six steps method. Our finding indicates that global warming potential is the major focus of examined LCA studies with relatively less attention on other impacts. Environmental impacts at the local level are less evaluated except water use for shale gas and geothermal power. Environmental impacts of exploitation with storage purposes are relatively low. For energy supply associated exploitation, the impacts largely depend on the types of underground activities and the exploited energy carriers. In the ERA studies, likelihood of a hazard occurrence is the focus of the probability assessment. There is limited information on the pathways and transport of hazard agents in the subsurface and on the relation between hazard exposure and the impacts. The leakage of the storing agents is the well-identified hazard for storage associated exploitation, while the migration of fluids and exploited energy carriers are the ones for exploitation with energy supply purposes. In general, understanding of environmental risks of soil contamination are limited. Very few number of ERA studies are available for assessing a CAES. Our research points out the need for developing a framework which allows the integration between LCA and ERA in subsurface environmental management.

1. Introduction

Increasing energy demand, ensuring energy security, mitigating climate change and enhancing flexibility of energy systems are four key challenges for a sustainable energy future. Exploitation of geo-resources for energy purposes, which goes well beyond fossil fuels exploitation, play an important role in meeting these challenges. Current geo-resources exploitation for energy purposes can be divided into three categories:

- *Primary energy supply*, such as oil and gas exploitation, coal mining, geothermal development, etc.
- *Retrieval storage*, such as compressed air energy storage, hydrogen and natural gas storage and thermal energy storage, etc.
- *Permanent storage*, such as radioactive waste storage and CO_2 geological storage, etc.

Geo-resources associated primary energy carriers, mostly oil, coal and natural gas, have accounted for more than 80% of the total world primary energy supply in the last four decades [1]. Future energy demand is forecasted to keep growing in the coming decades and energy security will remain an issue at both global and national levels [2,3]. Fossil geo-resources are expected to still play a significant role in the future energy mix. The US national shale gas production has increased from 1.97 tcf in 2005 to 13.34 tcf in 2015 [4]. It is expected to provide 50% of the US natural gas production in 2040 [5]. Fossil fuels are, however, not the only geo-resources with a growing trend. The global capacity of geothermal power has doubled since 1990 reaching 13.2 GW in 2015 [6]. A recent report on the potential of geothermal resources indicates an economic feasible geothermal power production in Europe at 174 TW h in 2030 and 4000 TW h in 2050 [7]. Note that the latter figure is higher than the current European electricity supply.

In addition to the activities of fuels exploitation, the use of under-

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ground for permanent storage is also important. CO_2 geological storage and geological disposal of radioactive wastes are two examples of using the subsurface with a permanent storage purpose. In order to meet the target of limiting the CO_2 concentration to 450 ppmv, the global cumulative CO_2 storage has been estimated at 2168 t in 2100 [8]. The global primary energy supply from nuclear power generation today is about five times as much as four decades ago [1]. Depending on the scenario, it is expected that nuclear power generation can increase from 2400 TW h in 2015 to 6500 TW h in 2050 [6,9]. Such growth will strengthen the burden of safe and long term radioactive waste disposal, for which storage in deep formation is regarded as the most promising option.

Another potential role of geo-resources is as a part of strategies to increase flexibility of future energy systems. Geo-storage, such as compressed air energy storage (CAES), underground hydrogen storage and thermal energy storage (TES), could potentially serve as a buffer to facilitate intermittent renewable energy integration. In fact, CAES systems have been proved as one of the most cost effective technologies to facilitate wind power integration [10,11]. As renewables gain a larger share in the energy mix, the need for these types of systems is very likely to increase.

Exploitation of geo-resources for energy purposes is however not free of environmental impact. The environmental effects of its life cycle chain generally include land use, atmospheric emissions, emissions to soil and water, water use and consumption, solid waste and waste heat, geological hazards as well as noise and impacts on biodiversity, etc. There are different approaches for identifying and assessing such effects. Two common ones are life cycle assessment (LCA) and environmental risk assessment (ERA). LCA is widely recognized as an effective tool to evaluate the aggregated environmental impacts over the entire life cycle of a product or service [12–14]. It facilitates decision making processes by allowing a quantitative comparison of environmental impacts of alternatives. ERA is a formal process for evaluating the negative environmental consequences of a hazard and their likelihoods [15].

There are several differences between LCA and ERA in terms of objectives, scope and focuses. LCA focuses on all the demands of raw materials, energies and water as well as wastes and emissions caused by the value chain of an investigated product or service. Most studies aim to compare the environmental impacts between two technologies or products *under normal operation conditions*. As an example, in LCA studies of CO_2 geological storage, CO_2 leakage from the reservoir is normally not considered in most studies due to it is caused by an unexpected failure. Similarly in LCA studies of shale gas, environmental consequences of discharging inappropriate treated wastewaters due to insufficient treatment capacity or leakage of on-site treatment are not included. ERA aims to assess the environmental impacts and likelihoods of a particular hazard along with the production, use and disposal of a specific substance [16]. It only focusses on the risks of potential *operational failures or failure condition* but does not cover the environmental impacts of all processes involved in a specific product or service. On this basis, LCA and ERA may be seen as complementary tools in providing a comprehensive picture of potential environmental consequences and thereby supporting environmental management.

Today, a large number of LCA and ERA studies of different geo-resource exploitation have been conducted. These studies provide valuable insights into either environmental impacts or risks of individual exploitation activities. It is however not clear what the general lessons learned are so far and how this knowledge can be applied to future exploitation activities. It is specifically true in the part of underground exploitation. An overview including the environmental consequences of both operational activities and failures would help in identifying the focuses, overlaps and potential knowledge gaps of current research.

To the best of our knowledge, such overview is missing. This paper aims to fill this gap by identifying the general lessons learned and key knowledge gaps on understanding the source, mechanism and scope of environmental consequences through evaluating the state of the art knowledge, methods and data sources applied to assess the environmental impacts and risks of underground geo-energy exploitation.

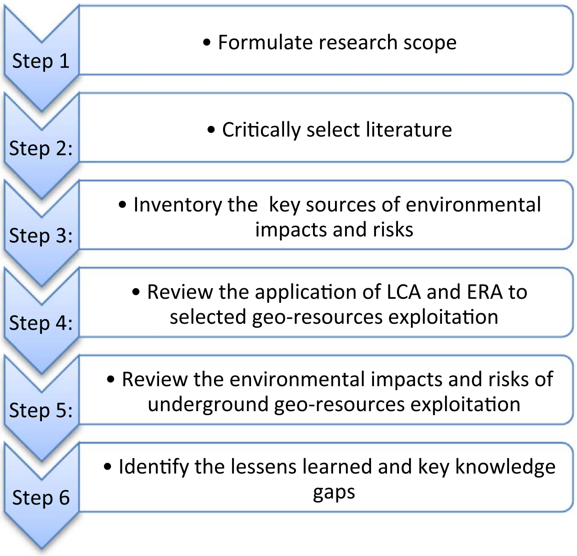

Fig. 1. Schematic diagram of the methodology used in this paper.

2. Methodology

In this paper, a six steps methodology has been applied. Fig. 1 shows a schematic diagram of the methodology.

2.1. Research scope

Shale gas, geothermal power, CO_2 geological storage and CAES were selected as the representative exploitation of the subsurface. They represent the three purposes of geo-resources exploitation and they are modern technologies with (or having the potential of) a large-scale deployment in the coming decades.

The focus of this research is the environmental impacts and risks caused by *the key processes of subsurface exploitation activities*. Impacts or risks caused by other activities in the life cycle chain are therefore not discussed.

2.2. Critical literature selection

About fifty LCA studies and sixty ERA studies were initial collected according to the following criteria: they were written in English; they were published between 2007 and 2015, and they are peer reviewed journal articles or peer reviewed reports.

As there are a large number of LCA studies on CCS and shale gas exploitation, a second selection round was carried out by applying two criteria. First, the environmental impacts of CO_2 storage and the underground activities of shale gas exploitation should be presented. It is because many studies only show the environmental impacts of the life cycle chain of CCS and shale gas without presenting the environmental impacts of individual phases. Second, priority was given to the studies investigating multiple impact categories. As a result, eight LCA studies on CCS and eight on shale gas exploitation were selected. Six LCA studies on geothermal power and four on CAES have been also included as they are the most recent published LCA studies on these two topics.

The first round collection of ERA studies was narrowed down according to two criteria. First, they should be quantitative studies and secondly, the selection aimed to cover as diverse environmental risks and hazard as possible. This finally resulted in ten studies on CCS, nine and ten studies on shale gas and geothermal exploitation respectively. Only two qualitative ERA studies on CAES were founded in open literature and were included in this analysis.

2.3. Key processes of underground geo-resources exploitation

The focuses of this step were to identify the key processes of subsurface geo-resources exploitation and to analyze the subsurface activities associated energy demands, material and water uses. Therefore, an inventory of the key processes of subsurface exploitation and associated energy demand, material and water uses was carried out. The investigation was based on the selected LCA and ERA studies.

2.4. Review application of LCA and ERA to geo-resources exploitation

As discussed in the introduction, LCA and ERA have distinctive objectives, approaches and system boundaries. LCA studies present the environmental impacts of normal operations in the entire life cycle processes of geo-resources exploitation. Potential failures, their likelihoods and corresponding environmental consequences of a given operation or process are the focus of ERA studies. On the basis of these differences, the application of LCA and ERA studies as well as the environmental impacts and risks of geo-resources exploitation were reviewed in different ways. In the case of LCA studies we:

- Identified the impact assessment methods and environmental impact categories.
- Identified and reviewed key parameters and critically discussed the data sources of each parameter.

For reviewing the ERA studies we:

- Reviewed the assessment stages and identified the focus of the examined studies.
- Reviewed and critically discussed the assessment methods and assessment period.

2.5. Review environmental impacts and risks of underground geo-resources exploitation

The underground environmental impacts and risks of geo-resources exploitation were reviewed and analyzed according to the potential spatial scale of the influence. Macro, meso and micro levels are three levels representing environmental impacts and risks at the global/continental, regional and local levels, respectively [12].

The following steps were taken for reviewing environmental impacts of underground geo-resources exploitation from the selected LCA studies:

- Categorizing the environmental impacts of the subsurface activities according to the spatial scale of the influence.
- Extracting and analyzing the environmental impacts of the subsurface activities from the results of the examined studies.
- Comparing the environmental impacts of the subsurface activities with those of the entire life cycle chain.

For the ERA studies, the risks of underground exploitation were reviewed by:

- Identifying the investigated hazards and their sources and pathways.
- Discussing the hazard receptors and the potential environmental consequences.
- Categorizing the environmental consequences of the hazard according to the spatial scale of the influence.

2.6. Identification of the lessons and key knowledge gaps

In general, lessons and potential knowledge gaps of environmental impacts and risks of the key processes of underground geo-resources exploitation were identified by processing, integrating and comparing reviewing results from the previous steps.

The key knowledge gaps of LCA and REA applications were identified by examining:

- Whether the key processes of subsurface exploitation activities were included and evaluated.
- Assessment focuses and potential assessment weakness on different spatial scales of environmental consequences.
- Potential weak fields of applied methods, data sources and assessment periods.

The lessons of environmental impacts and risks of the key processes of underground exploitation have been learned by:

- Comparing the environmental impacts and risks of underground activities in each geo-energy resource exploitation with those of the entire exploitation chain.
- Comparing the environmental impacts and risks of underground activities in one geo-energy resource exploitation with those in other exploitation.

The comparison facilitates understanding of the relative significance of environmental impacts and risks at different spatial scales. It also helps to identify potentially overlooked environmental consequences at a given spatial scale.

3. Geo-energy resources exploitation and potential sources of environmental impacts and risks

The first step in the analysis is to identify the key processes of subsurface exploitation activities. Here, a short description is provided and the key subsurface activities associated energy demands, materials and water uses are identified.

Geothermal power plants extract hot geothermal fluid or steam from a geothermal reservoir in the deep subsurface and convert heat to electricity. Water, heat and permeability are three key elements for forming a natural geothermal reservoir. An artificial geothermal reservoir may be created in formations where the temperature of dry and impermeable rocks is high. Permeability can be enhanced by a hydraulic stimulation (HS) process in an enhanced geothermal system (EGS). Three types of technologies exist for geothermal power generation, namely dry steam, flash and binary power plants [7].

The production of **shale gas** releases and collects natural gas from the shale formation with low permeability. Horizontal drilling and Hydraulic fracturing (HF) are two key processes that make shale gas exploitation different from conventional gas. Hydraulic fracturing involves the injection of fluids under great pressure to fracture the shale formation. The fluid carries and places the proppant into the fractures to keep the fractures open after the injection pumping pressure is terminated. Natural gas can then flows through the fractures into the well [17].

Suitable geological formations for **CO_2 geological storage** require a depth at least 800 m, good caprock integrity and good injectivity [12]. The geological reservoirs considered are (nearly) depleted or abandoned oil and gas reservoirs, deep saline aquifers and deep coal beds.

A **CAES** facility consists of an electricity generation system and an energy storage system. It uses off-peak electricity to compress air and store it into a subsurface reservoir. During an electricity peak demand period, compressed air will be released to a combustor in a gas turbine to generate electricity. The compressed air can be stored in under-

Table 1
Overview of the key processes of subsurface geo-energy sources exploitation and associated energy, material and water uses [13,19–24].

Geo-resources exploitation	Preparation and development				Production/storage	Well closure/ sequestration
Shale gas	**Site preparation**	**Well drilling**	**Well cementation**	**Horizontal drilling, HF and well completion**	**Work over**	**Wellbore sequestration**
	Diesel/electricity	Diesel/ electricity	Diesel/electricity	Diesel/electricity	Same as HF	Diesel/electricity
	Sand	Casing	Casing	Sand		Cement
	Cement	Bentonite	Cement	Chemical additives		
	Waterproof fabric	Chemicals	Sand	Water		
	Water	Lime	Silica flour			
		Water	Water			
Geothermal power	**Site preparation**	**Well drilling**	**Well cementation**	**Hydraulic stimulation (EGS)**	**Fluid injection**	–
	Diesel/electricity	Diesel/ electricity	Diesel/electricity	Diesel/electricity	Diesel/electricity	
	Cement	Oil	Cement	Chemical additives	Water	
	Water	Casing	Casing	Water		
		Chemicals	Sand			
		Lime	Silica flour			
		Water	Water			
CAES	**Site preparation**	**Well drilling**	**Well cementation**	**Water injection and brine withdraw**	**Air injection and release**	–
	Diesel/electricity	Diesel/ electricity	Diesel/electricity	Diesel/Electricity	Diesel/electricity	
	Cement	Casing	Cement	Water		
	Water	Chemicals	Casing			
		Lime	Sand			
		Water	Silica flour			
			Water			
CO_2 storage	**Site preparation**	**Well drilling**	**Well cementation**	–	**CO_2 injection**	**Monitoring**
		Diesel/ electricity	Diesel/electricity		Diesel/electricity	
		Casing	Cement			
		Bentonite	Casing			
		Chemicals	Sand			
		Lime	Silica flour			
		Water	Water			

ground salt caverns, depleted gas reservoirs and aquifers [18]. Table 1 highlights the key activities of subsurface exploitation and associated energy, material and water uses.

4. Application of LCA to geo-resources exploitation

4.1. Impact assessment methods and impact categories

A number of impact assessment methodologies has been used to assess the environmental impacts in LCA studies. The most common ones are ReCiPe, CML 2011 and IPCC. They generally provide similar characterization results for impact categories such as global warming potential (GWP), acidification potential (AP) and eutrophication potential (EP). The impact assessment methods and impact categories of the reviewed studies are shown in Table 2.

Global warming potential is the most common mid-point impact category investigated in the reviewed studies (24 out of the 27 studies), followed by the categories related to water use, e.g. eutrophication potential (12 studies) and acidification potential (9 studies).

The LCA studies for CCS and geothermal power trend to show a more diverse mix of categories while the focus of shale gas and CAES is on GWP. Toxicity related impact categories such as HTP, TETP, MAETP are almost not examined though most concerns for stakeholders and general public are related to these categories. This is particularly the case for shale gas exploitation where a thousand of chemical additives have been recorded in the use of HF to provide different chemical and physical functions [17]. Moreover, it is noticeable that relatively low attention is given to water use (WU). WU should receive more attention in future studies of EGS exploitation due to the considerable volume of water withdrawal in the HS process.

4.2. Data sources of key parameters

The environmental impacts of geo-resources exploitation depend, to a large extent, on the geological situation, technical specification and data inventory of mass and energy flows.

In the LCA studies of CCS, parameters such as well depth and injection rate have a relatively high influence on the impacts [12]. Table 3 presents these key parameters and their data sources. Note that no site specific data was applied in the reviewed studies. Generic storage fields were analyzed and most key parameters were based on a few existing CO_2 storage projects such as the Sleipner project in Norway (the project in offshore deep saline formation) or the Weyburn project in Canada (the enhanced oil recovery (EOR) project). Moreover, key parameter data in some cases is not available [30] or the sources of key parameters are not transparent [25,44]. These make comparison of data and results difficult.

In the shale gas exploitation studies, parameters such as estimated ultimate recovery (EUR), flaring rate and episodic emission factor (of both well completion and workover) are influential to GHG emissions [22,32,35]. Water withdrawal and the recovery rate of the HF fluids are the key parameters for determining WU of subsurface exploitation. Key parameters and data sources for assessing GHG emissions and WU are listed in Tables 4 and 5. As can be seen in Table 4, a large number of data in the studies has come from the data sources [48–51], which provide technical specifications and inventories of GHG emissions of

Table 2
Overview of LCA impact assessment methods, impact categories and studied technologies and storage options.

CO$_2$ storage

Study	Storage option	Impact assessment method	Impact category
[25]	Depleted gas reservoir	Umberto software	GWP, CED, AP, EP
[26]	Depleted gas reservoir	IPCC 2007, CML 1996	GWP, CED, AP, EP,
[27]	Saline aquifer	IPCC 2007, ReCiPe	GWP
[28]	Saline aquifer	ReCiPe 2008	GWP; AD; EP; HTP; POCP; TEPT; MAETP; FAETP
[29]	Below ocean sea bed	ReCiPe 2008	GWP; AD; EP; HTP; POCP; TEPT; MAETP; FAETP
[30]	Saline aquifer	CML 2011	GWP, HTP, AP, EP, POCP, MAETP, TEPT, FAETP
[31]	Geological storage	CML 2011	GWP
[23]	Saline aquifer and depleted gas reservoir	Eco-indictor 99, IPCC 2007	GWP

Shale gas

Study	Shale gas location	Impact assessment method	Impact category
[32]	Barnett shale	IPCC 2007	GWP
[22]	Marcellus shale	IPCC 2007	GWP, WU
[33]	US shale gas	IPCC 2007	GWP
[34]	Barnett shale	IPCC 2007	GWP
[35]	Generic unconventional gas	IPCC 2007	GWP
[36]	Marcellus shale	–	WU
[37]	Marcellus shale	–	WU
[21]	UK shale gas	CML 2011	GWP, AP, ADP, EP, HTP, FAETP, POCP, TETP, MAETP

Geothermal power

Study	Exploitation technology	Impact assessment method	Impact category
[19,38]	Flash, binary and EGS	IPCC	GWP
[20]	Flash, binary and EGS	–	WU
[39]	EGS	Ecoinvent database	GWP, CED, AP, EP
[40]	EGS	Ecoinvent database	GWP, CED, AP, EP
[41]	Binary	Simapro software	GWP, CED, ADP, AP, POCP, EP

Compressed air energy storage

Study	Storage option and exploitation technology	Impact assessment method	Impact category
[42]	Salt cavern, diabatic plant	IPCC	GWP
[24]	Salt cavern, diabatic plant	ReCiPe 2008	GWP
[43]	Mined hard rock cavern, diabatic and adisbatic plant	ReCiPe	GWP, EP, FETP
[18]	Salt cavern, diabatic	ReCiPe	GWP

(CED: cumulated energy demand; GWP: global warming potential; EP: eutrophication potential; AP: acidification potential; HTP: human toxicity potential; LU: land use; POCP: photochemical zone creation potential; MAETP: marine aquatic ecotoxicity potential; TETP: terrestrial ecotoxicity potential; ADP: Abiotic depletion potential; FAETP: fresh water aquatic ecotoxicity potential; WU: water use).

both conventional and unconventional gas exploitation in the US.

Key parameters and data sources for assessing environmental impacts of deep geothermal energy are shown in Table 6. It is observed that most of applied data in the examined studies is based on a few existing geothermal power projects. The data used in [19,20,38] is similar because it was based on the same geothermal power projects, namely the Cooper Basin EGS project in Australia and the Soultz-sous-Forêts project in France. It is also found that water withdrawal for hydraulic stimulation of an EGS is less reported in literature.

Four LCA studies on CAES exploitation were reviewed. However they provide very limited data regarding the underground activities. Three reviewed studies [18,43,62] do not provide any relevant emission factors or data of energy and mass flows. The study [24] provides data of material inventory but energy and water associated data is not reported.

5. Application of ERA to geo-resources exploitation

5.1. Stages and focuses of the risk assessment

Environmental risk assessment is a formal process of evaluating the environmental consequences of a hazard and their likelihoods [15]. A comprehensive quantitative ERA typically consists of five stages including site characterization, hazard identification, consequences assessment, probabilities assessment and risk and uncertainty characterization. The stages of hazard identification, consequences assess-

Table 3
Key parameters and data sources in the LCA studies of CO$_2$ storage.

Study	Well depth (m)	Injection rate (kg/s)	Well life time (year)	Data source	Notes of data source
[25]	–	113–162	–	–	Based on a local plant with the capacity of 700 MW
[26]	–	–		[44]	The Weyburn project
[27]	1000	125	30	[23]	The Sleipner project and other EOR projects
[28]	800	36.6–70	30	[23,45]	Ecoinvent database; the Sleipner project and other EOR projects
[29]	1000	36.6–70	30	[23,45]	Ecoinvent database; the Sleipner project and other EOR projects
[30]	1000			–	No relevant data and data sources are available
[31]	3000	231	30	[46]	Analog project-natural gas subsurface storage
[23]	800 (saline aquifer); 2500 (depleted gas reservoir)	125	15	[44,47]	The Sleipner project and other EOR projects

Table 4
Key parameters and data sources for determining GWP of underground shale gas exploitation.

Study	EUR (bcf)	Flaring rate (%)	Well completion emission (m^3)	No. of workover	Emissions per workover (m^3)	Data source	Notes of data source
[32]	3 (2.2–4.9)	15–51	2.6×10^5	2.4–3.6	2.6×10^5	[48–50]	EPA, NETL, API
[22]	3 (2.2–4.9)	15 (12–18)	2.6×10^5	3.5	2.6×10^5	Primary data collection, [48,51]	EPA
[52]	2.85 (0.5–91)	76 (51–100)	2.1×10^5 (0.18×10^5–16.1×10^5)	0	–	Primary data collection [53]	–
[33]	2 (1–3)	51 (0–98)	2.6×10^5 (0.76×10^5–5.3×10^5)	0–1	2.6×10^5 (0.76×10^5–5.3×10^5)	Primary data collection, [48,50]	EPA, API
[35]	3.5 (1.6–5.3)	41 (37–70)	1.36×10^5–3.01×10^5	2	1.36×10^5–3.01×10^5	[48,51]	EPA
[34]	1.4		8.09×10^5	–		[54,55]	TCEQ
[21]	1 (0.1–3)	–	0.24×10^5	–	0.24×10^5	[45]	–

(EPA: United States Environmental Protection Agency; NETL: United States National Energy Technology Laboratory; API: American Petroleum Institute; TCEQ: Texas Commission on Environmental Quality in the States).

ment and probability assessment basically address three questions: what may go wrong, what the consequences are and what the probabilities of the consequences are. Table 7 describes each stage in detail and presents the focus of reviewed ERA studies at each stage.

Regarding the first stage site characterization, all reviewed studies (31 studies) defined systems boundaries and 24 of them conducted an in-depth system characterization and discussed potential sources of hazards. However, only 6 studies identified measures and corresponding risk thresholds for the final comparison between the evaluated risks and the risk threshold. A lack of risk thresholds in reviewed studies can be explained by the difference in research focuses. For instance, 12 studies only focused on the assessment of environmental consequences of a specific hazard while 6 studies only focused on the probability evaluation of a hazard occurrence.

Hazard analysis is the most common assessment stage. All reviewed studies conducted investigations on hazard identification and analyses on mechanisms of a hazard occurrence, hazard pathways and environmental receptors. A few studies formulated scenarios as a pre-step according to the hazard pathways or environmental receptors for either a probability assessment or consequence assessment.

After the stage of hazard analysis, 19 studies (out of the 31 studies) assessed the environmental consequences of a hazard. Twelve of these studies examined a worst case scenario assuming occurrence of a hazard without conducting a probability assessment. For example, a hypothetical methane leakage [71] and a slow CO_2 leakage from a deep saline aquifer [72] were assumed and simulated to assess their environmental impacts on the groundwater quality. Occurrence of induced seismicity was stimulated in [73] to examine the maximum magnitude of seismicity.

Eleven studies (out of the 31 studies) conducted a probability assessment. As can be seen in Table 7, there are three steps in the probability assessment. All 11 studies evaluated the probability of a hazard occurrence, however only 3 studies evaluated the possibility of a receptor exposure to the hazard and only 2 studies investigated the possibility of the receptor being affected by the exposure. A lack of sufficient assessment on the probability of a receptor exposure to a hazard indicates insufficient information on the potential pathways and transport of hazard agents between the point of release to the so-called exposure point. For example, a probability assessment of water pollution caused by five failures in shale gas exploitation was carried out in [74]. In this study, the probability of a hazard occurrence, such as well casing failure and on-site wastewater leakage, has well supporting reference. However, the probability of hazard migration (migration of fracturing fluids to an aquifer through induced fractures) was recognized as “considerable debate” and estimated in a large range between extremely rare (1 in 1 million) and relatively common (1 in 10) without any supporting reference. Regarding the third assessment step, likelihood of negative effects depends on vulnerability of the receptor, the potency of the hazard itself and the amount or extent of exposure [15]. Lacking of this step assessment indicates that potential relations between exposure and harm are limited understood.

Only 5 studies (out of the 31 studies) combined the environmental consequence of a hazard and its likelihood for comparing the risks with relevant threshold. Sensitivity assessment was carried out by 9 studies to address the issue of uncertainty. It is noted that very limited amount of ERA studies was found in terms of CAES exploitation. Two qualitative studies were found to analyze the potential consequences of the hazards without further probability assessment.

5.2. Assessment methods and periods

Table 8 shows the approach and period in the assessment stages of consequence assessment and probability assessment. Numerical simulation and experiment approach, which is normally combined with field measurements and laboratory experiments, are two common applied methods in the consequence assessment. Probabilistic risk assessment (PRA) is the most widely applied approach for the probability assessment.

ERA studies have diverse assessment periods based on their research scope. In general, the studies on CO_2 storage have longer

Table 5
Key parameters and data sources for determining net water use of underground shale gas exploitation.

Study	Water for drilling (m^3/well)	Water for HF (m^3/well)	HF fluid recovered (%)	Flowback water recycled (%)	Data source	Notes of data source
[22]	287 (Marcellus); 174 (Barnett)	14380 (Marcellus); 8532 (Barnett)	–	–	[56]	GWPC
[36]	300–380	3500–26000	10–15	90–95	[57–59]	EPA
[37]	670 (Marcellus); 920 (Barnett)	9900–22000 (Marcellus); 6800–23500 (Barnett)	10 (Marcellus); 20 (Barnett)	95 (Marcellus); 20 (Barnett)	[60]	website database supported by voluntary operators
[21]	1000	12000	20–40	–	[61]	Database of a gas company

(GWPC: United States Ground Water Protection Council).

Table 6
Key parameters and data sources for determining environmental impacts of subsurface exploitation activities of geothermal power.

Study	Reservoir depth (km)	Capacity (MW)	Life cycle (yr)	Drilling		Hydraulic stimulation		Data source	Notes of data source
				Diesel	Water	Diesel	water		
[19,38]	2 (binary), 3(flash) and 4–6 (EGS)	50 (EGS and flash), 10 (binary)	30	48970 L/MW	–	180630 L/MW	26939 t/well	[63–65]	The Cooper Basin EGS project; the Soultz-sous-Forêts project
[20]	2 (binary), 3 (flash) and 4–6 (EGS)	50 (EGS and flash), 10 (binary)	30	–	–	–	26939 t/well	[63,64]	The Cooper Basin EGS project; the Soultz-sous-Forêts project
[39]	3.8 and 4.7	1.75	30	7673 MJ/m	671 kg/m	3000 GJ/well	260000 t/well	[66–68]	A German project
[40]	2.5 and 4	0.9–4.4	25	4000 MJ/m	1000 kg/m	1400 GJ/well	20000 t/well	[69,70]	The Upper Rhine Graben project (France), the Soultz-sous-Forêts project
[41]	0.45 and 0.73	2.9	25	0.86 kg/MW h	1.71 kg/MW h	90 kg/MW h	–	[39]	A German project

assessment periods than the studies of shale gas and geothermal power. This can be explained by the different purposes of geo-resources exploitation. CO_2 is expected to be sequestrated in a geological storage for a very long period (thousands of years). While the time interval of repetitive fluids injection and withdrawal in a geothermal power plant is very short and the time period of shale gas exploitation in average is a few months. An assessment period covering entire operation of geo-resources exploitation is recommended for future ERA studies.

6. Environmental impacts and risks of underground geo-resources exploitation

Environmental impacts and risks of geo-resources exploitation can be divided into three levels according to the spatial scale of the influence. Macro, meso and micro levels represent environmental impacts at global/continental, regional and local levels respectively [12].

The LCA mid-impact categories at the macro level include global warming potential (GWP), abiotic depletion potential (ADP) and cumulative energy demand (CED), etc. The meso level typically consists of the mid-point impact categories such as acidification potential (AP), eutrophication potential (EP), photochemical zone creation potential (POCP) and ecotoxicity potential, etc. Human toxicity potential (HTP) and water use (WU) are considered at the micro level [12].

Environmental risks at the macro level refer to the consequences of a hazard causing negative effects on the atmospheric environment. The consequences of a hazard affecting the environmental quality of a resource such as groundwater, surface water and soil are considered at the meso level. At the micro level, the environmental risks normally refer to the consequences of a hazard threatening the local environmental quality and health of human being above the ground.

6.1. Environmental impacts and risks of CO_2 geological storage

6.1.1. Environmental impacts

The environmental impacts of CO_2 storage are regarded as minor at all macro, meso and micro levels comparing with the entire CCS chain. They have a share between 1% and 5% depending on the impact category (see Table 9). Note that drilling is the only underground activity that has been taken into account for determining the environmental impacts of CO_2 storage. Drilling depth is proportional to the consumed energy, water and materials. For example, two types of CO_2 storage formations were investigated in [23]. Global warming potential of storing CO_2 in a depleted gas reservoir is three times as much as that of in a saline aquifer. It is because the drilling depth of the gas reservoir was taken about three times higher than in the aquifer.

6.1.2. Environmental risks/hazards

CO_2 leakage is one of the most recognized hazards of CO_2 storage (see Table 10). The sources of CO_2 leakage are mostly related to operational failure such as inadequately constructed wells or geological failure such as caprock failure. These two types of failure were identified and discussed in the ERA studies.

At the macro level, the consequences of CO_2 leakage are reported as an increase of CO_2 concentration in atmosphere and accelerating climate change at the global level. The probability of CO_2 leakage through various pathways to the surface was investigated in [75,76,82]. The study [82] assessed four scenarios of CO_2 leakage and the results indicate that the probability of CO_2 migration to the surface is in generally very small, especially in the scenarios of geological failure such as failure of caprock sealing and occurrence of existing and induced faults. It concluded that the probability of CO_2 leakage due to operational failures, such as leakage through abandoned oil & gas wells is higher than that due to a geological failure. The annual occurrence frequency of CO_2 leakage through abandoned oil & gas wells was estimated between 1.0E-5 to 1.0E-3 which is higher than the one through induced or existing fault 2.0E-8. Another study indicated that the probability of CO_2 leakage to the surface due to a pre-existing fault was 0.01% [76]. The study [75] shows that the CO_2 leakage rate increases after injection and reach a peak value 0.07% at around 40 days after injection and then keeps stable afterwards. This study provides valuable information for the leakage monitoring after the injection.

At the meso level, CO_2 leakage may cause negative impacts on the quality of groundwater, soil and surface water. The study [82] concluded that likelihood of leaked CO_2 reaching a shallow aquifer was low with the annual occurrence probability between 1E-08 and 1E-05. A similar study [76] recorded the result showing the probability of shallow groundwater contaminated by CO_2 migration through a pre-existing fault was 0.04%. Both numerical simulation and experiment studies were carried out to identify the change of groundwater geochemical condition caused by CO_2 leakage. Five potential consequences are: 1) pH value decreases by 1–2 magnitude [72,77–81]; 2) hazard trace elements such as Lead and Arsenic can be mobilized by the intrusion of CO_2 [72,77,78]; 3) the concentration of Lead and Arsenic increases and is close to (in [77,81]) or exceeds the maximum permitted value (in [78]); 4) the concentration of Fe and Ca increases following the CO_2 injection [72,79–81]; 5) CO_2 injection is also responsible for the detection of BTEX (e.g. benzene) [81]. When CO_2 is stored in a deep saline aquifer, likelihood and potential consequences of brine migration to groundwater were estimated in [83]. It shows that the lateral distance of brine migration is rather small and the chance of vertical brine migration through a sequence of layers into shallow groundwater is also small. It indicates that large-scale pressure changes may be of more concern to groundwater resources than the quality

Table 7
Five stages of ERA and the focus of examined studies.

Assessment stage	Action description	CO_2 storage		Shale gas		Geothermal power		CAES	
		Study	Number of studies	Study	Number of studies	Study	Number of studies	Study	Number of studies
Stage 1 Site characterization	Define the system	[72,75–83]	10	[71,74,84–90]	9	[73,91–99]	10	[100,101]	2
	Identify sources, event and process which may cause and control a hazard	[72,75,76,82,83]	5	[74,84–86,88–90]	7	[73,91–99]	10	[100,101]	2
	Identify appropriate measures of risk and corresponding risk threshold	[82]	1	[87]	1	[91–93,99]	4		–
Stage 2 Hazard analysis	Identify hazards	[72,75–83]	10	[71,74,84–90]	9	[73,91–99]	10	[100,101]	2
	Analyze the mechanism of hazard occurrence, pathways of hazard spread and consequence receptors	[72,75–83]	10	[71,74,84–90]	9	[73,91–99]	10	[100,101]	2
	Form scenarios according to hazards, pathways/mechanisms and receptors	[82,83]	2	[74,84,85]	3	[92]	1	–	–
Stage 3 Consequences assessment	Identify the consequences	[72,77–82]	7	[71,86–90]	6	[91–93,99]	4	[100,101]	2
	Evaluate the magnitude of consequences	[72,77–82]	7	[71,86–90]	6	[91–93,99]	4	–	–
Stage 4 Probabilities assessment	Evaluate the probability of a hazard occurring	[75,76,82,83]	4	[74,85,87]	3	[91–93]	3	–	–
	Evaluate the probability of exposure to a hazard	[82,83]	2	[74,87]	2	–	–	–	–
	Evaluate the probability of the receptors being affected by a hazard	[82]	1	[87]	1	–	–	–	–
Stage 5 Risk and uncertainty characterization	Combine the evaluated consequences and probabilities and compare them with risk limits	[82]	1	[87]	1	[91–93]	3	–	–
	Evaluate sensitivity of results to changes in parameters to gain further understanding	[72,76–78,82,83]	6	[74,85]	2	[92]	1	–	–

Table 8
Assessment approaches and periods in the stages of consequence assessment and probability assessment.

	Consequence assessment				**Probability assessment**			
	Numerical simulation		**Experiment approach**		**Probabilistic risk assessment**		**Deterministic risk assessment**	
	Study	Assessment period	Study	Assessment period	Study	Assessment period	Study	Assessment period
CO_2 storage	[72] [77,78,83] [82]	5 years 100 years 5000 years	[79] [80] [81]	400 days 30 days One month	[76] [75]	1000 years 100 days	[83]	100 years
Shale gas	[71]	4 days	[88] [89] [90] [86]	– 5 years 7 days 2 years	[74] [85] [87]	– 100 days One year	[87]	One year
Geothermal power	[93] [91] [92]	15 days 7 days One year	[99]	4 months	[93] [91] [92]	15 days 7 days One year		

change caused by brine migration. Unlike the well discussion on the quality change of groundwater, potential impacts on soil and surface water due to CO_2 leakage received less attention.

At the micro level, it was estimated that no health effects are likely to occur in the scenarios of rapid CO_2 leakage through caprock failure, injection wells and abandoned oil and gas wells [82]. Induced seismicity is another identified hazard at the micro level probably caused by the pressure change of CO_2 injection. Likelihood of induced seismicity with a magnitude larger than one was estimated as 0.3% on the condition of the CO_2 plume reaches a specific fault [76].

6.2. Environmental impacts and risks of shale gas exploitation

6.2.1. Environmental impacts

Table 11 presents the potential environmental impacts of shale gas exploitation. The life cycle of shale gas exploitation includes both

Table 9
Environmental impacts of CO_2 geological storage at the macro, meso and micro levels.

Macro level			**Meso level**		
GWP 100	Unit impact	$gCO_2eq/kW\ h$ ● 1.6^a (0.8% of CCS chain) [26]; ● 1–5% of CCS chain [25]; ● 0–3% of CCS chain [27]; ● 3.8^a (3% of CCS chain) [28]; ● 2.8^a (2% of CCS chain) [29]; ● < 2% of CCS chain [30]; ● 1.2 (0.15% of CCS chain) [31]; ● 2.1% of CCS chain in saline aquifer and 7.2% in depleted gas reservoir ^{a} [23]	**AP**	Unit Impact	$gSO_2eq/kW\ h$ ● 4.8×10^{-3} ^{a} (0.8% of CCS chain) [26]; ● 1–5% of CCS chain [25]; ● < 1% ^{a} of CCS chain [28]; ● 1%^{a} of CCS chain [29]; ● < 2% of CCS chain [30]
CED	Unit Impact	kJ/kW h ● 13.5^a (1.5% of CCS chain) [26]; ● 1–5% of CCS chain [25]	**EP**	Unit Impact	mgPO4eq/kW h ● 360 ^{a} (0.4% of CCS chain) [26]; ● 1–5% of CCS chain [25]; ● < 1% ^{a} of CCS chain [28]; ● 1%^{a} of CCS chain [29]; ● < 2% of CCS chain [30];
Micro level			**FAETP**	Unit	● g1,4DBeq/kW h
HTP	Unit Impact	● < 1% ^{a} of CCS chain [28]; ● 5%^{a} of CCS chain [29]; < 2% of CCS chain [30]		Impact	● < 1% ^{a} of CCS chain [28]; ● 2.5%^{a} of CCS chain [29]; ● < 2% of CCS chain [30]
			TETP	Unit Impact	g1,4DCBeq/kW h ● < 1% ^{a} of CCS chain [28]; ● 2.%^{a} of CCS chain [29]; ● < 2% of CCS chain [30]
			MAETP	Unit	G1,4DCBeq/kW h ● < 1% ^{a} of CCS chain [28]; ● 2%^{a} of CCS chain [29]; ● < 2% of CCS chain [30]
			POCP	Unit Impact	● < 1% ^{a} of CCS chain [28]; ● 1%^{a} of CCS chain [29]; ● < 2% of CCS chain [30]

(Note: a functional unit 1 kW h net electricity delivered to grids is used; a: the impact value refers to both CO_2 transport and CO_2 geological storage).

Table 10
Environmental hazards and risks of CO_2 storage at the macro, meso and micro levels.

Scale	Environmental hazard	Source of hazard/pathway	Receptor	Environmental risk	Study
Macro level	CO_2 leakage	● Through existing or induced fault and fractures; ● Through a spill point; ● Caprock failure or permeability increase; ● Failure of wellhead injection; ● Through inadequately constructed wells or abandoned wells	Atmosphere	● CO_2 concentration increases; ● Climate change acceleration	[75,76,82]
Meso level	CO_2 leakage	● Through existing or induced fault and fractures; ● Caprock failure or permeability increase; ● Failure of wellhead injection; ● Through inadequately constructed wells or abandoned wells	Groundwater	● pH modified (acid); ● Mineral dissolution; ● Trace element mobilization (lead, arsenic);	[72,76–82]
	Brine displacement	● Pressure build-up beyond the boundary of the CO_2 plume	Groundwater	● Salinization; ● Exposure to toxic compounds carried by brine migration	[83]
Micro level	CO_2 leakage	● Failure of wellhead injection; ● Through inadequately constructed wells or abandoned wells	Human being	● Negative health impact due to acute exposure	[75,82]
	Induced seismicity	● Pressure change and re-act fault and fracture	Human being above the ground	● Large event seismicity which cause damages	[76]

upstream and downstream processes. Upstream shale gas exploitation includes the processes such as site preparation, well drilling, well casing and cementation, well completion, gas production, gas on-site process and transportation. Downstream exploitation consists of the processes such as gas combustion in a power plant.

At the macro level, GWP of upstream exploitation is largely caused by methane fugitive emissions and flaming. The ratio of upstream exploitation associated GWP to the life cycle GWP was reported between 5% and 12%. Water use is the major environmental impact at the micro level. Even though the process of HF requires a large volume of water, the water use of shale gas upstream exploitation accounts only 5–10% of the life cycle demands. The cooling process of the energy conversion facility, natural gas steam turbine in [37] and combined cycle in [22], requires the largest amount of water use from a life cycle point of view. Shale gas upstream exploitation contributes to the vast majority of the life cycle environmental impacts except GWP and WU. For example, shale gas upstream exploitation contributes to 95% of the life cycle impacts in ADP, 85% in HTP and 90% in AP.

Table 11
Environmental impacts of upstream shale gas exploitation at the macro, meso and micro levels.

Macro level			**Meso level**		
GWP 100	Unit impact	$gCO_2eq/kW h$ ● 32.8 (6.7% of LC chain) [22]; ● 58.3 (11.3% of LC chain) [52]; ● 21.7 (4.3% of LC chain) [33]; ● 37.1 (8.4% of LC chain) [34]; ● 47.9 (8.0% of LC chain) [35]; ● 50.1 (10.8% of LC chain) [21]	**AP**	Unit impact	$gSO_2eq/kW h$ ● 0.9 (90% of LC chain) [21]
ADP	Unit Impact	MJ/kW h (fuel) ● 6.5 (95% of LC chain) [21]	**POCP**	Unit impact	$mgC_2H_4eq/kW h$ ● 205 (90% of LC chain)[21]
Micro level			**EP**	Unit	● mgPO4eq/kW h
WU	Unit impact	L/kW h ● 0.058 (6.1% of Marcellus shale LC chain); 0.097 (9.4% of Barnett shale LC chain) [22]; ● 0.036–0.051 [a] [36]; ● 0.092 (5.5% of Barnett shale LC chain); 0.072 (5.5% of Marcellus shale LC chain) [37]		impact	● 130 (94% of LC chain) [21]
HTP	Unit impact	g1,4DCBeq/kW h ● 18.4 (85% of LC chain) [21]	**FAETP**	Unit Impact	gDCBeq/kW h 7.9 (95% of LC chain) [21]
			TETP	Unit	gDCBeq/kW h
				Impact	3.3 (95% of LC chain) [21]
			MAETP	Unit	kgDCBeq/kW h
				Impact	25.2 (95% of LC chain) [21]

(Note: a function unit of 1 kW h net electricity generation is used; a: the original data are 20000–33000 m^3/well and it was converted to L/MJ by using the production rate 2.2 Bcf/well [22]; LC: life cycle).

Table 12
Environmental hazards and risks of shale gas underground exploitation at the meso and micro levels.

Scale	Environmental hazard	Source of hazard/pathway	Receptor	Potential environmental consequences	Study
Meso level	Stray gas migration	● Through well casing or well annulus; ● Along existing or stimulated faults and fractures by hydraulic fracturing and drilling	Groundwater	● Elevated methane, ethane and propane concentrations in shallow drinking water; ● pH increases; ● Salinization ● Bacterial sulfate reduction	[71,74,84,85,88,89]
	Leakage/migration of hydraulic fracturing fluid or formation/saline water	● Through conductive faults or fractures	Soil; Surface water; Groundwater	● Contamination with organics, salts, metals and other constituents; ● Accumulation of toxic and radioactive elements	[71,74,84,88,89]
	Spills and leakage of wastewater storage	● Due to shale gas drilling	Soil; Surface water; Groundwater	● Contamination with organics, salts, metals and other constituents; ● Accumulation of toxic and radioactive elements	[74,84]
	Disposal of inadequately treated wastewater	● Insufficient treatment capacity and ability	Surface water;	● Elevated the level or the concentration of salinity, toxic metals, radioactive and organic constituents	[74,86]
Micro level	Stray gas migration	● Through well casing or well annulus; ● Along existing or stimulated faults and fractures by hydraulic fracturing and drilling	Human being above the ground	● Elevated concentration of volatile organic compounds (VOC) and hydrogen sulfide	[87,90]

6.2.2. *Environmental risks/hazards*

Environmental hazards and risks of shale gas exploitation are presented in Table 12. The environmental risk at the macro level refers to methane migration to the atmosphere and contribution to climate change. Fugitive emissions caused by normal operations and their impacts at the macro level have been well discussed in the LCA studies. Potential environmental consequences of stray gas migration caused by technical and geological failure are discussed in the ERA studies only at the meso and micro levels.

At the meso level, a number of studies has been carried out to assess the risks of groundwater and surface water contamination. Hazard identification was carried out in [84] by testing and analyzing a wide range of inorganic, organic and radioactive constituents of water and waste streams. The results show that flowback waters, drilling muds and HF fluids all exceeded the limits of Safe Drinking Water Act (SDWA) to varying degrees. Regarding likelihood of the hazard occurrence, [74] indicates that the probability of surface water contamination due to wastewater disposal was several orders of magnitude larger than the one caused by stray gas migration, well casing leaks, drilling site discharge and leaks through existing faults or fractures. The study [85] developed two methane migration scenarios: communication between a shale gas reservoir and an aquifer via a connecting fracture/fault and communication via a pre-existing nearby well. It concluded that shale gas production is likely to reduce likelihood of methane migration through reduction of available free gas and lowering the reservoir pressure. In terms of the stage of consequences assessment, hypothetical leakage of methane from 1000 m below the surface was simulated in [71]. The simulation results show that the pH value of groundwater increased from about 7–9. It was suggested that 300 m below the potable-water aquifer is a critical depth for the sealing of the fracking wells. Such suggestion was given due to the fact that rising methane gas can induce fracking fluids, caused by faulty well seals, to travel up to 300 m vertically. The drinking water quality in active gas extraction areas was examined in [89]. Elevated concentrations of cations and anions including manganese, iron, bromide and chloride were identified in most drinking water wells. The average and maximum methane concentrations in drinking-water wells near the gas well were examined as 19.2 and 64 mg CH_4/L indicating a potential explosion hazard. These two numbers were significantly higher than the number (averaged at 1.1 mg/L) examined in neighboring non-extraction sites with the similar geological formations [89]. No evidence of contamination by deep saline brines and HF fluids was found in this study. The study [86] investigated the potential risk of shale gas wastewater disposal on the quality of surface water. Barium and radium were substantially reduced in the treatment effluents but their discharge increased downstream concentration of chloride and bromide above the background levels. Moreover, the level of radium-226 in stream sediments at the point of discharge was about 200 times greater than that of in upstream and background sediments, posing potential environmental risks of radium accumulation at the regional level.

At the micro level, potential population exposure to air toxics in shale gas exploitation regions was estimated in [87,90]. Both studies concluded that with a large number of measurements on volatile organic compounds (VOC), shale gas exploitation activities have not resulted in community-wide exposure to those VOCs at the levels that would pose a health concern. However, a significant contribution to regional VOCs from shale gas production was identified in [90].

6.3. *Environmental impacts and risks of geothermal power development*

6.3.1. *Environmental impacts*

Environmental impacts of geothermal power development at the macro level vary considerably according to the technology (see Table 13). A flash power plant has shown much higher life cycle

Table 13
Environmental impacts of geothermal underground exploitation activities at the macro, meso and micro levels.

Macro level			**Meso level**		
GWP 100	Unit impact	gCO$_2$eq/kW h ● 23.3 ^{a} (100% of EGS LC chain), 4.1 ^{a} (4% of Flash plant LC chain) and 6.1 ^{a} (100% of Binary plant LC chain) [19,38]; ● 42–46 (88% of EGS LC chain) [39]; ● 40–48 (82% of EGS LC chain) [40]; ● 3.8 (66% of Binary plant LC chain) [41];	**AP**	Unit Impact	gSO$_2$eq/kW h ● 0.35–0.39 (91–94% of EGS LC chain)[39]; ● 0.26–0.49 (84% of EGS LC chain) [40]; ● 0.01 (95% of binary plant LC chain) [41];
ADP	Unit Impact	gSbeq/kW h ● 0.023 (99% of binary plant LC chain) [41];	**EP**	Unit Impact	mgPO$_4$eq/kW h ● 50–56 (95–97% of EGS LC chain) [39]; ● 30–68 (84% of EGS LC chain) [40]; ● 42 (99% binary plant LC chain) [41];
CED	Unit Impact	kJ/kW h ● 620–704 (87–91% of EGS LC chain) [39]; ● 656–763 (82% of EGS LC chain) [40]; ● 504 (99% of binary plant LC chain) [41];	**POCP**	Unit Impact	mgC$_2$H$_4$eq/kW h ● 0.65 (97% of binary plant LC chain) [41];
Micro level					
WU	Unit Impact	L/kW h ● 3.8×10^{-2} (3.3% of EGS LC chain), 3.8×10^{-3} (0.4% of Binary LC chain) and 3.8×10^{-3} (10% of Flash LC chain) [20];			

(Note: a function unit of 1 kW h net electricity generation is used. a: the impact value refers to surface and subsurface construction and fuel production).

GWP than other types of technologies due to the processes of geo-fluids transport and flash. Most life cycle environmental impacts of a flash power plant are contributed by the surface exploitation activities. For instance, GWP and WU relating to underground exploitation activities only account for 4% and 10% of the life cycle values. On the contrary, a binary power plant or an EGS with the binary power generation technology has a zero direct greenhouse gas (GHG) emission in the phase of power generation because of the closed circulation of geo-fluids. Underground exploitation activities of these two systems contribute to the most life cycle environmental impacts except WU. When only looking at the environmental impacts of subsurface activities, an EGS has higher environmental impacts than a binary and flash plant.

6.3.2. Environmental risks/hazards

Only two hazards were identified in the reviewed ERA studies on deep geothermal energy exploitation. They are induced seismicity and geo-fluids migration. Environmental risks of geothermal power at the macro level were not discussed in the ERA studies. The hazard of geo-fluids migration was identified at the meso level [99] (see Table 14). The study focused on identifying sources and pathways of geo-fluids migration in a geothermal field. It concluded that the natural upward movement of geo-fluids, the faulty reinjection application and the uncontrolled discharge of waste geo-fluids were the potential sources of groundwater contamination [99].

At the micro level, the source and mechanisms of induced seismicity, especially the one triggering a large magnitude induced seismicity (defined as induced seismicity which can be felt by people above the ground) have been investigated [73,96,98]. The presence of pre-existing faults near the geothermal field was concluded as the most influential factor affecting the occurrence and magnitude of induced seismicity [73,93,94,96,97]. The volume of cold fluid injection was also identified as another important factor triggering induced seismicity [98]. The probability of induced seismicity causing by deep geothermal energy exploitation has been evaluated in [91–93]. The general conclusion is that even though induced seismicity has been observed in many geothermal fields, the estimated probability of large induced seismicity was low.

6.4. Environmental impacts and risks of CAES development

6.4.1. Environmental impacts

As shown in Table 15, the life cycle environmental impacts of a CAES system largely depend on the fuel consumed, normally natural gas, to heat up air but not due to the underground activities. An adiabatic plant has much lower life cycle GWP than a diabatic plant because the heat released by the process of air compression is captured and stored in an adiabatic plant. No fuel is then needed to heat up air afterwards.

6.4.2. Environmental risks/hazards

Only two qualitative ERA studies were found regarding CAES exploitation. Explosion and compressed air leakage were identified as

Table 14
Environmental hazards and risks of geothermal underground exploitation activities at the meso and micro levels.

Scale	Environmental hazard	Source of hazard/pathway	Receptor	Environmental risk	Study
Meso level	Geo-fluid migration	● through faulty boreholes; ● Upward movement along the fault line;	Groundwater	● Salinization; ● Exposure to toxic compounds carried by formation fluids	[99]
Micro level	Induced seismicity	● Pressure change; ● Volume change of fluid injection and withdraw; ● Temperature change ● Chemical change of fracture surface	Human being above the ground	● Large event seismicity which cause damages	[73,91–98]

Table 15
Environmental impacts of subsurface exploitation of CAES at the macro and meso levels.

Macro level			**Meso level**		
GWP 100	Unit impact	gCO$_2$eq/kW h ● 5[a] (1–1.5% of LC chain) [18]; ● 8[a] [24]; ● 1.2 (0.4% of LC chain) [42]; ● 3.6 (1% of diabatic plant LC chain), 1.6 (3% of adiabatic plant LC chain) [43]	**EP**	Unit Impact	mgPO4eq/kW h 0.1 (2% of diabatic plant LC chain), 0.1 (1% of adiabatic plant LC chain) [43]
			FAETP	Unit	g1,4DBeq/kW h
				Impact	0.006 (2% of diabatic plant LC chain), 0.013 (1% of adiabatic plant LC chain) [43]

(Note: a function unit 1 kW h storage of surplus electricity is used. a: the impact value refers to both subsurface storage construction and plant construction).

Table 16
Environmental hazards and risks of CAES development at the micro level.

Scale	Environmental hazard	Source of hazard/pathway	Receptor	Environmental risk	Study
Micro level	Explosion	● The presence of compressed air, residual hydrocarbon and heat or ignition source	Human being above the ground	● Air pollution ● Fatal risks	[100]
	Air leakage	● Through imperfect welds or constriction joints; ● Structured damaged points of the liner during operation	Human being above the ground	● Material degradation ● Efficiency reduction ● Structural instability	[101]

the hazards at the meso level. The mechanism of an explosion occurrence in terms of storing compressed air in depleted natural gas reservoirs was analyzed in [100]. Oxygen provided by compressed air, fuels provided by residual hydrocarbon and heat provided by either compression energy or friction were identified as the potential sources of explosion. Operational failure such as imperfect welds and construction joints, as well as the induced failures due to repetitive air compression and decompression were identified as the key sources and pathways of air leakage [101] (Table 16).

7. Lessons learned and key knowledge gaps

7.1. Application of LCA and ERA to geo-resources exploitation

Based on the examined studies, the potential key knowledge gaps of applying LCA and ERA to geo-resources exploitation were identified and are presented in Table 17.

Fig. 2 indicates the numbers of the LCA and ERA studies focusing on different spatial scales. The environmental impacts at the macro level are the focus of examined LCA studies on geo-resources exploitation for all energy related purposes. The impacts at the meso and micro

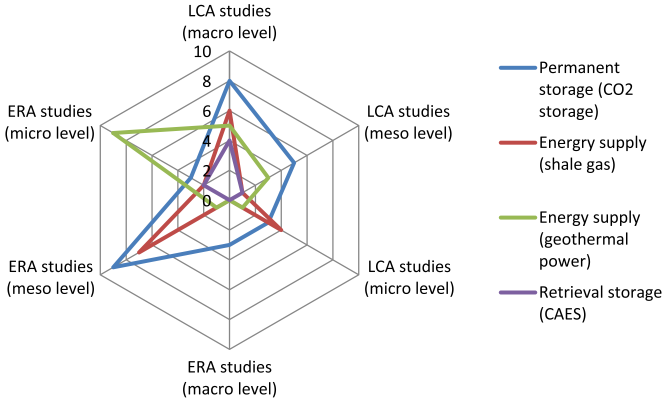

Fig. 2. The focus of the examined LCA and ERA studies at different spatial levels.

Table 17
The potential key knowledge gaps of applying LCA and ERA to geo-resources exploitation.

Purpose of geo-resources exploitation	**Key knowledge gaps**	
	LCA	**ERA**
All purposes	● Low understanding on the environmental impacts at the local level, e.g. HTP, WU, etc.	● Little understanding on the environmental risks of soil contamination ● A lack of learning on the probability assessment at: 1) the pathways and transport of hazard agents, and 2) the relation between hazard exposure and the impacts
Energy supply (shale gas and geothermal power)	● Focus on GWP with limited studies on other environmental impacts ● Low understanding on the water use of subsurface activities, such as hydraulic stimulation in EGS	● Low understanding on the environmental risks of geothermal exploitation other than induced seismicity, such as geo-fluids migration ● More lessens have to be learned by having a longer assessment period which covers the entire operation period in both probability assessment and consequence assessment
Permanent storage (CO_2 storage) **Retrieval storage (CAES)**	● More lessons have to be learned due to data of key parameters is mainly based on few existing projects ● Focus on GWP with limited studies on other environmental impacts ● Low understand on environmental impacts due to a lack of transparent data and information on the subsurface activities	● A lack of learning on environmental risks other than CO_2 leakage, such as brine migration ● Little understanding on the environmental risk

Table 18
The environmental impacts and risks of underground geo-resources exploitation.

Purpose of geo-resources exploitation	Level	LCA		ERA		
				Probability assessment		Consequences assessment
		Absolute impacts	Relative impacts	Operational failure	Geological failure	
Permanent storage (CO_2 storage)	Macro	Low	Low	Medium	Low	–
	Meso	Low (AP), high (EP)	Low	Medium	Low	High
	Micro	Low	Low	Low	Low	High
Fossil energy supply (shale gas)	Macro	High	Low (GWP), high (others)	Medium	Low	–
	Meso	Medium	High	Medium	Low	High
	Micro	High	Low (WU), high (others)	Medium	Low	High
Renewable energy supply (geothermal power)	Macro	High (EGS), low (flash and binary)	High (EGS and binary), low (flash)	–	–	–
	Meso	Low	High	–	–	–
	Micro	Low	Low (WU), high (others)	Low	Low	Medium
Retrieval storage (CAES)	Macro	Low	Low	–	–	–
	Meso	Low	Low	–	–	–
	Micro	–	–	–	–	–

levels receives less attention in the examined LCA studies except for CO_2 geological storage.

The ERA studies have different spatial focuses. In general, environmental risks of geo-resources exploitation at the macro level are often less evaluated. In particular, the ERA studies on renewable geo-resources exploitation only assess the environmental risks at the micro level, e.g. induced seismicity. While the environmental risks at the meso level are the emphases of the studies on fossil geo-resources exploitation and permanent storage exploitation. Very limited ERA studies are currently available for retrieval storage exploitation, e.g. CAES.

7.2. Environmental impacts and risks of underground geo-resources exploitation

Within the LCA studies, the absolute impacts refer to the results of the environmental impact comparison among different geo-resources exploitation (see Table 18). The relative impacts indicate the comparison results between the environmental impacts of underground activities and the impacts of its life cycle chain.

The normal operation of underground geo-resources exploitation for the storage purpose generally has low environmental impacts. They contribute to a minor part of the life cycle environmental impacts. Drilling is the only underground activity included in the LCA studies. A widely discussed hazard of exploitation for the storage purpose is the leakage of the storing agents, such as CO_2 and compressed air. The probability of the hazard caused by an operational failure has been evaluated potentially lower than the one caused by a geological failure. The effect and magnitude of the environmental consequences caused by the leakage largely depend on the property of the storing agent and existence of environmental receptors, e.g. groundwater. Very limited studies were carried out on the environmental risks of a CAES system may partially due to the storage period of compressed air is short and the storage agent, e.g. air, is harmless.

Environmental impacts of subsurface exploitation for the energy supply purpose depend on the underground activities and exploited energy carriers. The environmental impacts of geothermal power caused by normal subsurface operation have been evaluated as low, but having a relatively large share in its life cycle impacts. Power generation processes above the surface have lower environmental impacts than the underground exploitation activities have. The situation is different in the case of fossil geo-resources exploitation. The normal operation of underground shale gas exploitation generally has the highest environmental impacts among examined exploitation, largely due to the process of HF and the property of shale gas. The migration of fluids used for stimulating the exploitation processes and the migration of exploited energy carriers are identified as two major hazards for the exploitation activities with the energy supply purpose. An operational failure leads to greater likelihood of the hazard occurrence than a geological failure does. The environmental consequences of the hazard caused by fossil geo-resources exploitation is generally more serious than the one caused by renewable geo-resources exploitation.

7.3. Cooperation between LCA and ERA

LCA and ERA are two system analytical methods that provide approaches for structuring, assessing and presenting environmental information on potential impacts for (environmental) decision making. It is important to note that these two methods fulfill different purposes. LCA deals with environmental impacts caused by the full value chain of the examined service. In the context of geo-resources exploitation, the service is supplying energy or creating storage capacity. LCA uses a functional unit thereby facilitating the comparison of environmental impacts among different technologies or productions providing the same service under normal operation.

ERA deals with the environmental consequences and likelihood of a hazardous substance or event at specific time and conditions along with the exploitation activities. Unlike LCA studies investigating the demands of raw materials, energy, water as well as waste and emissions caused by normal operations, ERA focuses on addressing a hazardous substance or event due to potential operational failures or (geological) failure conditions.

The application of LCA and ERA has the potential to complement each other. They have different focuses on time and site specificity, on exploitation activities and conditions, as well as on spatial scales (see Table 19). LCA could point out possible environmental issues for particular operations or sites based on emission factors and impact indicators that could be then further examined in ERA with more site specific and detailed approaches [16]. Moreover, ERA focuses on environmental impacts mostly at the regional and local levels, while LCA studies provide the impacts at the global and regional levels. The

Table 19
Relation between LCA and ERA in terms of their focuses.

	LCA	ERA
Time and site specificity		
Time and site specific	Not necessary	Yes
Generic scenario	Maybe	Maybe
Product/service specific	Yes	Not necessary
Focus on the exploitation activities and conditions		
Normal operation	Included	Included
Operational failures/failure conditions	Not included	Included
Focus on the spatial scales		
Macro level	High	Low
Meso level	Medium	High
Micro level	Low	Medium

results of LCA and ERA studies may complement each other in providing an overview of environmental consequences of the subsurface activities of geo-resources exploitation.

8. Conclusion

This study aimed to identify general lessons and key knowledge gaps on understanding the sources, mechanisms and scope of environmental impacts of underground geo-energy resources exploitation. This was done by conducting an state of the art assessment of literature that have studied on assessing the environmental impacts and risks of geo-resources exploitation. CO_2 geological storage, exploitation of shale gas, geothermal power and compressed air energy storage were selected here as representative examples of different exploitation purposes. Twenty-six LCA studies and 31 ERA studies on selected geo-resources exploitation were reviewed.

The general observed trend regarding LCA application is that the environmental impacts at the macro level have received the most attention with a focus on the mid-point impact category GWP and relatively limited focus on other environmental impacts. The studies of CO_2 storage and geothermal power have relatively more investigations on the environmental impacts at the meso level, with AP and EP as the often investigated impact categories. Water use is the focus of the studies on shale gas and geothermal power at the micro level. In the cases of CO_2 storage and geothermal power exploitation, data of key parameters, such as well depth and water withdrawal are often based on a few existing projects. Limited and inconsistent data on water withdrawal is found in the studies of EGS. Moreover, the key parameters of subsurface activities in the CAES studies are often not available.

The ERA studies have similar priorities in the assessment stages with the sequence of hazard identification, consequences assessment and probability assessment. The probability of a hazard occurrence is the focus of probability assessment. In this assessment stage, there is limited information on the pathways and transport of hazard agents in the subsurface and on the relation between hazard exposure and the impacts. Numerical simulation and experiments are two widely applied approaches in the stage of consequence assessment. A relatively short assessment period is observed in both probability assessment and consequence assessment for exploitation with the energy supply purpose. An assessment period covering entire operation is recommended. Very limited ERA studies are available for the CAES systems.

According to the examined LCA studies, normal operation of geo-resources exploitation for **the storage purpose** has relatively low environmental impacts. Environmental impacts of geo-resources exploitation for **the energy supply purpose** depend on the type of underground activities and the exploited energy carriers. The environmental impacts of underground geothermal exploitation activities have a relatively large share in its life cycle impacts, even though absolute impacts during normal operation are evaluated as low. Normal operation of shale gas exploitation in general leads to high environmental impacts largely due to the process of HF and the property of shale gas (fossil fuel). The environmental impacts of underground share gas exploitation has accounted for a large share in its life cycle impacts, except for GWP and WU.

The environmental risks of soil contamination due to geo-resources exploitation are less understood. The leakage of the storing agents is a well-identified hazard in the ERA studies with **the storage purpose**. Basically, the probability of CO_2 leakage caused by an operational failure has been evaluated lower than the one caused by a geological failure. While the migration of fluids used for the exploitation processes and the migration of exploited energy carriers are identified as two major hazards for **the energy supply purpose** related exploitation. The effect and magnitude of environmental consequences caused by the leakage largely depends on the property of storing agents, the property of exploited energy carriers and the occurrence of environmental receptors.

There is a need for developing a framework that allows integrating the insights provided by LCA and ERA into decision making processes for subsurface environmental management. Such framework can support obtaining a more complete picture of potential environmental consequences of geo-resources exploitation caused by both normal operations and potential failures.

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