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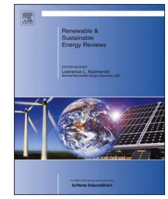

State of the art review of the environmental assessment and risks of underground geo-energy resources exploitation

Wen Liu[a,*], Andrea Ramirez[a,b]

[a] Energy & Resources, Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, 3584 CS, Utrecht, The Netherlands
[b] Engineering System and Service Department, Delft University of Technology, Jaffalaan 5, 2628 BX, Delft, The Netherlands

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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-

* Corresponding author.
E-mail address: w.liu@uu.nl (W. Liu).

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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.

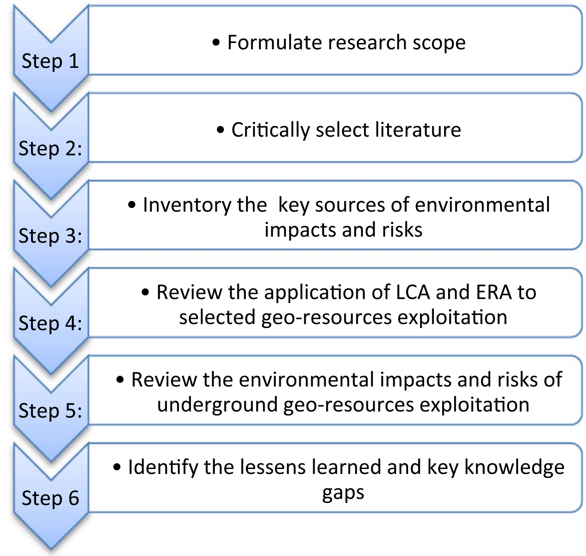

Fig. 1. Schematic diagram of the methodology used in this paper.

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