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Life cycle, PESTLE and Multi-Criteria Decision Analysis of CCS process alternatives

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ABSTRACT

CO_2 is the primary greenhouse gas (GHG) due to its large quantity of anthropogenic emission. In this work the amine based carbon capture process and the CO_2 storage, called Carbon Capture and Storage (CCS) is analysed from different viewpoints. PESTLE (Political, Economic, Social, Technological, Legal and Environmental) analysis of the CCS alternatives (Fossil based, Improved process, Renewable based) is investigated in detail and the alternatives are also compared with the uncontrolled CO_2 release using Life Cycle Assessment (LCA) methods. Life cycle inventory data is set up and analysed with four life cycle impact assessment methods. In order to conclude the comparison of CCS and the uncontrolled release of CO_2 a Multi-Criteria Decision Analysis (MCDA) is also applied with Multi Attribute Value Theory (MAVT) method. Our results show that applying process improvement and renewable energy sources (e.g., biogas) for absorbent regeneration result in a CCS technology of much smaller environmental and social impacts, and therefore the CCS technology becomes more favorable than the uncontrolled release.

1. Introduction

Carbon dioxide is the primary greenhouse gas (GHG). Its contribution to the anthropogenic emission to Earth atmosphere leads to global warming, and irreversible changes in the nature. Fossil based power plants are responsible for 30% of the annual anthropogenic CO_2 emission (Gohar and Shine, 2007) and these point like CO_2 sources provide a good opportunity for effective emission reduction. There are many alternative techniques for the CO_2 removal of power plants: oxy-fuel technology, pre- and post-combustion CO_2 removal (Boot-Handford et al., 2014; Metz et al., 2005). During post-combustion CO_2 removal, fuel is burnt conventionally in the combustion chamber generating a lean flue gas (CO_2 concentration is between 5 and 15%). An absorber column is installed before the stack where CO_2 is removed from the previously decontaminated (NOx, SO_2, HCl, particulates etc.) flue gas. The environmental effect of CO_2 emission and its possible capture have been studied by many researchers from different points of views, like capture and storage by macrophytes (Means et al., 2016), mathematical modelling of carbon dioxide absorption using hollow fiber membrane contactor (Motahari et al., 2016). Tock and Maréchal (2013) presented a thermo-environomic optimization strategy and process developments for greenhouse gas emission mitigation. Kim et al. (2016) identified various physical, chemical, and biological factors which could be changed during CO_2 emission and leakage. Badr et al. (2017) described potential environmental hazards (acute and chronic toxicity, irritation, water mediated effects) in an amine based capture system. Lee et al. (2016) and Chen et al. (2016) showed that retrofit optimization is a fundamental task because it can result in significant thermal and total energy reduction. The most frequently applied technique for CO_2 removal uses the principle of chemical absorption: CO_2 is absorbed in a solvent (usually a kind of ethanol-amine), then, several reactions take place between CO_2 and the solvent, therewith equilibrium of absorption is shifted to the direction of total absorption. In a second operation, the solvent can be regenerated by using heat and CO_2 leaves in high concentration at top of the desorber column (Nie et al., 2011).

Due to the technological potentials and existing challenges, post carbon capture (PCC) is studied from a variety of approaches. Nagy and Mizsey (2013, 2015) have discussed the effect of how the fuel, CO_2 separation efficiency, and solvent regeneration energy

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converted to equivalent carbon-dioxide (CO_2eq) are in the function of each other. They have demonstrated their results and highlighted with the frequently used solvent, monoethanolamine (MEA) that special considerations are devoted to the proper design and control of the carbon dioxide capture system operating at a boiler and/or power station. A similar study was focusing on the dynamic behavior and transients by Léonard et al. (2013) who completed the dynamic modelling and control of a pilot plant for post-combustion CO_2 capture. The work of Khan et al. (2015) demonstrated that monoethanolamine based CCS systems work at high CO_2 removal efficiency (99.13%) in case of flue gas. In addition, a previously conducted LCA analysis between several CCS processes showed that the average environmental effect of MEA is below 5% (García-Gusano et al., 2015), thus in our work MEA based CCS alternatives are examined.

Another approach was presented by Tock and Maréchal (2014) realizing energy and cost correlations in a process design optimization strategy for such systems. They enhanced their approach by the comparison of different CO_2 capture options. One of the greatest challenge that inhibits the commercialization of CO_2 capture is the lack of demand of the economic utilization of CO_2. This serious issue was addressed in the article of Dumont (2012) by making an assessment on the environmental potential of carbon dioxide utilization along a graphical targeting approach.

Further on the approach from the life cycle analysis is also a known tool to evaluate the CO_2 capture. Case scenarios were published by Koornneef et al. (2008), Ou et al. (2016) and von der Assen et al. (2014), who studied how different technological carbon capture examples/techniques influence the environmental impact of a power plant. They point out that over 70% (ψ) capture is achievable but this result comes on the cost of other environmental impacts. These impacts are divided into categories such as human toxicity, ozone layer depletion, eco-toxicity, etc. The work of Marx et al. (2011) points out that LCA approach of CCS should consider very similar cases in order to provide accurate parametric sensitivity.

Cuéllar-Franca and Azapagic (2015) made a summary of recent LCA studies of CCS, in which it can be pointed out that the number of LCA impacts is generally limited to only 1–4 environmental factors. In order to get an evaluation of the overall environmental impact of different carbon capture configuration techniques and removal rate, multi-criteria impact assessment methods give more precise results. A current tendency in LCIA method development aims at reconciling midpoint-based impact assessment and damage oriented methods. Both of them have their merits separately, and optimal solutions can be expected if the midpoint-oriented methods and the damage-oriented methods are fitted into a consistent framework. Hence, in our work we applied different types of LCA methods (e.g., IPCC 2007 100a, IMPACT 2002+, Eco-indicator 99(H) and EPS 2000) to evaluate CCS alternatives.

The uncontrolled release of CO_2 is mostly approached as a sole environmental issue (Stefanica et al., 2016; Gładysz and Ziebik, 2016). In turn, beyond the undoubtable environmental aspects there could be other important areas that are influenced by the direct flue gas release (e.g, political, social, economic, legislative, technological, etc. aspects). In our investigation a PESTLE risk analysis is performed where potentially affected factors are identified. Taking into account these factors CCS process alternatives are evaluated by Multi-Criteria Decision Analysis (MCDA).

In Section 2, data and methods are discussed then the research methodology is described in Section 3 including cost analysis, process improvement, carbon capture based on fossil fuels and renewable sources. In Section 4 the MCDA results are presented. The conclusions are presented in Section 5.

2. Data and methods

2.1. System setup for Life Cycle Assessment

The investigated systems setup is shown in Fig. 1. System boundary includes CO_2 capture, compression, transport to the place of storage and the injection of CO_2 into the final reservoir. Korre et al. (2010) presented input output data of CO_2 capture from coal fueled power plant, including supplementary stream such as NaOH and activated carbon consumption during absorbent reclamation. The reported data include material and energy requirements for the CO_2 removal at 92% efficiency (Ψ), while this value is 90% in case of white wood pellets based combustion plants (Al-Qayim et al., 2015). Output of the CO_2 capture process is the cleaned flue gas and the captured CO_2 of high purity.

For the better overview, only the CO_2 content of the flue gas is considered and other components, such as SOx, NOx, CO etc. are omitted. Transportation of the captured CO_2 is much easier and requires less volume if the CO_2 gas is compressed and liquefied. In our work, we consider the compression up to 100 bars. Relevant input of this step is the energy requirement of the compression, which data are obtained from House et al. (2009).

Transportation of the compressed CO_2 is possible by several ways like via railway, on road and on sea that requires the lowest investment; however, these options have high risk of accidents. Therefore, the transportation of the compressed CO_2 is considered in pipelines. The work of Wei et al. (2016) demonstrates that pipeline transportation is a cost-effective method and the total cost (including capital and operating costs, CAPEX and OPEX) of 100 km pipeline varies between 0.83 and 11.7 USD/t_{CO_2}. Ecoinvent database 3.1 (Ecoinvent, 2013) includes data describing environmental impacts of pipeline erection, material and energy requirement of the transportation of the compressed CO_2 via pipeline. Finally, the liquefied CO_2 is injected into a geological reservoir. The relevant energy (electricity) input of the injection step is taken from House et al. (2009) and Fozer et al. (2016). Xiao et al. (2016) presented that CO_2 leakage from the final reservoir could influence negatively the groundwater quality. In the worst-scenario, the concentration of TDS (Total Dissolved Solids), nitrate and trace metals increases twice compared to the basic values after 200 years and that could affect the environmental impact results given by LCA methods. The storage serves as a landfill, thus this LCA is considered as a cradle-to-gate life cycle analysis.

In our work, the uncontrolled CO_2 release is compared to three CCS alternatives, namely CCS based on Fossil fuel, CCS Improved process and CCS based on renewable energy. CCS Fossil is selected as a base case, life cycle inventory (LCI) set up for the investigated base case is shown in Table 1. Based on process improvements the required energy for MEA regeneration can be significantly decreased (approx. 60%) (Nagy and Mizsey, 2015; Yu et al., 2016), while applying renewable energy instead of fossil fuel is a growing tendency which results in GHG emission reduction.

Input/output database of electricity generation is obtained from the Ecoinvent database. LCI data is evaluated by the professional LCA software SimaPro 8.0.1 including Ecoinvent 3.1 database. Environmental impact assessment step is carried out for the same LCI dataset. The applied impact assessment methods are listed below:

- *IPCC 2007 (100a)* is a mid-point impact assessment method with one impact category that is the global warming potential (GWP). Environmental impact is expressed after characterization in CO_2 equivalent (kg CO_2 eq) with the time horizon of 100 years.
- *Eco-indicator 99* is a damage oriented, end-point impact assessment method including normalization and weighting of