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Simplified dynamic life cycle assessment model of CO2 compression, transportation and injection phase within carbon capture and storage

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Abstract

Carbon capture and storage is significant technology in the limitation of greenhouse gases in the atmosphere worldwide. Carbon capture and storage consists of four general processes within the system: carbon capture, carbon compression and transport, carbon injection and carbon storage. All the processes require energy to operate the system and therefore produce additional amount of carbon dioxide emissions. The energy penalty decreases the efficiency of the plant: the total conditional efficiency of the CCS system is often characterised as difference between CO2 emissions eliminated by CCS and CO2 emissions produced by CCS processes. Additionally, CCS is associated with environmental, safety and human consequences because of CO2 leakage from storage sites and its impact to ecosystems, stability of geological layers and changes in geological properties of formations, etc. This paper is aimed at the identification and optimisation of costs and the environmental impact categories caused by energy consumption at a CCS power plant for the realization of carbon compression, pipeline transport and carbon injection phases.

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Keywords: CO2; LCA; transport; injection; costs.

1. Introduction

Energy production sector is one of the key players making to increase the greenhouse gases (GHGs) concentrations in the atmosphere and resulting the global warming processes. Implementation of carbon capture and storage technologies in the energy production sector presents a challenge to limit the concentration of CO2 in the atmosphere.

Implementation of carbon capture and storage chain is an energy intensive process and requires additional energy and infrastructure. Life Cycle Assessment (LCA) is an objective procedure used to evaluate the environmental impacts associated with a product’s or process’s life cycle, through the quantitative determination of all the exchange flows between the product’s system and the environment [6]. Carbon capture and storage, for example, requires a significant amount of energy to supply the capture units, compressors and pumps to generate the thermal and electrical energy that ensure safe storage of carbon dioxide in geological storage sites. The CO2 emissions are produced in energy generation processes and also might be emitted to the atmosphere during transportation and injection processes directly from the pipelines and injection wells as leakages. Despite the drawback of the CCS energy consumption impacts, CCS performs the promising possibilities to reduce the global effects caused by CO2 emissions in the atmosphere. The European Union policy requirements forcing the implementation of CCS
technologies in the energy production sector are considered as strong instrument to replace the existing low efficiency energy technologies with high efficient technologies with carbon capture and to minimise the side impacts to the environment. Building of a LCA model provides the possibility to understand the potential benefits and threats of the advanced energy production technologies.

The focus of the research lies on definition of the energy consumption associated with CO2 compression, transport and injection phases.

2. Method

Life cycle assessment is chosen as a method for the environmental evaluation of the carbon dioxide compression, transport and injection processes. The assessment of the environmental impact categories is conducted using the life cycle analysis. Selection of the evaluation method is based on the following considerations:

- life cycle analysis makes it possible to investigate in detail the environmental impacts related with primary and secondary process flows along the whole system chain;
- energy production at power plants is characterized by irregular, time dependent capacity load and therefore changeable efficiency rate of the plant.
- dynamic life cycle analysis (LCA) gives the opportunity to clear the time horizon limitations and to define the prescribed environmental impacts for each unit step for subprocesses and the whole system.

Definition of environmental impacts through life cycle assessment approach gives the anticipation for selection of different alternatives from environmental protection point of view. The combination of the LCA results and cost analysis determinates the broader outlook to prevention and correction of the environmental processes. In the research the dynamic processes of energy costs are merged with the environmental impact categories (climate change, minerals, acidification/eutrophication, carcinogens, land use, radiation, ecotoxicity, etc.)

The LCA is performed in accordance to the standard ISO 14040 [6] which describes the principles and the framework of the life cycle assessment. The model is developed in the Sima Pro life cycle assessment software tool.

3. Life cycle inventory

3.1. System definition

The research is focused on definition of the environmental impacts from CO2 compression, transport and injection processes. All other stages of carbon capture and storage are excluded from the system boundary. Two interconnection between the analysed stages are defined – CO2 flow and electricity taken from the reference power plant with carbon capture for implementation of the compression, transport and injection processes. The simplified scheme of the analysed model is shown in Figure 1.

![Figure 1](image-url)
3.2. Functional unit

The main objective of an energy system is to provide energy to an end user. The environmental restrictions set by the policy makers (for ex. limitation of the CO2 concentration in the atmosphere) and forwarding the implementation of carbon capture and storage put the operational limits to energy producers. Thus the functional unit defined in the research is 1MWh of electricity delivered to end users and the CO2 emissions associated with CO2 compression, transport and injection.

3.3. Power plant description

The reference power plant used in the research is a natural gas combined-cycle (NGCCT) gas turbine with post combustion capture (MEA sorbent) technology with a net power of 400 MWe. The net efficiency of the power plant with CO2 capture is 43%. The installed capture technology captures about 94% of CO2. It is assumed that the compression and pumping units are operated with a load of 70%. The life time of the power plant is assumed as 20 years and the decrease of energy efficiency over the years is assumed as minus 4% by the end of the life time and this obstacle gives the time dependent evaluation results. The amount of the CO2 produced at the power plant is 1.1 million tonnes per year.

The carbon capture process is stated as the most energy intensive process in the CCS chain [8, 13, 14]. Still the energy generation (power plant construction and operation) and CO2 capture processes (incl. solvent regeneration, cooling water pumps and solvent pumps, etc.) are not included in the system boundary upon the research. Unless the electricity generated in the NGCCT plant is used as energy agent for implementation of CO2 compression, transport and injection processes.

Data used at inventory stage are extracted from the existing LCA databases (Ecoinvent, ETH-ESU, IDEMAT), technical reports or scientific literature sources [2, 7, 8, 11, 13, 14].

3.4. Transport phase description

Onshore pipeline transport option is selected as optimal way for transportation of the carbon dioxide from the CO2 source (NGCC plant with post combustion capture) to the storage site (a saline aquifer). The CO2 is assumed to be transported in supercritical aggregative state. Therefore after the CO2 capture plant, CO2 flow is compressed to the supercritical state. The technical parameters of the CO2 compression are overtaken from McCollum [10] and Koorneef [7].

Two scenarios for CO2 transport distances are evaluated in the research - 100 km and 400 km. The selection of the distance scenarios is based firstly on the requirements of recompression along the CO2 transportation route. It is assumed in the research that the distance between the recompression stations is 160 km (the environmental impacts from the recompressions stations are integrated in the evaluation of the transportation phase and are not estimated separately). Secondly, the appropriate storage sites for the CO2 are located in the western part of Latvia, and therefore the transport distance from central and eastern parts of the country vary from 200 to 400 km. It is assumed in the research that CO2 two phase flow is avoided.

The energy consumption, land occupied for CO2 transport infrastructure and the materials needed for the pipeline production/operation are taken into account in the research from the technical report on geological carbon sequestration in the Illinois basin [3] and McCoy [11].

The CO2 flow transport parameters (temperature, pressure, density) are defined within the margins of the supercritical phase and the iterative calculation of the parameters (velocity, diameter, roughness, etc.) for the optimisation model is harmonized to this principle too.

The data on materials and equipment used for the CO2 pipeline are based on the technical reports and scientific papers [3, 7, 10, 11, 16]. The level of the data uncertainties for the CO2 transport phase is assumed from average to low.
3.5. Storage site description

It is assumed that CO2 is injected into a saline aquifer: there are more than 10 potential saline aquifer reservoirs in Latvia [5]. The storage site processes include well drilling, well cementing, CO2 injection and monitoring. The well cementing and monitoring processes are not assumed as energy intensive processes, therefore the well drilling and CO2 injection processes are only included in the system boundary. Land required for CO2 injection and storage site development is adopted from the topical report on Carbon Dioxide Capture and Transportation options in the Illinois Basin [3], Wildbolz [16] and J.P.Meyer [9]. The data on geological parameters of the saline aquifer are taken directly from (1) the geological surveys carried out in Latvia from 1960 to 1989; (2) theoretical geological modelling surveys [1] or (3) calculated and assumed data. Thus the level of the data uncertainties for the geological storage site varies from high to average.

The energy requirement for CO2 injection is calculated for the storage depth of 1000 m – the depth typical for the saline aquifer available in Latvia. Taking into account the CO2 mass flow, it is assumed that one injection well is used to store CO2 in the reservoir.

4. Cost analysis of the environmental impacts

The purpose of a cost analysis of the environmental impacts is to estimate the overall costs of the CCS and to demonstrate the allocation of the costs between the impact categories. The cost analysis of the CCS technologies includes the following cost components: capital investments, energy production costs (incl. CCS introduction, operation and maintenance (O&M) costs) and, against the LCA, are calculated for all the stages of the CCS - CO2 capture, CO2 compression and transport, CO2 injection and storage. Such approach will show the economic effects caused by the environmental impacts from CO2 compression, transport and injection stages.

4.1. Calculation of capture, compression and pumping costs

CO2 capture costs build up to 70% of the full cycle CCS costs [8] and include investment costs for the development of the capture unit and O&M costs of the unit, incl. costs for extra fuel consumption to compensate energy consumption used for capturing. The capture costs are calculated according to [8, 11, 15].

An additional component often included into the CO2 capture phase is CO2 compression before transportation. Compression is done for two reasons: (1) to change the aggregative state of CO2 from gas to liquid; and (2) to reach the technically and economically optimal CO2 flow conditions suitable for CO2 transport via pipelines. Firstly, the gaseous CO2 is compressed to a critical point (7.38 MPa) with a compressor and then the liquid CO2 is compressed to the transportation pressure with a pump. The total capital costs of the CO2 compression phase are calculated as a sum of the capital costs of the compression and pumping units. The operation and maintenance costs (O&M) of the compression and pumping are calculated with O&M factor.

4.2. Calculation of transport cost

Compressed CO2 flow is transported via pipeline to the storage site. As was stated before, the distances between the compression unit and the storage site observed in the research are 100 km and 400 km.

By this time the CO2 transportation via pipelines is well researched area because of the existing technical similarities of transportation of oil products/ natural gas and carbon dioxide and different cost models for calculation of the CO2 transport via pipelines are available also in [4, 10, 11, 12]. In the research the calculation of the CO2 transport costs is based on several methodologies: McCollum model, Ogden model, MIT model, Ecofys model, IEA GHG 2005/3 report model and Cobb – Douglas model [10, 11, 12]. This combined calculation method is chosen to get that various pipeline structure and landing parameters are included in the cost model at the high degree of detailed elaboration.
4.3. Calculation of injection and storage costs

The calculation model of injection and storage costs is based on two existing models [10, 11] and includes the injection site development costs, storage place costs and monitoring costs.

Results and discussions

The life cycle analysis provides the results on the environmental impacts caused by the CO2 compression, transport and injection processes. Figure 1 shows the absolute scores for two evaluation scenarios: (1) CO2 transport via pipelines of 100 km without recompression stations and (2) CO2 transport via pipelines of 400km with additional recompression. The dynamic analysis is estimated through change of the power plants technical age: the first case - a new power plant with CCS, the second case – the power plant with CCS operated for 20 years.

![Figure 2. Comparison of the environmental impact categories for two distance routes (the new power plant).](image)

The increase of CO2 transport distance increases the impacts to the environment from the whole CO2 compression, transport and injection chain. At the same time, for some impact categories (fossil fuels, ecotoxicity and land use) the increment rate is very high and is caused by laying of additional pipelines and installment of recompression station between the capture plant and the storage site.

The power plant technical age put the effect to the environmental impact categories (Figure 2). The energy efficiency of the power plant during 20 operation years decreases for 4% and thus the impacts to fossil fuels (natural gas) and climate change increase for 18% and 21% accordingly.
Figure 3. The effect of the power plant technical age to the environmental impacts (CO2 transport without recompression stations).

Any impact category can be expressed in financial term. The impact categories are defined in millipoints per 1 MWh of energy delivered to end users; end users pay for energy production and delivery. Thus the ratio between the electricity cost and the environmental impact score will indicate the cost for limitation of the environmental impacts caused by implementation of the CO2 compression, transport and injection. The summary of the costs results is given in the Table 2.

Table 2
Results of the costs analysis of impact categories.

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Operated power plant with CO2 transport distance of 400 km</th>
<th>Operated power plant with CO2 transport distance of 100 km</th>
<th>New power plant with CO2 transport distance of 400 km</th>
<th>New power plant with CO2 transport distance of 100 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil fuels</td>
<td>13,6</td>
<td>6,5</td>
<td>5,5</td>
<td>1,6</td>
</tr>
<tr>
<td>Minerals</td>
<td>3,0</td>
<td>1,5</td>
<td>0,6</td>
<td>0,4</td>
</tr>
<tr>
<td>Land use</td>
<td>1,5</td>
<td>0,9</td>
<td>0,4</td>
<td>0,3</td>
</tr>
<tr>
<td>Acidification</td>
<td>0,9</td>
<td>0,5</td>
<td>0,3</td>
<td>0,1</td>
</tr>
<tr>
<td>Ecotoxicity</td>
<td>2,5</td>
<td>1,4</td>
<td>0,7</td>
<td>0,4</td>
</tr>
<tr>
<td>Ozone layer</td>
<td>0,1</td>
<td>0,0</td>
<td>0,0</td>
<td>0,0</td>
</tr>
<tr>
<td>Radiation</td>
<td>0,1</td>
<td>0,1</td>
<td>0,0</td>
<td>0,0</td>
</tr>
<tr>
<td>Climate change</td>
<td>5,3</td>
<td>4,4</td>
<td>1,2</td>
<td>1,0</td>
</tr>
<tr>
<td>Carcinogens</td>
<td>3,1</td>
<td>2,1</td>
<td>0,8</td>
<td>0,6</td>
</tr>
</tbody>
</table>
The results of the costs analysis show that the decrease of the energy efficiency at the power generation plant puts the effect on the environmental and economic values of the CO2 compression, transport and injection processes: the limitation of the climate change impact costs from 1 Euro to 5 Euro per impact point. The costs associated with the land use however slightly vary from the power plant age and even the CO2 transport distance – laying of the CO2 pipelines do not require the large land area.

It is found that acidification and eutrophication processes are mainly forced by the increase of the fuel consumption for compensation of the energy efficiency of the power plant. However this cost value might be minimised by including the CO2 capture plant in the system boundary of the LCA.

The future work must be focused on definition of additional variables (types of pipelines, number of injection wells, storage depth, etc.) and the expansion and specification of the system boundary.

References

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