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Environmental assessment of a membrane-based air separation for a coal-fired oxyfuel power plant

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ABSTRACT

CO_2 reduction from fossil-fired power plants can be achieved by carbon dioxide capture and storage (CCS). Among different CO_2 capture technologies for power plants the oxyfuel power plant concept is a promising option. High temperature ceramic membranes for oxygen production have the potential to reduce the associated efficiency losses significantly compared to conventional air separation using cryogenic techniques. Focus of this paper is the environmental performance of membrane-based oxygen production for oxyfuel power plant technology. Included into the analysis are the production of the perovskite membrane (BSCF=$Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$), the incorporation into a steel module, and the integration of several modules into an oxyfuel power plant. The membrane-based oxygen production is compared to the conventional cryogenic air separation in oxyfuel power plants in an ecological way. The evaluation is performed using life cycle assessment (LCA) methodology from "cradle to grave". The share in the overall environmental impacts of respective life cycle elements like membrane and module production but also coal supply processes as well as the operation of the oxyfuel power plant are identified. Sensitivity analyses referring to life-time, permeability and housing conditions of the membranes set benchmarks for further membrane development.

1. Introduction

The reduction of CO_2 emissions released into the atmosphere in order to protect our climate is the main focus of Carbon dioxide Capture and Storage (CCS) technology. Every capture technology lowers the net efficiency of power plants to some extent. In order to compensate for this efficiency loss, additional fuel input per unit of electricity output is necessary, leading to additional emissions. While capturing CO_2 from the power plant reduces direct CO_2 emissions, upstream emissions resulting from these additional fuel and materials supply are not captured usually. Among different CO_2 capture technologies the oxyfuel concept is a promising option. In an oxyfuel process coal is directly burned with oxygen in recirculated flue gas instead of air, resulting in a higher concentration of CO_2, facilitating its capture. State-of-the-art oxygen producing technology is cryogenic air separation, a method already being applied worldwide in large scale in the steel industry and 'gas-to-liquid' plants. Its use in power plants however can cause efficiency losses of 8–10%-points [1]. A promising alternative is oxygen production by a membrane-based air separation process. Ceramic membranes are selected as suitable material for oxygen production, reducing the efficiency losses to 7%-points or even less. Here, oxygen is separated by transporting ionised oxygen at high temperature throughout ceramic membranes (HTM). These membranes, also known as Mixed Ionic Electronic Conducting (MIEC) membranes, can separate oxygen with a selectivity of 100% at temperatures above 700 °C. Therefore, the development of novel membranes for advanced power plant technology is currently very much in focus of research [2]. The presented work is based on experimental results of the Helmholtz project "MEM-BRAIN" [2]. It considers environmental effects during production of a perovskite-membrane (BSCF=$Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$), its integration into a module as well as during operation in an oxyfuel power plant. The detailed modelling of the oxyfuel processes within the simulation software ASPEN PLUS® has been carried out in a previous study [3]. A life cycle approach provides an adequate method for a comprehensive evaluation of various environmental effects. It includes upstream processes like additional fuel and material supply as well as downstream processes such as waste treatment into the analysis. In recent years several LCA studies investigating oxyfuel systems have been published [4–8], however, no study considers air separation by membranes. The life cycle inventory (LCI) results are assigned to selected impact categories e.g. global warming potential (GWP) and acidification potential (AP). The results of the membrane-based oxygen production are compared to cryogenic air separation in an oxyfuel power plant. Additionally, sensitivity analyses are undertaken to investigate effects of highly uncertain basic assumptions such as the life-time, permeability of membrane and the steel amount for module production to set benchmarks for further membrane development.

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Table 1
Description of selected impact categories.

Impact category	Abbreviation	Short description	Example of relevant LCI data	Characterisation factor
Global warming potential	GWP	Impact of human emissions on radiative forcing of atmosphere, causing a temperature rise	CO_2, N_2O, CH_4, SF_6, $CHCl_3$, CF_4, CFCs, HCFCs, CH_3Br	kg CO_2-equivalents
Acidification potential	AP	Emission of acid-forming substances	SO_x, NO_x, HCl, HF, NH_3, HNO_3, H_2SO_4, H_3PO_4	kg SO_2-equivalents
Eutrophication potential	EP	Excessive supply of nutrients	PO_4^{3-}, N_2, NO_2, HNO_3, NH_3, H_3PO_4, COD	kg PO_4^{3-} equivalents
Photochemical ozone creation potential	POCP	Summer smog; formation of reactive chemical compounds by action of sunlight on primary pollutants	Ethylene, polycyclic aromatic hydrocarbons, NO_x, NMVOC, CH_4	kg ethylene-equivalents
Human toxicity potential	HTP	Degree to which a chemical substance elicits a deleterious or adverse effect upon human exposed to the substance over a designated time period	Chlorinated solvents and compounds, pesticides, hydrocarbons, heavy metals, CO, SO_2, NO_x	kg 1.4 dichlorobenzene-equivalent (DBC)

2. Life cycle assessment methodology

Life Cycle Assessment (LCA) is an appropriate tool to analyse environmental effects in a comprehensive way from cradle-to-grave. From the mining of the necessary materials and energy carriers, the production and operation of power plants and capture facilities as well as the final disposal after its life time all life stages are taken into account. In an international standard [9], the methodology of LCA was structured and guidelines for practitioners are given. It distinguishes between 4 stages:

- *Goal and scope definition*. This step describes the main purpose of the analysis. Also the investigated system is described and the basis for comparison (functional unit) as well as system boundaries concerning time frame and region is defined.
- *Life cycle inventory (LCI)*. In this step, all relevant material and energy inputs and outputs of the investigated system are collected, calculated and analysed on a single process scale. As one has to deal with a huge amount of data in this step, databases are usually used to handle these.
- In the *Life cycle impact assessment (LCIA)* the gathered and aggregated inputs and outputs of the system are categorised and allocated to impact categories, such as global warming, acidification, photochemical ozone creation potential, eutrophication or human toxicity potential, etc. (Table 1). Characterisation of environmental impacts is based on method of the Institute of Environmental Sciences at the Leiden University (CML), updated in November 2010 [10]. The final normalisation step relates the results of the impact assessment to the total amount of the corresponding impact category in a specific region (e.g. Germany, EU, world).
- *Interpretation*. This step summarises the results from the inventory analysis and impact assessment. The outcome is a set of conclusions, recommendations and limitations.

3. Goal and scope

Goal of the investigation is the evaluation of environmental effects of the new developed membrane technology for oxyfuel power generation. The results are compared to those of a conventional cryogenic system.

At first the BSCF membrane module has to be defined and the production is described and modelled in a LCA structure (Fig. 1). For this analysis a steel container housing BSCF hollow tubes is chosen, combining the concepts of Vente et al. [11] and that of the MEM-BRAIN project [2]. Fig. 1 shows the process chain for a BSCF membrane module, starting from the basic minerals (cobalt, strontium and barium ores, Fe turnings), production of the BSCF basic components (Co_3O_4, $SrCO_3$, $BaCO_3$, FeOOH), production of the BSCF membrane hollow tubes, and finally the production of the membrane module.

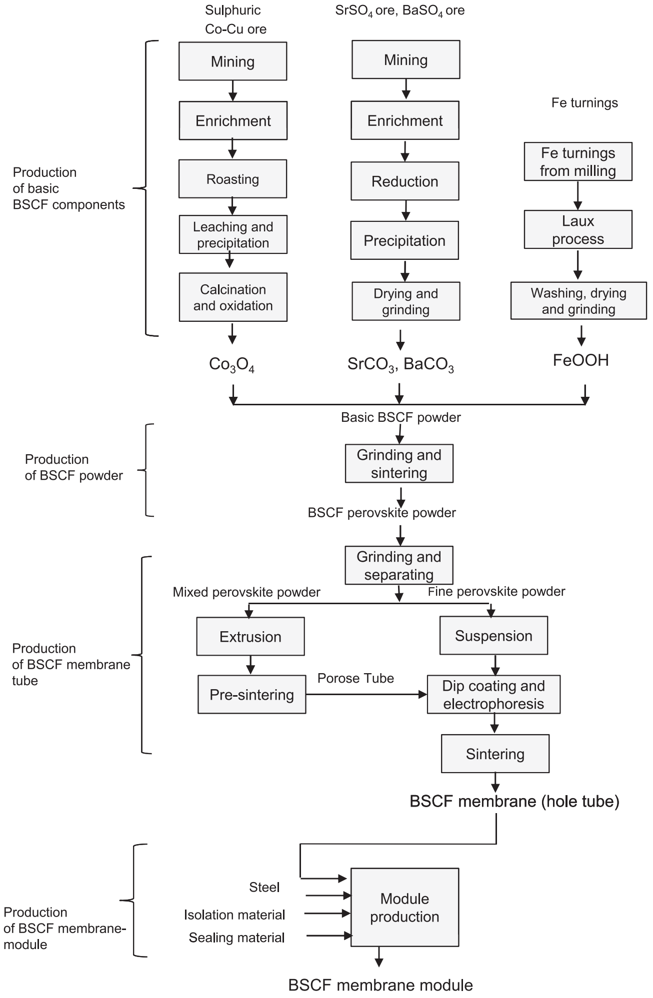

Fig. 1. Main processes of BSCF membrane module production.

Afterwards the BSCF membrane modules are integrated into the oxyfuel power plant with high temperature ceramic membrane based air separation unit (HTM-ASU). The oxyfuel power plant is based on a state-of-the-art coal-fired power plant situated