Applied Energy 150 (2015) 161–175

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Comparative life cycle analyses of bulk-scale coal-fueled solid oxide fuel cell power plants

Jake Nease, Thomas A. Adams II *

Department of Chemical Engineering, McMaster University, 1280 Main Street West, Hamilton, Ontario, Canada

HIGHLIGHTS

- A full LCA of a solid oxide fuel cell power plant fuelled by coal is performed using *ReCiPe 2008*.
- LCAs are performed for modern state of the art (IGG, SCPC) coal plants for comparative purposes.
- Mid- and end-point impacts are tabulated for each plant with and without the use of carbon capture.
- SOFC plants with carbon capture have much lower life cycle impacts than state of the art plants.
- Results are compared with natural gas plants using *ReCiPe* to assess the impact of different fuels.

ARTICLE INFO

Article history:
Received 27 January 2015
Received in revised form 18 March 2015
Accepted 21 March 2015
Available online 21 April 2015

Keywords:
Life cycle analysis
Solid oxide fuel cells
Coal
Natural gas
Gasification

ABSTRACT

Detailed cradle-to-grave life cycle analyses are performed for bulk-scale solid oxide fuel cell power plants fueled by gasified coal. These results are compared to cradle-to-grave life cycle analyses of the supercritical pulverized coal and integrated gasification combined cycle power generation plants, which are also performed as a part of this study. Life cycle inventories for each plant including the inputs (resources and fuels) and outputs (emissions and waste) of the gate-to-gate plants and their associated up- and down-stream sub-processes are computed. The impact of carbon capture and sequestration on each plant is quantified and assessed using the *ReCiPe 2008* life cycle inventory method for three socioeconomic perspectives. The results of each coal plant are compared to one another and to plants generating power from natural gas at the end-point level. Results indicate that not only do coal-fed SOFCs generate power with a significantly lower life cycle impact than the current state-of-the-art coal plants, but when carbon capture is enabled they can do so with a lower impact than the most modern plants utilizing natural gas, as well.

1. Introduction and motivation

The growth of industrialization, worldwide population and overall quality of life in most regions of the world has led to increasing demands for the production of reliable electricity. Moreover, increasing concern regarding greenhouse gas emissions and the environmental impact of fossil fuel consumption has resulted in the need for efficient, reliable and environmentally responsible energy production strategies [1]. Research dedicated to the development of wind, solar and biofuel energy sources has been significant, but these technologies are not yet ready to completely replace more traditional methods utilizing fossil fuels [2]. Over the next 20 years, it is anticipated that wind, solar, and biomass use will comprise approximately 10% and 16% of the electricity markets in Canada [3] and the United States [4], respectively. Contrarily, electricity derived from natural gas (NG) is anticipated to account for 15% and 34% of all power produced by 2035 for Canada [3] and the United States [4], respectively. Furthermore, even with the expected growth of renewable technologies, coal is still anticipated to be a dominant contributor to the United States' power mix in 2035, supplying approximately 34% of demand [4]. Not only is coal anticipated to remain a large contributor, but over 250 years of coal capacity (at the current usage rate) is available in North America. The abundance of coal coupled with its forecasted importance in the North American energy mix motivates the development of processes that can use it in an environmentally and socially sustainable manner [5].

Solid oxide fuel cell (SOFC) power plants with integrated carbon capture and sequestration technology (CCS) have been proposed as

* Corresponding author at: 1280 Main Street West, Hamilton L8S 4L7, Ontario, Canada. Tel.: +1 (905) 525 9140x24782.

E-mail address: tadams@mcmaster.ca (T.A. Adams II).

http://dx.doi.org/10.1016/j.apenergy.2015.03.105

Nomenclature

ALO	agricultural land occupation
ASU	air separation unit
CAES	compressed air energy storage
CC	climate change
CCS	carbon capture and sequestration
DCB	Dichlorobenzene
ED	damage to ecosystem diversity
FD	fossil depletion
FE	freshwater eutrophication
FET	freshwater ecotoxicity
HH	damage to human health
HHV	higher-heating value
HRSG	heat recovery and steam generation
HT	human toxicity
IR	ionizing radiation
LCA	life cycle analysis
MD	metal depletion
ME	marine eutrophication
MET	marine ecotoxicity
NGCC	natural gas combined cycle
NLT	natural land transformation
NMVOC	non-methane volatile organic compound
OD	ozone depletion
PEN	positive-electrolyte-negative
PM_{10}	particulate matter with radius 10 μm
PMF	particulate matter formation
POF	photochemical oxidant formation
RD	damage to resource depletion
SOFC	solid oxide fuel cell
TA	terrestrial acidification
TET	terrestrial ecotoxicity
ULO	urban land occupation
WD	water depletion
WGS	water gas shift

a way of producing electricity from coal with almost no CO_2 emitted directly from the power plant itself, while also significantly reducing water consumption [6]. This process and its many variants have been studied by many different groups (see [6] for an extensive review) and has repeatedly been shown to be a very promising way of using coal with potentially higher efficiencies and reduced direct CO_2 emissions than the current state-of-the-art supercritical pulverized coal (SCPC) process or even the integrated gasification combined cycle (IGCC) process with carbon capture.

However, to the best of our knowledge, a cradle-to-grave life cycle analysis (LCA) of large-scale coal-based SOFC power plants has not been presented in the open literature. This is important because, although the downstream CO_2 emissions of this process are lower than state-of-the-art coal-based processes, the effects of upstream portions of the supply chain have not previously been considered. Similarly, other environmental factors such as resource depletion, human health impacts, and acid rain formation should also be considered in order to understand if global warming potential might be reduced at the expense of other forms of environmental damage. There have been prior investigations for plants at smaller scales such as auxiliary power units without CCS [7,8], studies focused on the impact of using alternative fuels in SOFC stacks [9], or studies which only considered the life-time cost impact of using SOFCs [10]. However, none of these investigations have used a method to incorporate a broad range of environmental factors such as human health, ecosystem destruction and resource consumption, and none have considered gasified coal as a feedstock [11].

To this end, this work presents a comprehensive cradle-to-grave life cycle analysis (LCA) of a large-scale power plant utilizing solid oxide fuel cells (SOFCs). The SOFC plant is fueled by the gasification of coal. The LCA is determined using the *ReCiPe 2008* (revised 2013) method, which is also applied to the state-of-the-art supercritical pulverized coal (SCPC) process and a more futuristic integrated gasification combined cycle (IGCC) for the first time. This work is a significant extension of our prior work in which a similar analysis was applied to NG-based power plants [12]. The supply chains for coal and NG-based processes are very different, and thus required separate consideration. However, since the methodology, standards, and assumptions are consistent, useful comparisons between the coal and NG-based processes can be made, which are also presented in this work.

1.1. Solid-oxide fuel cells

The SOFC is an emerging device in which a fuel gas is electrochemically oxidized by the transport of oxygen ions through an impermeable solid oxide barrier which can be formed from a variety of zirconia and perovskite materials [14–19]. SOFCs are an exciting frontier for power generation because they possess some very strong synergistic advantages. First, the anode of the SOFC can accept a variety of carbonaceous or hydrogen-based fuels such as gasified coal [20], methanol [21], natural gas [22], gasified biomass [23] and more [6,24–27]. Furthermore, the cell drives exothermic electrochemical reactions and typically operates at high temperatures (up to 1000 °C depending on material limitations), and is thus well-suited to downstream heat, power and even energy storage integration to improve its efficiency and utility at the systems level [25,26]. Moreover, the impermeable electrolytic barrier separating the anode and cathode of the SOFC prevent the mixing of fuel with air, therefore resulting in an exhaust stream of H_2O, CO_2 and unspent fuel. This allows for efficient and reliable carbon capture without the use of solvents or other methods of absorption that encumber typical CCS strategies [14]. A more detailed SOFC description is omitted from this work for the sake of brevity, but a simplified diagram depicting a typical planar SOFC is provided for reference in Fig. 1. There have been multiple studies in literature that have shown the effectiveness of SOFCs at the systems level for providing highly efficient power (beyond 60% electrical efficiency) [26–33]. A comprehensive review of the industrial and academic status of SOFC research is given by Adams et al. [6].

1.2. Producing power from coal: the current state-of-the-art

1.2.1. Supercritical pulverized coal process description

For this study, the SCPC process is assumed to be the plant of choice were a new greenfield plant to be constructed. What follows is a brief description of the SCPC process for the reader's reference; however, a full detailed process description and plant diagram are omitted for the sake of brevity, and can be found in the NETL bituminous baseline report [34].

Coal is combusted with air in a high-efficiency boiler, the energy from which is used to generate supercritical steam at approximately 240 bar and 593 °C. The steam is expanded in a series of turbines to generate power. The combustion products are