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Life Cycle Analyses of Bulk-Scale 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

* Corresponding author. 1280 Main Street West, Hamilton, Ontario, Canada, L8S 4L7. Tel.: +1 (905) 525-9140
x24782; E-mail address: tadams@mcmaster.ca

Abstract

In this work, detailed cradle-to-grave life cycle analyses are performed for a current state-of-the art natural gas combined cycle and a bulk-scale solid fuel cell power plant fuelled by natural gas. Life cycle inventories are performed for multiple configurations of each plant, including designs with carbon caption capability. Consistent boundaries (including all supply chain and upstream processes) and unit bases for each process are defined for each process. The *ReCiPe 2008* life cycle assessment method is used to quantify the impacts of each plant at both mid- and end-point levels. Three impact assessment perspectives (individualist, humanitarian and egalitarian) are considered. The results of these life cycle analyses are compared in order to determine the environmental trade-offs between potential power generation pathways. Results indicate that power generation using solid oxide fuel cells has a smaller life cycle impact than the natural gas combined cycle when the entire life cycle of each option is considered.

1 Introduction

In a time of dwindling natural resources, emphasis on sustainable alternatives, increasing human activity and an increasing public awareness of global warming and environmental impact, the need for reliable and sustainable energy has become a matter of global importance [1]. With regards to power generation, there are several emerging methods that aim to convert sustainable sources such as biofuels, solar, and wind energy into usable and reliable electrical energy. However, although the growth rates of these industries is quite high, these methods are still decades away from being applied on the large scale even in the most developed and forward-looking economies. For example, renewable electricity is anticipated to contribute only 10% and 16% of the electricity produced in Canada and the United States by the year 2035, respectively [2],[3]. Moreover, it is anticipated that the role of natural gas (NG) as a fuel source for electricity generation will only increase in the coming years, well exceeding that of all combined renewables. NG currently accounts for 9% of the electricity generated in Canada and is anticipated to rise to 15% by 2035 [2]. In the United States, NG supplies the fuel requirements for 24% of all electricity generated, and is anticipated to inflate as high as 27% by 2035 [3].

There is hence a strong motivation to improve the current methods that utilize NG as a fuel source for electricity production, both environmentally and economically. Moreover, there is a strong chance that policy-induced economic incentives (such as a cap and trade system, emission restriction or carbon tax) will lead to the requirement for CO_2 capture and sequestration in various geological storage sites [4]. However, strictly quantifying direct emissions (mainly CO_2) may not be an appropriate method of assessing a plant's environmental impact. Instead, it is becoming more common to consider the entire life cycle emissions of a plant, including all upstream and downstream emissions associated with its operation. Moreover, additional considerations such as pollutants, ozone depleting species and particulates have an effect on ecosystem and human health, and are hence being more closely considered.

To this end, this work performs a comprehensive life cycle analysis (LCA) using the *ReCiPe 2008* (using the version released in July 2013) method on a recently proposed power plant design utilizing solid-oxide fuel cells (SOFCs) for base-load power and compares the results with a state-of-the art natural gas combined cycle (NGCC) plant. This investigation is important because although the plant-gate emissions of bulk SOFC plants which use carbon capture and sequestration (CCS) have been shown to be nearly negligible, the complete cradle-to-grave life cycle impact of such a process might be much more significant due to upstream and downstream emissions, plant commissioning emissions and the consumption of relatively rare resources required for the SOFC. The following sections briefly introduce the two power generation strategies to be compared and the LCA method used in this work.

1.1 Solid-Oxide Fuel Cells

A SOFC is a high-temperature device that electrochemically oxidizes a fuel gas by transporting oxygen ions through a solid-oxide barrier [5]. There are several advantages to this device that result in synergistic benefits to using SOFCs for power generation: they may run on a variety of gaseous fuels including methanol [6], gasified coal [7], natural gas [8], biomass [9] and others [10],[11]; selective O_2 transport through the solid-state electrolyte acts as an effective O_2/N_2 separator from atmospheric air therefore allowing for low-cost and highly efficient carbon capture [5]; and its high operating temperatures and pressures lend itself to various systems integration options, including bottoming cycles and energy storage techniques [12]-[13]. A simplified block diagram of a typical SOFC process with carbon capture is shown in Figure 1; detailed descriptions of the SOFC and its application to bulk power generation strategies are available in the literature [11]. Several studies have shown that SOFC systems utilizing fossil fuels are capable of high electrical efficiencies (greater than 60% in some cases) while potentially capturing and sequestering essentially 100% of CO_2 emissions [14]-[20]. There have also been several studies that have investigated the full life cycle impact of constructing SOFC stacks and tubes and their associated appurtenances and balance-of-plant components, several of which are used as sources of information for this study [21]-[22]. There have been a number of life cycle impact studies on the operation of SOFCs. For example, SOFC-based auxiliary power units [23]-[24] and studies regarding the impact of using alternative fuels in SOFC stacks [25] have been a topic of recent study.

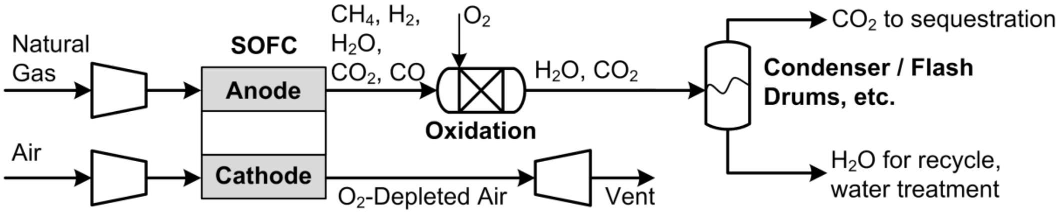

Figure 1: Simplified strategy for generating power from natural gas using SOFCs. Reproduced with permission from [11]

However, to the best of our knowledge, no studies have yet been performed to assess the entire cradle-to-grave life cycle impact of a bulk power generation system using NG as fuel and SOFCs as the main power source. Prior studies that claim SOFC-based systems can eliminate direct CO_2 emissions have not yet accounted for any emissions or environmental impacts of upstream NG processing, nor have they considered other factors that affect human health, ecosystem impact, or resource depletion.

1.2 Natural Gas Combined Cycle Plants

NGCC plants are one of the most common strategies for power generation from NG in North America. NGCC plants burn NG with air in a combustion turbine at high temperatures and pressures, producing electricity through a generator. Waste heat from the system is typically used to generate high-pressure steam that can be used in a heat recovery steam generation (HRSG) system to produce additional power, or used for heating purposes as required elsewhere [26]. If desired, various CCS strategies may be employed to recover as much as 90% of the CO_2 in the exhaust stream, including but not limited to solvent-based absorption, pressure-swing adsorption or vacuum swing adsorption [27],[28]. However, all of these CO_2 capture strategies have high parasitic energy costs, leading to reduced plant efficiencies, higher electricity costs and greater resource consumption.

There are several LCA studies regarding the NGCC available in the literature, each of which were used as sources of information for this investigation. Several government-initiated studies have recently been performed in the United States that inventory the impact of NGCC plants and their associated upstream processes [29]-[30]. Other investigations have been performed as well using various impact analysis methods and levels of detail (see Table 1 in [31] and the references therein for a review of recent studies). However, at the time of this work, no studies have used the *ReCiPe 2008* method to assess the end-point impact of these analyses.

1.3 Description of Life Cycle Assessment Method: ReCiPe 2008

A LCA is a tool that is used to analyze the life cycle of a product or process in the context of its environmental impact and, to that end, its effect on the sustainability of our standard of living. Although there is no singular LCA method that has been identified to be all-encompassing, a common theme among most commonly accepted methodologies is to define a set of standardized metrics to categorize the impacts of products at the mid-point (such as climate change, ecotoxicity or land occupation) and end-point (such as loss of human life and ecosystem degradation) levels. However, each model that attempts to characterize a product's life cycle contains underlying discrepancies leading to varying results. *ReCiPe 2008* offers a unified approach to quantify the impact of a product's life cycle at both the mid-point and end-point levels based on its inventory of flows to or from the environment (designated as elementary flows) [32]. End-point results are normalized to a unified point system to obtain a description of the product's entire life cycle impact. The point system is scaled such that 1,000 points is equivalent to the average human's impact over one year. Figure 2 shows a simplified depiction of the harmonized mid-point to end-point model adapted in *ReCiPe 2008*. It is also important to note that although there is no universally accepted life cycle assessment tool, a meaningful comparison between product life cycles can be obtained if a consistent model is employed.

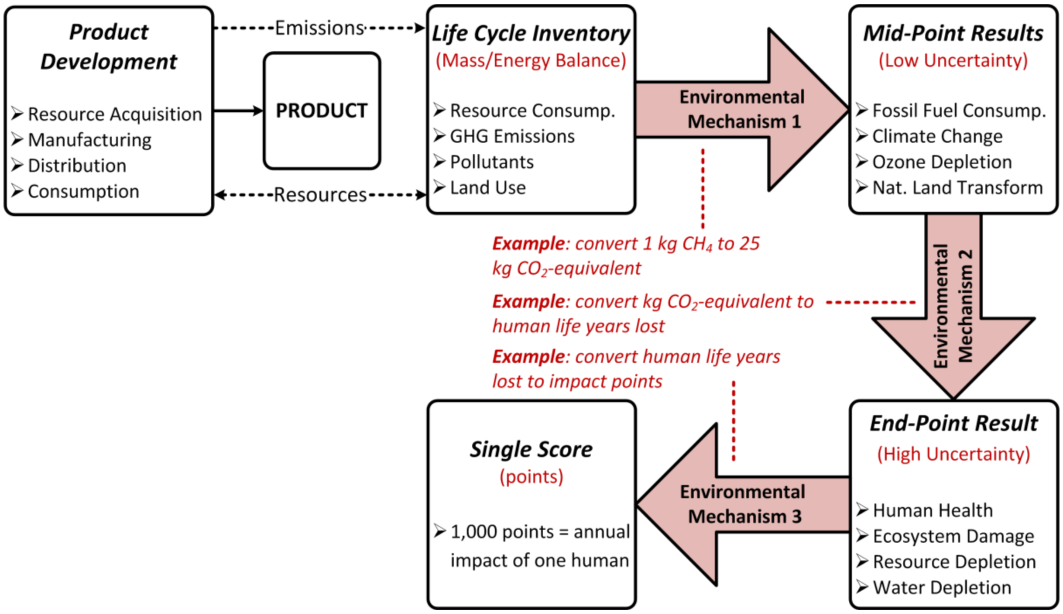

Figure 2: Example of a mid-point to end-point life cycle assessment strategy. Adapted from [32]

The selection of what mid-point and end-point factors are to be considered in a LCA is at the discretion of the investigator. To this end, Table 1 lists the mid- and end-point impact categories for *ReCiPe 2008* and which of them are considered in this study. Mid-point impacts map material and energy flows to and from the environment into quantifiable metrics such as climate change potential (measured in kg of CO_2 equivalents) and fossil fuel depletion (measured in kg of oil equivalents). These mid-point metrics are objective, but have some degree of uncertainty. End-point methods map the mid-point metrics into smaller groups of impacts such as the damage to human health (measured in years of human life lost) or the damage caused to future generations by making it more expensive to recover non-renewable resources (measured in dollars). This too is objective, but with some additional uncertainty. These end-point metrics can then be mapped into one final metric called ecoPoints. A certain number of ecoPoints are assigned per year of life lost and a certain number of ecoPoints per dollar of damage inflicted to future generations, for example. This provides a single, useful metric from which one can compare all of the different categories of environmental impacts. However, this mapping into ecoPoints contains some degree of subjective judgement in determining the weighting factor between end-point categories. As such, *ReCiPe 2008* considers three different sets of weights, called "perspectives", based on various time horizons and cultural perspectives: Individualist (I), Heirarchist (H), and Egalitarian (E) [32]. For details regarding the assumptions and implications of these perspectives, the reader is referred to the *ReCiPe 2008* documentation [32]. This study considers all three of these perspectives in order to form comprehensive conclusions.

Table 1: ***ReCiPe 2008*** **mid- and end-point factors and indication of their inclusion in this study [32]**

Mid-Point Characterizations			
Category	**Tag**	**Units**	**Considered**
Agricultural Land Occupation	ALO	m^2	NO
Climate Change	CC	kg CO_2-Eq	YES
Fossil Depletion	FD	kg oil-Eq	YES
Freshwater Ecotoxicity	FET	kg (1,4)-DCB-Eq	YES
Freshwater Eutrophication	FE	kg P-Eq	NO
Human Toxicity	HT	kg (1,4)-DCB-Eq	YES
Ionizing Radiation	IR	kg U^{235}-Eq	NO
Marine Ecotoxicity	MET	kg (1,4)-DCB-Eq	YES
Marine Eutrophication	ME	kg N-Eq	YES
Metal Depletion	MD	kg Fe-Eq	YES$^{\alpha}$
Natural Land Transformation	NLT	m^2	NO
Ozone Depletion	OD	kg CFC-11-Eq	NO
Particulate Matter Formation	PMF	kg PM_{10}-Eq	YES
Photochemical Oxidant Formation	POF	kg NMVOC	YES
Terrestrial Acidification	TA	kg SO_2-Eq	YES
Terrestrial Ecotoxicity	TET	kg (1,4)-DCB-Eq	YES
Urban Land Occupation	ULO	m^2	NO
Water Depletion	WD	m^3	YES
End-Point Characterizations			
Category	**Tag**	**Units**$^{\beta}$	**Considered**
Damage to Human Health	HH	DALY$^{\delta}$	YES
Damage to Ecosystem Diversity	ED	Species-yrs	YES
Damage to Resource Depletion	RA	$	YES

α: Metal depletion is not included in the NGCC analyses used as sources for this study. As such metal depletion is included in the impact analysis for the SOFC systems for completeness, but is omitted from case comparisons.

β: End-point units are converted to "points" in this investigation. Please see the online supplement submitted with this article for conversion information.

δ: Daily Average Life Years.

For this work, agriculture is not a part of the supply chain, and so agricultural land occupation and freshwater eutrophication (commonly caused by fertilizer runoff) are not considered in the analysis. However, marine eutrophication was considered to account for effects such as oil leaks from the importation of LNG via ocean barge. Similarly, urban land occupation and natural land transformation were also not considered because the environmental impact from occupying land required by the power plant is trivially small compared to the impacts of its heavy use throughout its lifetime. Ionizing radiation was not considered because nuclear energy plays only a tiny role in the supply chain in the form of the consumption of grid electricity during manufacturing processes and it was assumed that no radioactive components were emitted to the environment during this step. However, rare metal consumption (in the form of U^{235}) was accounted for resource depletion purposes. Ozone depletion was not considered because, based on the available data, no ozone-harming chemicals are released during the supply chain of either NGCC or SOFC in any significant quantity.

2 Methodology

2.1 Bases of Calculations

In order to compare the results of each process investigated in this study, a consistent unit basis for the product was defined. The final basis of comparison for each case was selected to be 1 MW-hr (3,600 MJ) of useable electrical energy. 1 MW-hr of net electricity takes into account any process inefficiencies (and hence upstream implications), and distribution losses (considered in some specific cases). The “grave” of this electrical energy is assumed to be its final consumption, which is assumed to be 100% efficient. It should be noted that when comparing different processes with the same end-product (in this case electrical energy being consumed), its final use bears no impact on the comparative life cycle impact of each process.

An exception to this basis is for the manufacturing of the SOFC stacks and their associated balance of plant (BoP). In this study, the entire life cycle impact, from construction to decommission, is desired for the SOFC process. However, current studies thus far have only considered the construction phase of the SOFC stacks. As such, the product basis for the SOFC manufacturing step is assumed to be 1 kW (net production) of finished SOFC stacks and their required BoP implementations. In order to apply these results to the entire lifetime LCA of an operating SOFC plant, a usable lifetime of 10 years when operating at full capacity (as previously reported in the literature) was assumed [12],[14]. With this useful lifetime, the overall impact of constructing 1 kW of SOFC stacks may be normalized to a per-kW-h basis, and therefore used in the overall LCA of the SOFC plant.

The basis unit of processed NG (used in each of the plants investigated) is taken to be 1 MJ by higher heating value (HHV). Assumptions regarding the energy density and sources of NG used for this study are discussed further in section 2.2.

2.2 Natural Gas Supply Chain

In order to perform a full cradle-to-grave comparative study of NGCC and SOFC plants, the NG supply chain and its associated losses and inefficiencies had to be defined. The following subsections define the boundaries of the NG supply chain and any assumptions that were required for this investigation. Several sources were consulted to obtain this information [30],[33].

2.2.1 Boundary Region Definition

The boundary of the NG supply chain is shown below in Figure 3. The final product is defined to be 1 MJ of processed and delivered NG, which is derived from a combination of domestic and imported sources, each with different emissions resulting from their respective supply chains.

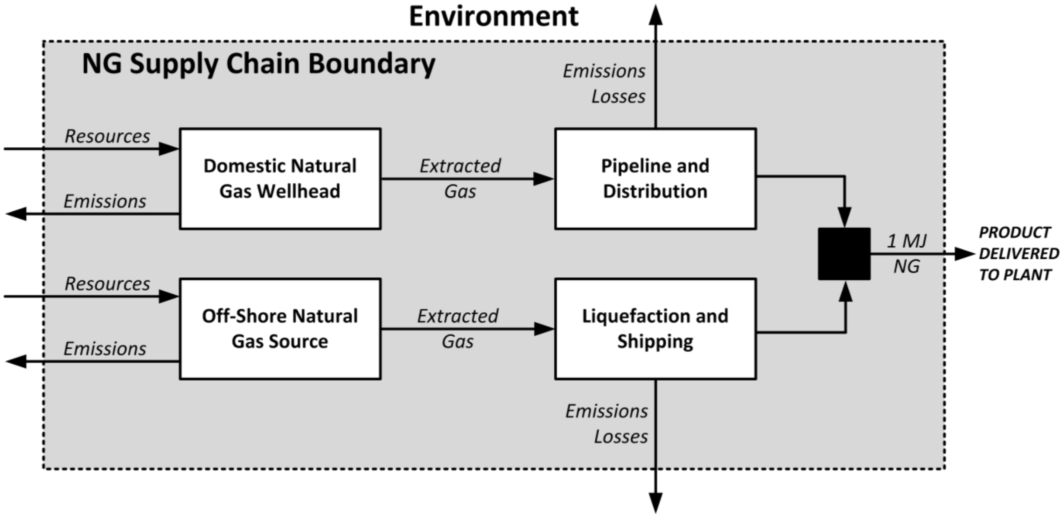

Figure 3: Cradle-to-gate life cycle boundary of the NG supply chain considered in this work

2.2.2 Necessary Assumptions

The NG used in the SOFC and NGCC plants is assumed to be the same composition in order to make fair comparisons. Literature sources defining the "average" NG used in the United States and the life cycle impacts of each source were considered for this study [29],[30],[34]. A summary of the contributions of each NG source is provided in Table 2. It is assumed that 98% of the final NG is from domestic sources, and 2% is liquefied NG (LNG) imported from Trinidad and Tobago. Please see the supplement provided with this article for detailed emission breakdowns and calculations.

Table 2: Breakdown of NG sources in the United States

Domestic Gas$^{\alpha}$	**Source**	**% of Domestic Gas**
Conventional	Onshore	24.5
	Associated	12.5
	Offshore	7.0
Unconventional	Tight	31.0
	Shale	16.0
	CBM	9.0
Imported Source	**Source**	**% of Imported Gas**
Offshore	**LNG**	100.0

α: Domestic gas is assumed to account for 98% of the NG consumed in the United States. 2% is imported.

The further assumptions made in the definition of the upstream supply chain for NG are as follows:

- NG is assumed to have a HHV of 41.1 MJ/kg [26].
- 13% of the gas extracted from the wellhead is either flared or lost throughout the supply chain as fugitive emissions [29],[33].

- The only source of imported NG is assumed to be LNG that is liquefied off-shore, shipped via tanker and re-vaporized domestically [31].

2.3 SOFC Manufacturing Cradle-To-Gate Study

This section combines the results of previous SOFC manufacturing studies and adapts them to the unit basis of this investigation. Several sources were consulted and cross-referenced to obtain reliable life cycle inventories [21],[22],[34]. Shown in Figure 4 is a flowsheet describing the manufacturing process for the positive-electrolyte-negative (PEN) component of the SOFC, including resource inflows and potential emission sources. Figure 4 is a sub-network of the total cradle-to-gate boundary of the SOFC manufacturing process, which is described in the following section.

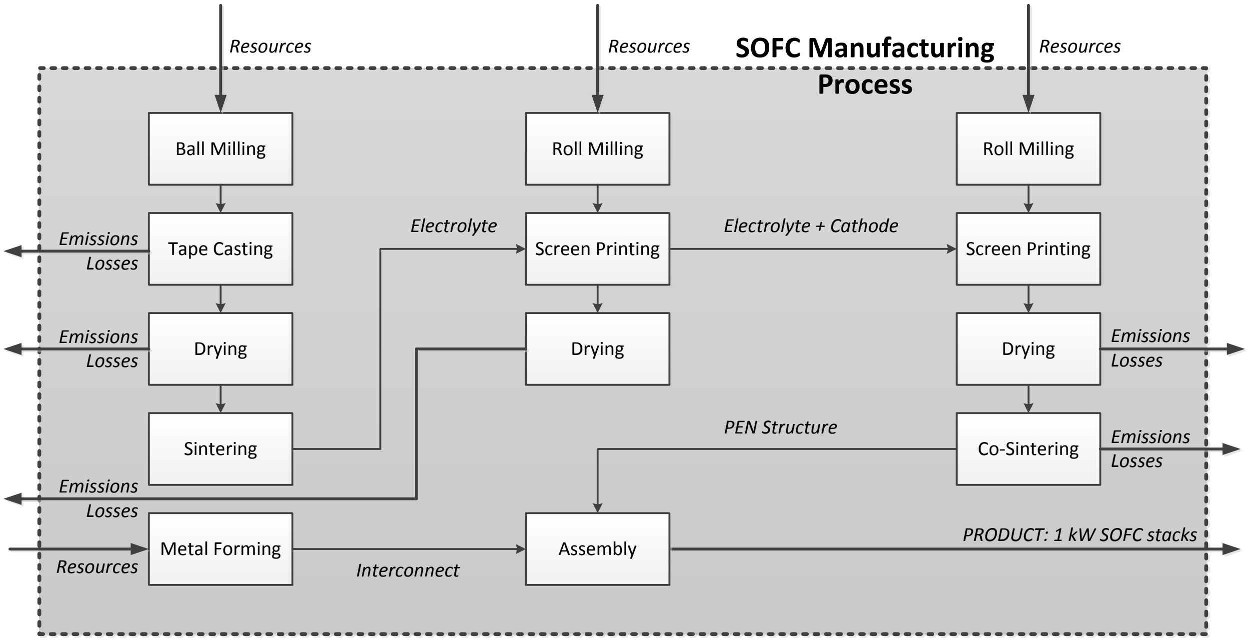

Figure 4: Example of a SOFC manufacturing process with resource entry points and potential emissions labelled. Adapted from [22]

2.3.1 Boundary Region Definition

The boundaries of the SOFC and BoP manufacturing stage are depicted in the simplified block diagram of Figure 5. This sub-system contains all of the processes and contributions contributing to the cradle-to-gate life cycle impact of 1 kW of operating SOFC stacks, which are then normalized to the same basis units as the SOFC plant’s operation (MW-h) before being considered as an intermediate product in the full cradle-to-grave LCA. It should be noted that only metals that characterized by *ReCiPe 2008* were considered in this study. Please see the online supplement for detailed emission rates for each sub-process.

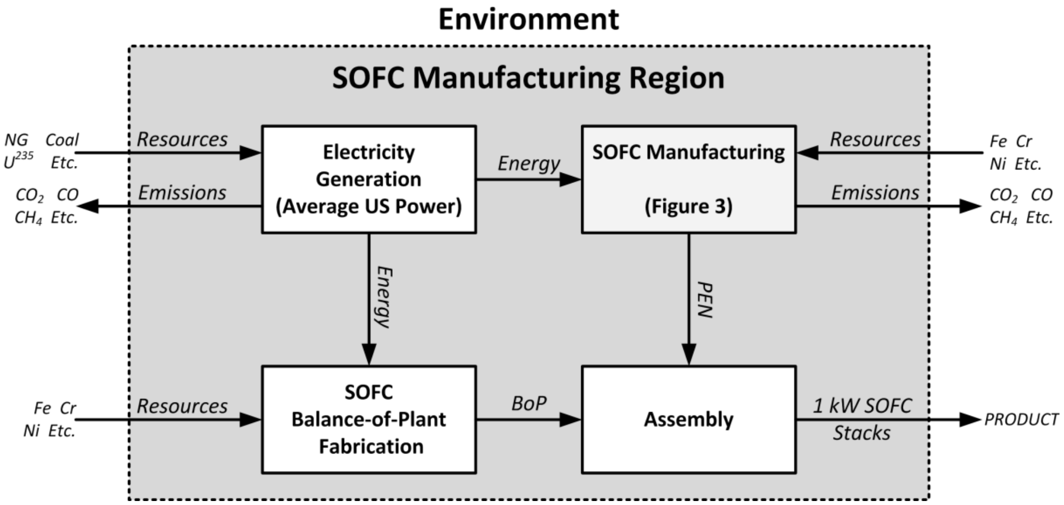

Figure 5: Life cycle boundary of the SOFC manufacturing step.

2.3.2 Necessary Assumptions

Beyond the definition of the process boundaries, the following assumptions were also made with regards to the manufacturing of SOFC stacks:

- All energy consumed in the SOFC manufacturing process is assumed to be electricity. This is because the source data does not specify the type of energy consumed. However, most manufacturing processes of this type are typically electricity-driven.
- This electricity consumed in the SOFC manufacturing process and its associated emissions are assumed to be comprised of the average electricity mix in the United States. See Table 3 for a breakdown of each source. Typical system efficiencies are considered when tabulating resource depletion [34]-[36].
- The GHG and pollutant emissions associated with electricity generation from renewable sources (i.e. wind, hydroelectric) are neglected since they generate no emissions during use and the emissions from their manufacture are small.
- The materials and energy required to develop the electricity generation infrastructure (plants, transmission systems, etc.) are assumed to already exist and therefore not taken into account. Specifically, the effects of constructing the existing power grid are not within the boundaries of this study.
- All emissions are to the atmosphere since no liquid-phase emissions were reported in the source data (to-air).
- The BoP is assumed to account for the majority of unit operations extending beyond the SOFC stacks. The commissioning phase of the NGCC has been reported to be negligible when compared to the SOFC stacks, and therefore any units required beyond the SOFC/BoP structure are assumed to insignificantly contribute to the LCA impact of the SOFC commissioning phase [14],[26].
- Emissions caused upstream of the power grid from which the energy consumed during SOFC manufacturing was omitted since it had a miniscule impact to the overall analysis.

Table 3: Average Unite States electricity mix by source

Electricity Source	Percentage
Coal	44.50%
Oil	1.12%
Gas	23.30%
Hydro	6.80%
Nuclear	20.20%
Other Renewables	4.08%

2.4 NGCC Full Life Cycle Study

2.4.1 Boundary Region Definition

The boundary for a fully operating NGCC plant includes all species that are transferred to and from the natural environment in order to produce one unit of useable electrical power, including the commissioning and decommissioning of the plant itself. Furthermore, there are two decision points that are considered in this study: (1) whether or not CCS is utilized; and (2) whether or not the electricity distribution infrastructure (transmission lines) inefficiencies are considered. Utilizing CCS results in altered emissions to the environment at the cost of lower system efficiencies (and therefore greater upstream impacts) and accounting for the commissioning of a necessary CCS pipeline. Considering the transmission infrastructure further reduces the efficiency of the plant in question, leading to proportionally higher impacts for each sub-process within the LCA boundary. However, to consider the TML, assumptions must be made about the average energy losses between the power plant and the end user; we have assumed 7.0%, which is a continental average and is used in a study by the NETL [29]. The results of this work are considering both with and without TML to make it easy for others to apply our results to different transmission infrastructures.

The full boundary region considered for the NGCC plant is depicted in Figure 6. Optional sub-processes and resulting emissions are denoted by dashed lines and borders. For this study, each of the combinations of optional cases accounting for CCS and transmission losses (TML) were considered. The definition of each case is given in Table 4. Plant efficiencies for the NGCC cases were obtained from the literature [26]. Please see the online supplement for detailed emissions calculations for each sub-process. It is assumed that the distribution network already exists in this study; hence the life cycle impacts of commissioning and decommissioning the network are assumed to be negligible.

Table 4: Description of each combination of optional sub-processes in the NGCC cradle-to-grave boundary region

Case Tag	TML Included?	CCS Included?	Net Efficiency (HHV)
NGCC-1	No	No	50.2%
NGCC-2	Yes	No	46.7%
NGCC-3	No	Yes	42.8%
NGCC-4	Yes	Yes	39.8%

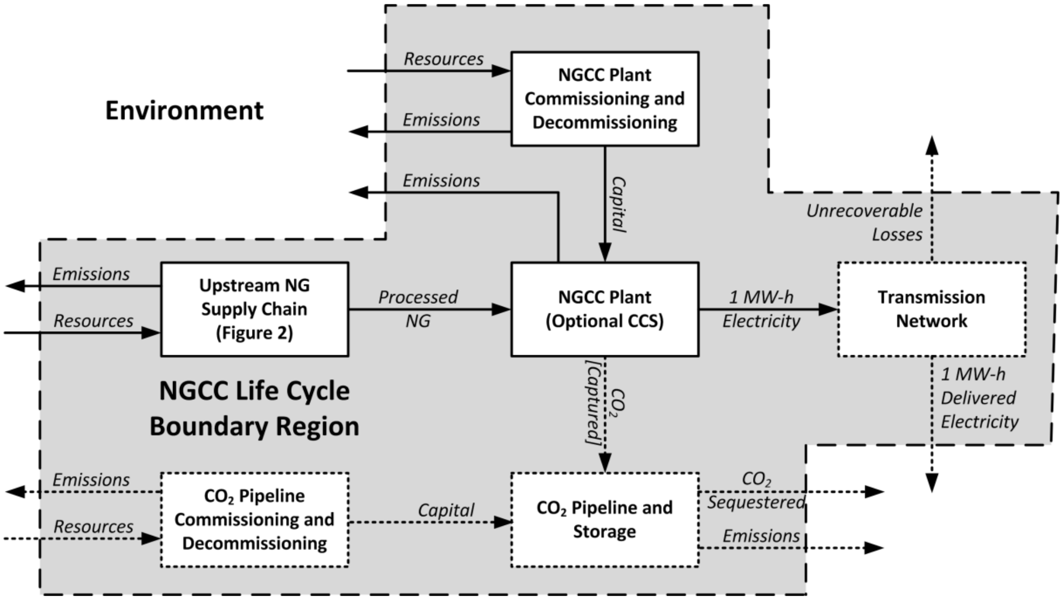

Figure 6: Cradle-to-grave boundary region block diagram for an NGCC plant including commissioning and decommissioning. Optional streams and sub-process are denoted by dashed lines

2.4.2 Necessary Assumptions

Beyond the definition of the process boundaries, the following assumptions were also made with regards to the NGCC cradle-to-gate impact:

- The transmission efficiency of the distribution infrastructure is assumed to be 93% [26].
- All emissions are to the atmosphere (to-air). No water emissions were indicated in the available data.
- 1% of all sequestered CO_2 escapes from the CCS pipeline as a fugitive emission [29].

2.5 SOFC Full Life Cycle Study

2.5.1 Boundary Definition

The boundary region for the SOFC plant contains the same main sub-processes as the NGCC plant, namely plant commissioning, upstream NG acquisition and processing, the operating plant itself, and optional blocks for the transmission network and the CCS pipeline. Similarly to the NGCC study, four boundary regions are considered for the SOFC plant each including a combination of CCS and TML, as summarized in Table 5. As mentioned previously, the product output of the SOFC manufacturing sub-process is normalized to units of energy in the same fashion as the NGCC plant [26]. The full LCA boundary region for the SOFC plant is shown in Figure 7, with the dashed blocks and lines representing optional sub-processes and consequent flows, respectively. It should be noted that the final unit of energy produced by the SOFC plant is the net result of the SOFC, HRSG and other bottoming cycles less any parasitic energy loads. For detailed information about the operation of the SOFC plant the reader is referred to the literature [12],[14]. Detailed emissions per basis unit of energy for each sub-process are provided in the online supplement, and are omitted for the sake of brevity.

Table 5: Description of each combination of optional sub-processes in the NGCC cradle-to-grave boundary region

Case Tag	TML Included?	CCS Included?	Net Efficiency (HHV)
SOFC-1	No	No	65.6%
SOFC-2	Yes	No	61.0%
SOFC-3	No	Yes	64.8%
SOFC-4	Yes	Yes	60.3%

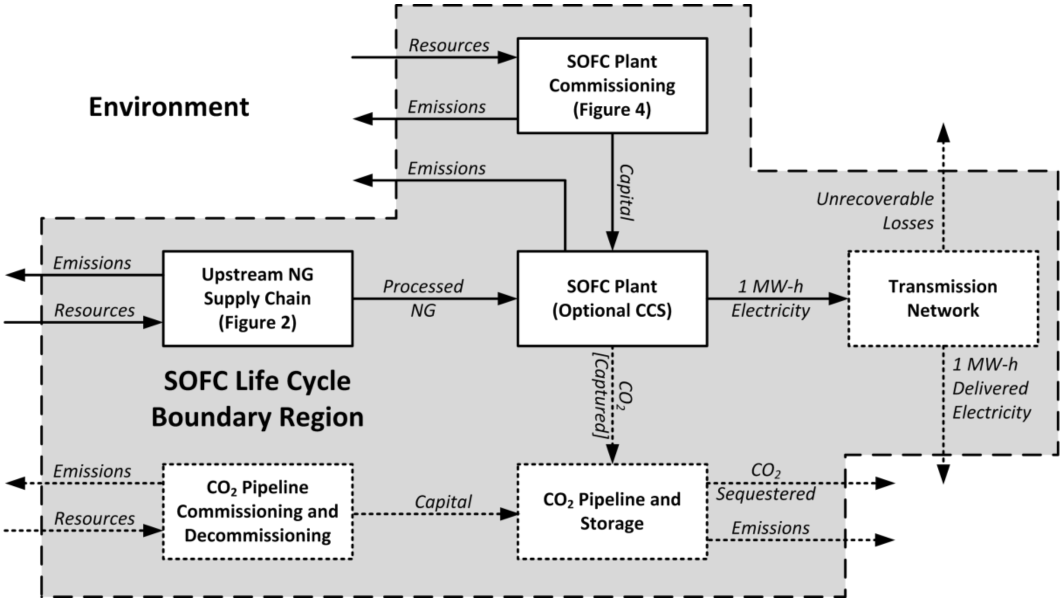

Figure 7: Cradle-to-grave boundary region block diagram for a SOFC plant including commissioning and decommissioning. Optional streams and sub-process are denoted by dashed lines

2.5.2 Necessary Assumptions

The assumptions for the SOFC boundary region include all of those listed in section 2.4.2. The following assumptions are unique to the SOFC plant:

- Since the fuel for the SOFC system is cleaned upstream of the power production step and is not combusted in air, the emissions of NO_x, SO_x and N_2O were predicted to be negligible in prior studies and are therefore neglected for this analysis. However, the plant flue gas (with and without CCS) contains a non-trivial amount of H_2 that is accounted for (The literature studies consulted for the NGCC plant ignore this product) [12],[14].

2.6 Calculation Strategy

Stream data for the SOFC plants were obtained from a combination of *Aspen Plus v8.2* simulation files and previously documented results by the authors [12],[14]. Mid-point characterization calculations were performed using *OpenLCA v.1.3.0*, an open-source life cycle inventory flowsheeting software [37]. However, due to the discovery of several bugs and inconsistent impact factor calculations in *OpenLCA* itself, all end-point characterization calculations were performed in-house using the *ReCiPe 2008* impact factor guidelines available in the literature [38]. Weighting factors for end-point impacts were selected as the average of those used in ReCiPe 2008 (40% human health, 40% ecosystem health and 20% resource depletion). Please see the on-line supplement for more information.

3 Results and Discussion

For the sake of brevity, the results and discussion presented herein are those using the heirarchist (H) perspective for *ReCiPe 2008*. It should be noted that the perspective does impact the mid- and end-point results of each LCA, but the impact is consistent for each case investigated and therefore bears no impact on any comparative studies. The remaining perspectives (individualist and egalitarian) were calculated and are reported in the online supplement for the reader's interest.

3.1 SOFC Manufacturing Phase

3.1.1 Inventory and Mid-Point Characterization Results

Shown in Table 6 are the elemental flow inventory results for the construction of 1 kW of SOFC stacks and any required BoP materials. It can be seen that in order to manufacture a 1 kW stack of SOFCs, significant amounts of Ni, Cr and Fe are required. Ni and Cr are particularly difficult to obtain and process, which has a large impact on resource depletion (as will be discussed later). Moreover, it can be seen that a high amount of coal (over 238 kg) must be consumed to partly fulfill the energy requirements of the manufacturing process. This is an expected result, since coal power is inefficient (with an optimistic process efficiency of 39% by HHV), has a lower average energy density than other fossil fuels (24.8 MJ/kg versus the 44.1 MJ/kg in NG, for example) and accounts for the highest proportion of electrical energy consumed in the United States (see Table 3). This high consumption of coal in current pulverized coal (PC) power plants without CCS, combined with the consumption of other fossil fuels, leads to CO_2 emissions of over 944 kg per kW of SOFC stacks; the highest emission rate by a significant margin. Interestingly, the second- and third-highest emission rates are for SO_x (again from the high consumption of coal) and particulate matter.

Table 6: Cradle-to-gate life cycle resource flow inventory for the SOFC manufacturing stage

Inventory	Amount
Input Flows (kg)	
Chromium: 25.5% (chromite); 11.6% (crude ore)	26.79
Coal (hard)	283.29
Iron: 46% (ore); 25% (crude ore)	65.37
Natural Gas (44.1 MJ/kg)	64.88
Nickel: 1.13% (sulfide); Ni 0.76% and Cu 0.76% (crude ore)	8.75
Oil (crude)	4.30
Uranium (mined)	0.01
Output Flows (kg)	
Carbon Dioxide (CO_2)	944.19
Carbon Monoxide (CO)	0.29
Dinitrogen Monoxide (N_2O)	0.01

Methane (CH_4)	0.02
Nitrogen Oxides (NO_x)	0.87
Particulates > 2.5 µm and < 10 µm	1.85
SOFC STACK (1 kW + BoP)	***1.00***
Sulfate	0.89
Sulfur dioxide (SO_2)	2.39

Shown in Table 7 are the mid-point characterization results for the SOFC manufacturing process. Full detailed results are available in the online supplement. It can be seen that the high rate of CO_2 emission for this operation results in a high climate change (CC) potential of nearly one tonne of CO_2-equivalents (CO_2-Eq) per kW of SOFC stacks, or approximately the emissions of a typical passenger vehicle over a 2.5 month period [39]. Therefore, the CC potential of commissioning a 500 MW SOFC plant (ignoring operation) scales up to roughly 500,000 tonnes CO_2-Eq, or the equivalent impact of 100,000 vehicles operating for a calendar year. Due to the high consumptions of Ni, Cr and Fe, the metal depletion impact for the construction of 1 kW of SOFC stacks is also significant at roughly 842 kg of Fe-equivalents (kg Fe-Eq), even though only 65 kg of Fe is actually consumed; this is due to the inaccessibility and much lower supplies of Ni and Cr occurring in the environment. Moreover, commissioning 1 kW of SOFC stacks consumes approximately 193 kg of oil-equivalents (oil-Eq), which is a significant amount of fossil fuels, especially when scaled to a bulk scale of 500 MW or larger. It should be noted that in the sources used to obtain the life cycle inventory information for this study, water consumption and toxic species were not documented.

Table 7: Mid-point characterization results (H perspective) for the SOFC manufacturing process per 1 kW SOFC stack constructed along with associated BoP

Mid-Point Inventory	Amount	Units
Climate Change	948.84	kg CO_2-Eq
Fossil Depletion	192.76	kg oil-Eq
Freshwater Ecotoxicity	0.00	kg 1,4-DCB-Eq
Human Toxicity	0.00	kg 1,4-DCB-Eq
Marine Ecotoxicity	0.00	kg 1,4-DCB-Eq
Marine Eutrophication	0.03	kg N-Eq
Metal Depletion	841.92	kg Fe-Eq
Particulate Matter Formation	2.52	kg PM_{10}-Eq
Photochemical Oxidant Formation	1.08	kg NMVOC
Terrestrial Acidification	2.88	kg SO_2-Eq
Terrestrial Ecotoxicity	0.00	kg 1,4-DCB-Eq
Water Depletion	0.00	m^3

3.1.2 End-Point Characterization Results

Shown in Figure 8 are the cumulated end-point characterization results (in points, which are sometimes referred to as “EcoPoints”) for the three main end-point impact categories. Breakdowns of the contributions of each mid-point characterization to specific end-points are omitted for the sake of brevity, but may be found in the online supplement.

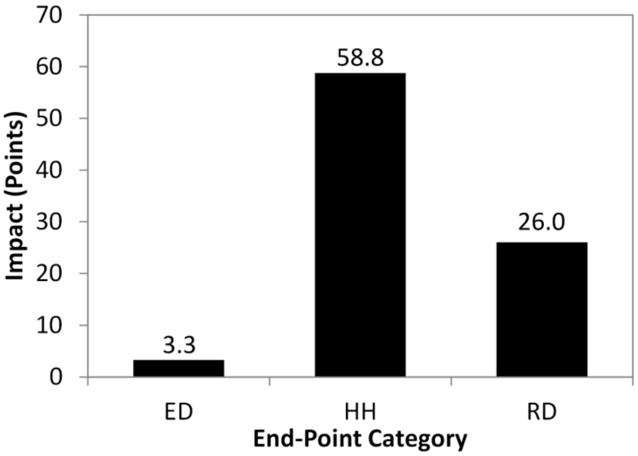

Figure 8: End-point impacts of the SOFC manufacturing process to produce 1 kW of SOFC stacks. Acronyms are defined in Table 1.

The total impact for producing 1 kW of SOFC stacks is equal to 88.1 points, which is the equivalent to approximately 9% of a human's impact on the environment over one year. Human health (HH) clearly experiences the largest impact (59 points), mainly due to the impacts of global warming chemicals and particulate emissions from the electricity supply chain. Resource depletion (RD, 26 points) is impacted by the high degrees of oil-Eq and Fe-Eq consumption. Interestingly, greenhouse gas species do not contribute significantly to ecosystem destruction (ED), resulting in a low contribution to the total (just over 3 points).

3.2 NGCC Plant Complete Life Cycle

3.2.1 Inventory and Mid-Point Characterization Results

Shown in Table 8 are the life cycle inventory results for each of the NGCC cases investigated in this study. Detailed results can be found in the online supplement. Note that metal and material consumptions were not available for this analysis and are therefore not present in the cradle-to-grave life cycle inventory for the NGCC process. As expected, the addition of CCS significantly decreases the global CO_2 emissions of the NGCC process (388 kg/MW-h for case NGCC-1 versus 74.4 kg/MW-h for case NGCC-3). However, the addition of CCS does not decrease global CO_2 emissions by 90% (recall that this is the recovery of CO_2 for the NGCC) due to increased upstream emissions and pipeline losses; instead, only an 81% reduction is achieved. Moreover, the addition of CCS requires 17.3% more NG to achieve the same power output, which not only results in greater fossil fuel depletion, but also increases the amount of upstream fugitive CH_4 emissions by the same proportion. Depending on the LCA perspective used (all of which are reported in the online supplement), the impact of atmospheric CH_4 can vary significantly and thus such large increases in CH_4 emissions can have a large influence on a plant's global life cycle impact. The remaining inventories can be seen to increase in direct proportion to the NGCC plant's overall thermal efficiency.

Table 8: Resource flow inventory for the NGCC cradle-to-grave life cycle.

Inventory	**NGCC-1**	**NGCC-2**	**NGCC-3**	**NGCC-4**
Input Flows (kg)				

Natural Gas (44.1 MJ/kg)	186.91	200.99	219.23	235.73
Water (unspecified natural origin)	110.05	118.34	129.64	139.40
Output Flows (kg)				
Emissions to air (kg; unspecified population density and height)				
Ammonia (NH_3)	0.02	0.02	0.02	0.02
Carbon Dioxide (CO_2)	387.75	417.46	74.39	79.99
Carbon Monoxide (CO)	0.09	0.10	0.11	0.12
Dinitrogen Monoxide (N_2O)	6.35×10^{-4}	6.83×10^{-4}	7.50×10^{-4}	8.06×10^{-4}
Lead (Pb)	3.76×10^{-6}	4.04×10^{-6}	4.32×10^{-6}	4.64×10^{-6}
Mercury (Hg)	8.16×10^{-8}	8.77×10^{-8}	1.02×10^{-7}	1.09×10^{-7}
Methane (CH_4)	2.64	2.84	3.10	3.33
Nitrogen Oxides (NO_x)	0.37	0.40	0.43	0.47
NMVOC (non-methane volatile organics)	0.02	0.02	0.02	0.03
Particulates > 2.5 μm and < 10 μm	0.01	0.01	0.01	0.01
Sulfur dioxide (SO_2)	0.02	0.02	0.02	0.02
Product Flows (MW-h)				
Electricity Delivered, AC, Grid Quality	**1.00**	**1.00**	**1.00**	**1.00**

Shown in Table 9 are the mid-point characterization results for the complete NGCC life cycle. Full detailed results are available in the online supplement. It can be seen that the addition of CCS to an NGCC plant reduces the CC impact by as much as 66.5%. This is an important result, because it shows the importance of boundary definition and species tracking when performing a LCA. The addition of CCS is capable of reducing direct plant CO_2 emissions by 90%, but extending the LCA boundary to include the full life cycle and additional species with global warming potential (GWP) reduces any apparent improvements in environmental impact by 23.5 percentage points. Moreover, it is important to note the trade-offs that exist between reducing life cycle CC potential and the impact that CCS has on other life cycle factors. It can be seen in Table 9 that although utilizing CCS yields a marked improvement to CC potential, every other mid-point impact category increases. Due to the decreased thermal efficiency of a NGCC plant using CCS, more NG and water is consumed, thereby eliciting higher fossil depletion and emissions from the upstream NG processing stage of the life cycle. Moreover, any species that are uncaptured at the gate of the NGCC plant (particulates, fugitive NO_x and SO_x) increase directly with fuel consumption (and inversely to thermal efficiency). An end-point analysis, discussed in the next section, is the best method with which to determine if this trade-off results in a lower total life cycle impact. As a final note, it is clear that accounting for transmission inefficiencies results in a proportional increase to all mid-point factors.

Table 9: Mid-point characterization results (H perspective) for the NGCC life cycle

Mid-Point Inventory	NGCC-1	NGCC-2	NGCC-3	NGCC-4	Units
Climate Change	454.04	488.72	152.12	163.58	kg CO_2-Eq
Fossil Depletion	170.46	183.30	199.94	214.99	kg oil-Eq
Freshwater Ecotoxicity	2.87×10^{-7}	3.08×10^{-7}	3.55×10^{-7}	3.82×10^{-7}	kg 1,4-DCB-Eq

Human Toxicity	0.10	0.11	0.12	0.13	kg 1,4-DCB-Eq
Marine Ecotoxicity	5.42×10^{-5}	5.83×10^{-5}	6.69×10^{-5}	7.19×10^{-5}	kg 1,4-DCB-Eq
Marine Eutrophication	0.02	0.02	0.02	0.02	kg N-Eq
Metal Depletion$^{\alpha}$	N/A	N/A	N/A	N/A	kg Fe-Eq
Particulate Matter Formation	0.10	0.11	0.11	0.12	kg PM_{10}-Eq
Photochemical Oxidant Formation	0.42	0.45	0.49	0.53	kg NMVOC
Terrestrial Acidification	0.27	0.29	0.27	0.34	kg SO_2-Eq
Terrestrial Ecotoxicity	8.61×10^{-6}	9.26×10^{-5}	1.07×10^{-5}	1.15×10^{-5}	kg 1,4-DCB-Eq
Water Depletion	110.05	118.34	129.64	139.40	m^3

α: *The data required for computing metal depletion impacts were not available for the NGCC process.*

3.2.2 End-Point Characterization Results

Shown in Figure 9 are the cumulated NGCC end-point characterization results (in points) for the three main end-point impact categories. Breakdowns of the contributions of each mid-point characterization to specific end-points are omitted for the sake of brevity, but may be found in the online supplement. The total impact of producing 1 MW-h of electricity from a NGCC without CCS is 44.2 points before TML and 47.5 points when considering TML. Interestingly, the global warming impact of an NGCC plant (reflected in the scores for ED and HH) is overshadowed by the resource depletion score. Consequently, according to *ReCiPe 2008* it is evident that, with regards to achieving a more sustainable life-cycle impact, the consumption of fossil fuels is just as important as (or even more important than) the emission of global warming chemicals. This reinforces the notion that improved efficiencies will have a significant impact on the life cycle impact of generating electricity from fossil fuels; a lower fuel consumption for the same product not only decreases the largest life cycle impact contributor but also decreases all three of the main end-point impact categories simultaneously. However, it is clear that the addition of CCS reduces the ED and HH impacts of the NGCC by approximately 65%, yielding a decrease of 9.5 life cycle impact points (21%) overall in the case not considering TML. Two conclusions can be drawn from this result: (1) that capturing 90% of the CO_2 generated in a NGCC plant only reduces its cradle-to-grave life cycle impact by 21%; and (2) that the direct CO_2 emissions of a NGCC plant only account for approximately 23.3% of its life cycle impact. The consideration of TML can be seen to increase all impact categories in direct proportion to the additional efficiency losses of the transmission infrastructure.

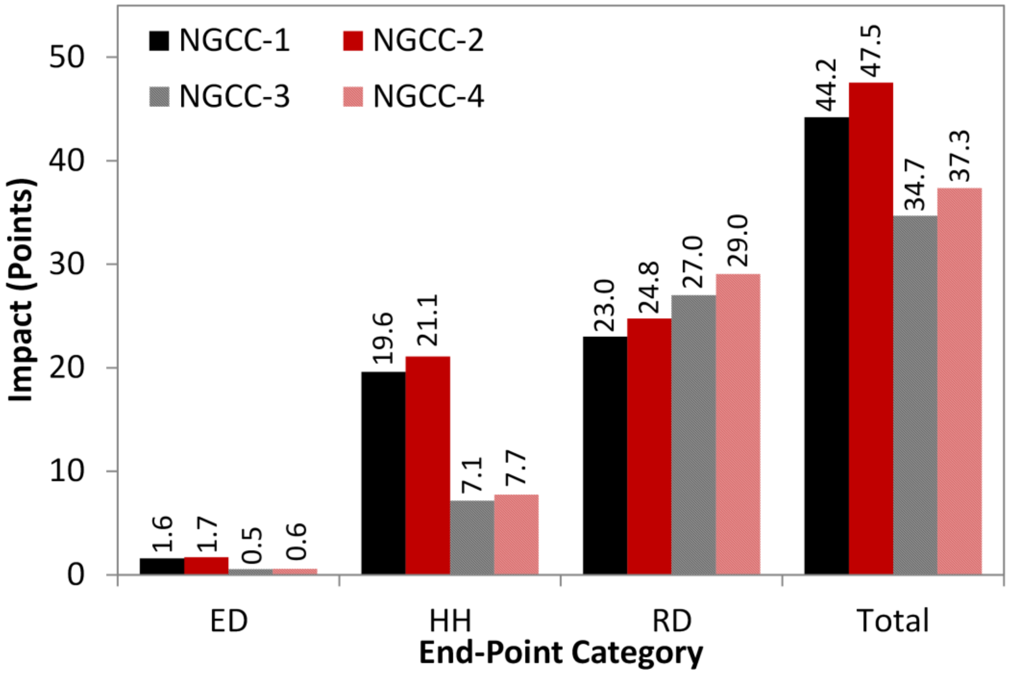

Figure 9: End-point impacts of the NGCC process to produce 1 MW-h of delivered electricity. Acronyms are defined in Table 1. SOFC Plant Total Life Cycle

3.3 SOFC Plant Complete Life Cycle

3.3.1 Inventory and Mid-Point Characterization Results

Shown in Table 10 are the life cycle inventory results for each of the SOFC cases investigated in this study. Note that the results in Table 10 include the normalized SOFC manufacturing results discussed in section 2.3. Detailed results and breakdowns can be found in the online supplement. Unlike the NGCC plant, it can be seen that adding CCS to the SOFC plant greatly reduces its global CO_2 emissions with only very marginal increases in the other inventories (compare cases SOFC-1 and SOFC-3, for example). The small increases in other inventories is due to the marginal effect CCS has on the efficiency of the SOFC plant (approximately 1 percentage point). However, it should still be noted that although essentially 100% of the direct CO_2 generated by the SOFC plant is captured at the plant gate, cradle-to-gate CO_2 emissions are only reduced by 93% due to upstream emissions, the SOFC commissioning phase and pipeline losses. Methane emissions are unable to be eliminated due to upstream NG losses that occur before the plant gate and increase with the addition of CCS and TML as the total system efficiency declines.

Shown in Table 11 are the mid-point characterization results for the complete SOFC life cycle (including the SOFC commissioning phase). Detailed results are available in the online supplement. As with the NGCC plant, CCS is able to eliminate the majority of the SOFC plant's CC potential, decreasing it by 77% (274.3 points in the case of SOFC-1 versus SOFC-3). Although this decrease is significant, it exemplifies the role CH_4 leaks and the NG distribution network play in the cradle-to-grave life cycle impact of the SOFC process. However, unlike the NGCC process, the addition of CCS to the SOFC cases does not result in a marked increase in other mid-point characterizations; this is due in large part to the small parasitic energy load of CCS in a SOFC system. Overall, the SOFC process can be seen to compare favourably to the NGCC process in all mid-point categories and does not suffer from increased characterizations peripheral to CC potential with the introduction of CCS.

Table 10: Resource flow inventory for the SOFC cradle-to-grave life cycle.

Inventory	**SOFC-1**	**SOFC-2**	**SOFC-3**	**SOFC-4**
Input Flows (kg)				
Chromium: 25.5% (chromite); 11.6% (crude ore)	0.31	0.31	0.31	0.31
Coal (hard)	3.23	3.23	3.23	3.23
Iron: 46% (ore); 25% (crude ore)	0.75	0.75	0.75	0.75
Natural Gas (44.1 MJ/kg)	143.78	154.56	145.54	156.35
Nickel: 1.13% (sulfide) (crude ore)	0.10	0.10	0.10	0.10
Oil (crude)	4.91×10^{-2}	4.91×10^{-2}	4.91×10^{-2}	4.91×10^{-2}
Uranium (mined)	1.24×10^{-5}	1.24×10^{-5}	1.24×10^{-5}	1.24×10^{-5}
Water (unspecified natural origin)	83.65	89.96	84.68	91.00
Emissions to air (kg; unspecified population density and height)				
Ammonia (NH_3)	1.41×10^{-3}	1.51×10^{-3}	1.42×10^{-3}	1.53×10^{-3}
Carbon Dioxide (CO_2)	306.51	328.81	31.81	33.36
Carbon Monoxide (CO)	7.73×10^{-2}	8.29×10^{-2}	7.19×10^{-2}	7.70×10^{-2}
Dinitrogen Monoxide (N_2O)	4.75×10^{-4}	5.11×10^{-4}	4.81×10^{-4}	5.17×10^{-4}
Hydrogen (H_2)	2.95×10^{-2}	3.17×10^{-2}	2.95×10^{-4}	3.15×10^{-4}
Lead (Pb)	9.41×10^{-7}	1.01×10^{-6}	9.53×10^{-7}	1.02×10^{-6}
Mercury (Hg)	4.52×10^{-8}	4.86×10^{-8}	4.58×10^{-8}	4.92×10^{-8}
Methane (CH_4)	2.03	2.19	2.05	2.20
Nitrogen Oxides (NO_x)	0.26	0.28	0.27	0.28
NMVOC (non-methane volatile organics)	1.72×10^{-2}	1.85×10^{-2}	1.74×10^{-2}	1.86×10^{-2}
Particulates > 2.5 µm and < 10 µm	3.30×10^{-3}	3.55×10^{-3}	3.39×10^{-3}	3.64×10^{-3}
Sulfur dioxide (SO_2)	4.08×10^{-2}	4.18×10^{-2}	4.10×10^{-2}	4.20×10^{-2}
Product Flows (MW-h)				
Electricity Delivered, AC, Grid Quality	**1.00**	**1.00**	**1.00**	**1.00**

Table 11: Mid-point characterization results (H perspective) for the SOFC cradle-to-grave life cycle

Mid-Point Inventory	**SOFC-1**	**SOFC-2**	**SOFC-3**	**SOFC-4**	**Units**
Climate Change	355.85	382.64	81.55	86.93	kg CO_2-Eq
Fossil Depletion	132.31	142.28	133.92	143.78	kg oil-Eq
Freshwater Ecotoxicity	1.53×10^{-7}	1.65×10^{-7}	1.55×10^{-7}	1.67×10^{-7}	kg 1,4-DCB-Eq
Human Toxicity	0.04	0.04	0.04	0.04	kg 1,4-DCB-Eq
Marine Ecotoxicity	2.83×10^{-5}	3.04×10^{-5}	2.86×10^{-5}	3.07×10^{-5}	kg 1,4-DCB-Eq
Marine Eutrophication	0.01	0.01	0.01	0.01	kg N-Eq
Metal Depletion[α]	N/A	N/A	N/A	N/A	kg Fe-Eq

Particulate Matter Formation	0.09	0.09	0.09	0.09	kg PM$_{10}$-Eq
Photochemical Oxidant Formation	0.31	0.34	0.32	0.34	kg NMVOC
Terrestrial Acidification	0.19	0.21	0.19	0.21	kg SO$_2$-Eq
Terrestrial Ecotoxicity	4.69×10^{-6}	5.04×10^{-6}	4.75×10^{-6}	5.10×10^{-6}	kg 1,4-DCB-Eq
Water Depletion	83.65	89.96	84.68	91.00	m^3

α: Metal depletion statistics were not available for the NGCC process and are therefore considered only for the SOFC manufacturing stage for reference

3.3.2 End-Point Characterization Results

Shown in Figure 10 are the cumulated SOFC end-point characterization results (in points) for the three main end-point impact categories. Breakdowns of the contributions of each mid-point characterization to specific end-points are omitted for the sake of brevity, but may be found in the online supplement.

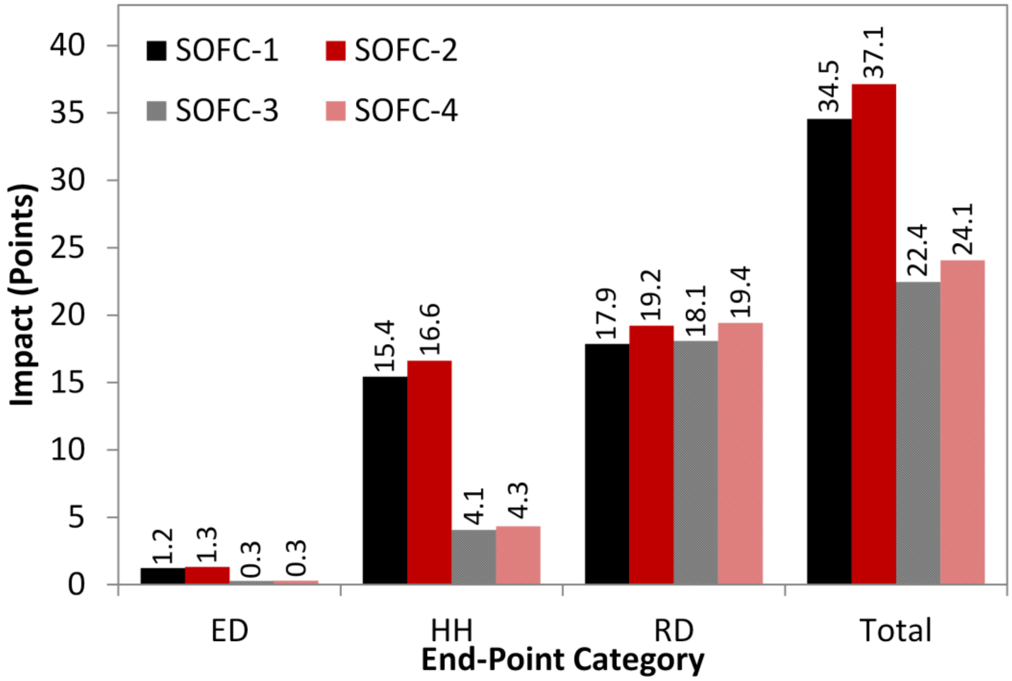

Figure 10: End-point impacts of the SOFC process to produce 1 MW-h of delivered electricity. Acronyms are defined in Table 1.

Due to higher system efficiencies and low parasitic energy costs for CCS, each SOFC case can be seen to have a lower overall life cycle impact compared to the equivalent NGCC case. As expected, the addition of CCS to the SOFC system reduces ED and HH each by over 70%. However, as the mid-point characterization results may suggest, the increase in RD due to CCS addition is slight (less than 1 point). The overall improvement to end-point impact is approximately 35%. Even for the more efficient SOFC process, RD clearly has the highest end-point impact (18-19 points) and accounts for more than 50% of the total plant life cycle impact even when CCS is not utilized. This further reinforces that improved utilizations of fossil fuels are an important route through which the life cycle impact of electricity generation may be reduced regardless of the energy conversion strategy. As a final note, it should be mentioned that even though the commissioning and manufacture phase of the SOFC accounts for a significant amount of CO_2 emissions (which can add up to the equivalent of about 100,000 cars driving for one year for a 500 MW power plant), it still pales in comparison to the environmental impact of the regular use of the system; only approximately 1% of the total life cycle impact of 1 MW-h of electricity from the SOFC plant arises from commissioning and manufacture. This is typical of bulk-scale power plants.

3.4 Selected Case Comparisons

The following section discusses some interesting selected case comparisons between the NGCC and SOFC systems. The results discussed in the following sections have been normalized for comparative purposes, and thus the cases considering TML are omitted because they offer no direct comparative insight.

Shown in Figure 11 and Figure 12 are selected mid-point and end-point characterization comparisons between each of the NGCC and SOFC cases investigated, respectively. It can be seen in Figure 11(B) that even when CCS is not used the SOFC plant is capable of producing electricity with lower values of all mid-point characterizations than NGCC without CCS. When CCS is introduced to the SOFC system as in Figure 11(A), CC potential drops significantly to only 18% of that of the NGCC plant without CCS. Moreover, the other mid-point characterizations do not increase substantially for the SOFC process due to the low parasitic energy cost (and therefore upstream impact) of adding CCS to the SOFC plant. This result can be extended to the end-point characterization results as shown in Figure 12(A), where it can be seen that case SOFC-3 scores approximately 80% lower than NGCC-1 for ED and HH, and 21% lower for RD.

Another interesting comparison is shown in Figure 11(C), wherein the NGCC plant with CCS (case NGCC-3) is compared to a SOFC plant without CCS (case SOFC-1). Although using CCS with a NGCC plant results in a marked reduction in CC potential (42.7% of that of the SOFC plant without CCS), each of the other mid-point characterizations are still inferior to the SOFC plant. This is in large part due to the increased consumption of NG by case NGCC-3, which results in higher upstream impacts and greater emissions of uncaptured species at the plant gate.

The end-point characterization results for this comparison are particularly interesting. As shown in Figure 12(C), the ED and HH impacts of case NGCC-3 are less than 50% of those of SOFC-1. However, due to the much lower efficiency of NGCC-3 versus SOFC-1, the RD metric for NGCC-3 is more than 50% higher than for SOFC-1. Consequently, since RD has been shown to be the most significant contributor to each life cycle impact, the improvements to ED and HH for case NGCC-3 relative to SOFC-1 are outweighed by its higher RD score. This leads to the very interesting result that a NGCC plant operating with CCS actually has a slightly higher life cycle impact than a SOFC process without CCS (although for all practical purposes they are statistically indistinguishable due to the uncertainty inherent in the *ReCiPe* method). This result is significant in that it motivates the pursuit of developing electricity generation strategies utilizing SOFCs. Not only were SOFC systems shown to be economically favourable for many potential future market conditions in prior studies [12]-[16], but their total life-cycle impact (including all upstream impacts and material requirements) are lower than the current state-of-the-art strategies for generating electricity from NG.

It is possible to combine the results of this study with that of previous techno-economic analyses to determine the added cost of CO_2 reductions and eco-point reductions for the SOFC and NGCC cases. Based on the results of our prior work [12], the costs of adding CO_2 capture to bulk scale NGCC and SOFC plants (assuming a NG price of $2.33 per GJ) are $52.92 per MW-h and $2.52 per MW-h, respectively. Therefore, the cost of reducing global CO_2-Eq emissions can be calculated to be $175.28 and $9.19 per tonne of CO_2-Eq avoided for the NGCC and SOFC plants, respectively. Similarly, the cost per eco-point avoided can be computed to be $5.56 and $0.21 per eco-point avoided, respectively. It is therefore evident that the addition of CCS to a SOFC plant is both economically and environmentally preferable. Moreover, adding CCS to the SOFC plant effectively provides an impact reduction of 1,000 points (one human over a calendar year) at the cost of $210, which is an extremely effective trade-off between cost and environmental sustainability.

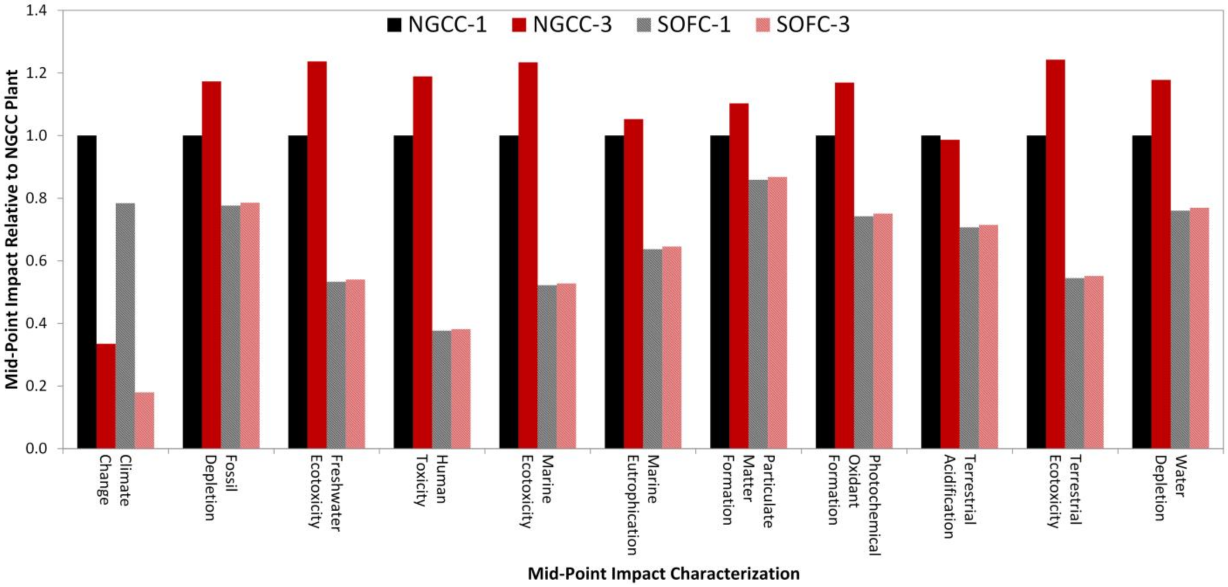

Figure 11: Selected normalized mid-point characterization comparisons the NGCC and SOFC systems

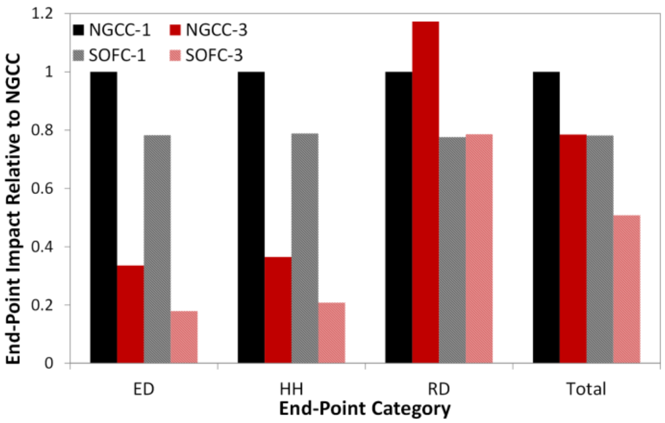

Figure 12: Selected normalized end-point characterization comparisons the NGCC and SOFC systems

4 Conclusions and Future Work

A complete life cycle analysis was performed for a system that generates electricity using natural gas-fueled solid oxide fuel cells (SOFCs) and compared it to the state-of-the-art natural gas combined cycle. Both LCAs accounted for all upstream material and fuel acquisition and processing in order to form a complete cradle-to-grave perspective. The LCA method *ReCiPe 2008* was used to perform both mid- and end-point characterization calculations for three socioeconomical perspectives, all of which are documented in the online supplement. The boundary regions for each process and any necessary sub-process were defined and any required assumptions were made to develop a consistent basis of comparison between the processes. Carbon capture and sequestration and transmission network losses and their impacts on the life cycles of each process were also considered.

It was found that the manufacturing stage of 1 kW of SOFC cells and their associated balance of plant contributes a noticeable portion to the entire life cycle impact of the SOFC process. The manufacturing of 1 kW of SOFC cells was found to release approximately 950 kg CO_2-equivalents, consume 193 kg of oil-equivalents and requires approximately 840 kg of iron-equivalents. Most emissions from SOFC manufacturing are the result of consuming electricity during the manufacturing process, which was assumed to be supplied by the average electricity mix in the United States. With regards to end-point impacts, the manufacturing of 1 kW of SOFCs has the impact of 88.1 points, which is approximately 9% of the impact of a human being over one year.

The addition of CCS to the NGCC process reduced direct CO_2 emissions by 90%, but reduced global CO_2 emissions by only 81%. Moreover, the decreased efficiency of the NGCC plant with CCS resulted in increases of NG and water consumptions of 17% in order to produce the same amount of electricity. Uncaptured direct emissions were found to increase with added fuel consumption as well. The NGCC process without CCS was found to have an end-point impact of 44 points per MW-h of electricity generated, which is approximately 4.4% of a human's impact over one year. The end-point reduction of adding CCS to the NGCC plant was found to be partially offset by increased resource consumption, but yielded an overall decrease of approximately 21% to 35 points. Considering TML was found to increase all life-cycle impact categories proportionally to its added inefficiency, details of which can be found in the online supplement.

The addition of CCS to the SOFC process reduced direct CO_2 emissions by 100% and decreased global CO_2 emissions by approximately 93%. However, adding CCS to a SOFC process has a very low parasitic energy penalty and hence does not facilitate the need for significantly more NG. As such, the impacts of upstream NG acquisition and processing were small. The SOFC process without CCS was found to have an end-point impact of 35 points per MW-h of electricity generated, which is approximately 3.5% of a human's impact over one year and 9 points (20%) lower than the NGCC plant without CCS. The end-point reduction of adding CCS to the SOFC plant was significant, yielding an overall decrease of approximately 35% to 22 points. Considering TML was found to increase all life-cycle impact categories proportionally to its added inefficiency, details of which can be found in the online supplement.

A comparison of cases showed that the SOFC plant without CCS is capable of producing 1 MW-h of electricity with a lower life-cycle impact than the NGCC process in all scenarios, even when CCS is used with the NGCC exclusively. As a final note, if a current NGCC plant running without CCS were to be replaced with an equivalent SOFC system utilizing CCS, the complete life cycle impact of generating electricity of such a scenario would be reduced by 50% for the same amount of power produced.

This work has reinforced the applicability and potential of utilizing NG in SOFC systems to produce clean, reliable electricity to the current state-of-the-art. Not only can direct system CO_2 emissions be essentially eliminated, but the entire life cycle impact of the electricity generation infrastructure using NG can be reduced by as much as 50% without requiring any changes to the upstream NG supply chain.

5 Nomenclature

ASU	Air Separation Unit
CAES	Compressed Air Energy Storage
CCS	Carbon Capture and Sequestration
DCB	Dichlorobenzene
HHV	Higher-Heating Value
HRSG	Heat Recovery and Steam Generation

NGCC	Natural Gas Combined Cycle
NMVOC	Non-methane Volatile Organic Compound
PEN	Positive-Electrolyte-Negative
PM_{10}	Particulate Matter with Radius 10µm
SOFC	Solid Oxide Fuel Cell

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