Life cycle analyses of SOFC/gas turbine hybrid power plants accounting for long-term degradation effects

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Keywords: Solid Oxide Fuel Cells, Life Cycle Analysis, Turbines, SimaPro, Natural Gas, Coal

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In this study, cradle-to-product life cycle analyses were conducted for a variety of natural-gas-based and coal-based SOFC power plant conceptual designs, while also accounting for long-term SOFC degradation. For each type of plant, four base case designs were considered: a standalone SOFC plant, a standalone SOFC plant with a steam cycle, an SOFC/GT hybrid plant, and an SOFC/GT hybrid plant with a steam cycle. The boundary of each base case was subsequently expanded to include either wet cooling or dry cooling options and DC to AC conversion, and was subjected to additional cradle-to-product life cycle analyses. The environmental impact results were computed using ReCiPe 2016 (H) and TRACI 2.1 V1.05 in SimaPro. The main factors affecting the midpoint impacts between cases were the plant efficiency and total SOFC manufacturing required over the plant's lifetime, which were both strongly connected to long-term degradation effects. The findings also showed that the standalone SOFC plant with a steam cycle (which featured higher plant efficiency) had lower midpoint impacts with respect to global warming potential and fossil resource scarcity, which were largely the product of plant operation. The case with the longer SOFC stack lifetime (e.g., a SOFC/GT hybrid power plant with a steam cycle) had lower midpoint impacts with respect to fine particulate matter formation, terrestrial acidification, terrestrial ecotoxicity, and mineral resource scarcity due to the large proportion of midpoint contributed by SOFC manufacturing. Ultimately, the SOFC/GT hybrid plant with a steam cycle was found to be the best option, as it had the lowest endpoint impact among both the natural gas-based and coal-based cases.

Life cycle analyses of SOFC/gas turbine hybrid power plants accounting for long-term degradation effects

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Keywords: life cycle analysis, SOFC, SOFC/GT hybrid, SOFC degradation, environmental impacts

Abstract

In this study, cradle-to-product life cycle analyses were conducted for a variety of natural-gas-based and coal-based SOFC power plant conceptual designs, while also accounting for long-term SOFC degradation. For each type of plant, four base case designs were considered: a standalone SOFC plant, a standalone SOFC plant with a steam cycle, an SOFC/GT hybrid plant, and an SOFC/GT hybrid plant with a steam cycle. The boundary of each base case was subsequently expanded to include either wet cooling or dry cooling options and DC to AC conversion, and was subjected to additional cradle-to-product life cycle analyses. The environmental impact results were computed using ReCiPe 2016 (H) and TRACI 2.1 V1.05 in SimaPro. The main factors affecting the midpoint impacts between cases were the plant efficiency and total SOFC manufacturing required over the plant's lifetime, which were both strongly connected to long-term degradation effects. The findings also showed that the standalone SOFC plant with a steam cycle (which featured higher plant efficiency) had lower midpoint impacts with respect to global warming potential and fossil resource scarcity, which were largely the product of plant operation. The case with the longer SOFC stack lifetime (e.g., a SOFC/GT hybrid power plant with a steam cycle) had lower midpoint impacts with respect to fine particulate matter formation, terrestrial acidification, terrestrial ecotoxicity, and mineral resource scarcity due to the large proportion of midpoint contributed by SOFC manufacturing. Ultimately, the SOFC/GT hybrid plant with a steam cycle was found to be the best option, as it had the lowest endpoint impact among both the natural gas-based and coal-based cases.

1. Introduction

Increases in global energy demand and public awareness of global warming have amplified the importance of reliable and sustainable power production [1]. Although sustainable power production technologies such as solar and wind are rapidly developing, their implementation is challenging due to their intermittent nature. Successful integration of wind and solar power into a large-scale energy system depends heavily on other power-generation systems that can produce power when sunlight and wind are in insufficient supply [2]. For this reason, conventional baseload power production using fossil fuels such as natural gas (NG) or coal remains highly prominent, and is anticipated to continue to account for a major share of global power production (e.g., anticipated for a share of 40-50% in 2030 in the U.S.) [3,4]. As such, it is critical to improve existing NG-based and coal-based baseload power production methods, especially from an eco-technoeconomic perspective. Solid oxide fuel cells (SOFC) are a promising technology for reliable baseload power production, as their use of electrochemical reactions allows them to generate electricity more efficiently compared to conventional combustion-based power production technologies. From an emissions perspective, SOFCs not only produce lower CO_2 emissions due to their higher efficiency, but they also enable efficient CO_2 capture at a low cost [5,6]. However, the life cycle environmental impacts of SOFCs are uncertain, as their efficiency and lifetime are dynamically influenced by their degradation rate.

An SOFC's degradation rate is strongly affected by its operating conditions [7]. The most common operating strategy for baseload power production is to maintain a constant SOFC power output; this results in a higher degradation rate and, thus, a shorter SOFC lifetime. Changing the operating strategy to utilize constant voltage instead of constant power output significantly slows the degradation rate and dramatically increases the SOFC's lifetime (up to more than 10 times). However, the trade-off with this approach is a decrease in power output over time. As the power output decreases in this constant voltage operating mode, the amount of unspent fuel in the SOFC exhaust increases, which can be used by a gas turbine (GT) for secondary power production to maintain a net baseload power production [7–10]. While an SOFC/GT hybrid plant that accounts for degradation effects has been shown to be technically and economically feasible in prior works, its life cycle environmental impacts are still unclear [10,11]. Given the huge difference (more than 10 times) in SOFC stack lifetime due to degradation effects under different operating conditions, it is possible that the environmental impacts of SOFC manufacturing might strongly affect the full LCA result from case to case.

A review of the literature shows that researchers have conducted life cycle analyses (LCA) focusing on various aspects of SOFCs. For instance, Strazza et al. conducted an LCA on a 230 kW SOFC system and compared its impact to a micro-gas turbine system that utilized NG and biogas as fuel sources [12]. To account for degradation effects, they assumed four SOFC stack replacements over a 10-year system lifetime for simplicity [12]. In a different study, Rillo et al. conducted an LCA for a 250 kW biogas-fed SOFC system, wherein they assumed a stack lifetime of six years and that 17% of the stack would be replaced each year over its lifetime [13]. Elsewhere, Bicer and Khalid performed an LCA comparison that assumed a 5-year lifetime for a 250 kW SOFC system fueled by various sources, including NG, hydrogen, ammonia, and methanol [14], while Al-Khori et al. conducted an LCA for the integration of an SOFC into an NG plant that assumed a 10-year SOFC lifetime [15]. In another work, Nease and Adams performed cradle-to-grave LCAs for bulk-scale SOFC plants powered by NG and coal and compared their results to those obtained for conventional power plants such as natural gas combined cycle plants and supercritical pulverized coal power plants. In that study, Nease and Adams assumed that the SOFC could be operated at full capacity for 10 years [16,17]. Reenaas conducted an LCA for an SOFC/GT system and compared the results to those for a diesel auxiliary power production unit on a ship, assuming SOFC stack lifetimes of 40000 or 20000 hours depending on the case study [18].

Although the above studies assumed various SOFC stack lifetimes, their degradation effects were not considered in detail. In another work, Ghorbani et al. performed exergoeconomic and exergoenvironmental analyses of an SOFC-GT-ORC (Organic Rankine Cycle) hybrid system with an approximate power scale of 1.2 MW [19]. Although they included voltage loss calculations in their SOFC model, the life cycle environmental impacts remained unclear, as did the effect of degradation on the SOFC stack's lifetime. Naeini et al. conducted an LCA on an NG-based SOFC system that accounted for degradation effects and considered 5- and 10-year stack replacement plans [20]. To reduce the degradation rate, they allowed the operating conditions of the SOFC stack to change over time instead of maintaining constant power output, which resulted significantly improved stack lifetimes of up to 10 years [21,22]. Although they considered various operating conditions to counteract the degradation effects, they focused on a standalone SOFC system without considering power integration at the systems level—for example, they did not consider utilizing the waste heat from the SOFC exhaust stream for secondary power production.

To the best of our knowledge, the present study is the first detailed cradle-to-product LCA for large-scale NG-based and coal-based SOFC/GT hybrid plants (including SOFC/GT hybrid plants with a steam cycle). This work both accounts for degradation effects and compares the results to those recorded for standalone SOFC plants (including standalone SOFC plants with a steam cycle). In our prior work, the SOFC stacks in SOFC/GT hybrid plants were found to have much longer lifetimes (more than 10 times) compared to those in standalone SOFC plants due to the much slower degradation in constant voltage operating mode [10,11]. Thus, SOFC/GT hybrid plants would potentially have a much lower environmental impact with respect to SOFC manufacturing than standalone SOFC plants. However, we also found that standalone SOFC plants with a steam cycle had higher net efficiency compared to SOFC/GT hybrid plants, which would potentially result in lower environmental impact from plant operation [10,11]. Therefore, it is vital to perform full LCAs to further compare the respective life cycle environmental impacts of SOFC/GT hybrid plants and standalone SOFC plants with a steam cycle.

2. Methodology

The cradle-to-product LCAs were performed for four base cases utilizing NG and four base cases utilizing coal as the fuel sources. These base cases were discussed in detail in a prior study by the authors, to which the reader is referred for detailed stream information, dynamic operating trajectories, and techno-economic analyses. [10,11]. The base cases were named based on their major components for power production as follows:

- Base Case 1 (BC1): standalone SOFC plant
- Base Case 2 (BC2): standalone SOFC plant with a steam cycle
- Base Case 3 (BC3): SOFC/GT hybrid plant
- Base Case 4 (BC4): SOFC/GT hybrid plant with a steam cycle

These base case designs applied to both NG-based cases and coal-based cases (as shown in Table 1), with the major differences being in the upstream treatment processes for fuel prior to entering the SOFC stack. The upstream treatment process in NG-based cases included major components such as the steam reforming of NG and a water-gas shift process, while the upstream process in coal-based cases mainly included coal gasification, scrubbing, water-gas shift, and Selexol processes. All the base cases were designed to have a power scale of 550 MW (mixed AC and DC electricity output) and a plant lifetime of 30 years. A basis of 1 MWh electricity product (mixed AC and DC) was chosen for the LCA.

Table 1. Basic data for the examined base cases [10,11]. ST = steam turbine system (a classic combined cycle using waste heat from the upstream units).

	NG-based Cases				Coal-based Cases			
	BC1	BC2	BC3	BC4	BC1	BC2	BC3	BC4
Overview								
Description	SOFC	SOFC + ST	SOFC/GT	SOFC/GT + ST	SOFC	SOFC + ST	SOFC/GT	SOFC/GT + ST
Net Power (MW)	550	550	550	550	550	550	550	550
Plant efficiency (LHV)	46.8%	65.0%	50.8%	53.0%	30.7%	48.7%	41.6%	44.6%
LCOE ($/MWh)	$327	$194	$38.5	$35.1	$430	$241	$82	$77
SOFC stack								
Stack size (cm^2 active membrane area)	1.26×10^9	9.18×10^8	1.04×10^9	1.03×10^9	1.4×10^9	9.04×10^8	9.8×10^8	9.14×10^8
Stack lifetime (year)	0.4	0.5	7.2	8.2	0.4	0.4	6.7	6.7
Total number of stacks	79	63	5	4	83	69	5	5
Components of BoP manufacturing								
SOFC sub-processes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Upstream treatment processes for fuel	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Gas turbine	No	No	Yes	Yes	No	No	Yes	Yes
Steam cycle	No	Yes	No	Yes	No	Yes	No	Yes

2.1. Boundaries

The boundaries of the LCA for all base cases included gate-to-product plant operation, cradle-to-gate SOFC manufacturing, cradle-to-gate balance-of-plant (BoP) manufacturing, and cradle-to-gate plant maintenance, with a final product of 1 MWh mixed AC and DC electricity (Figure 1). For analysis purposes, the plant is in a non-specific United States location. For example, the fuel at plant data for the NG-based and coal-based plants were obtained from the SimaPro library as cradle-to-product high-pressure market NG in the U.S. and market hard coal in North America, respectively, with average transportation accounted being account for in both cases.

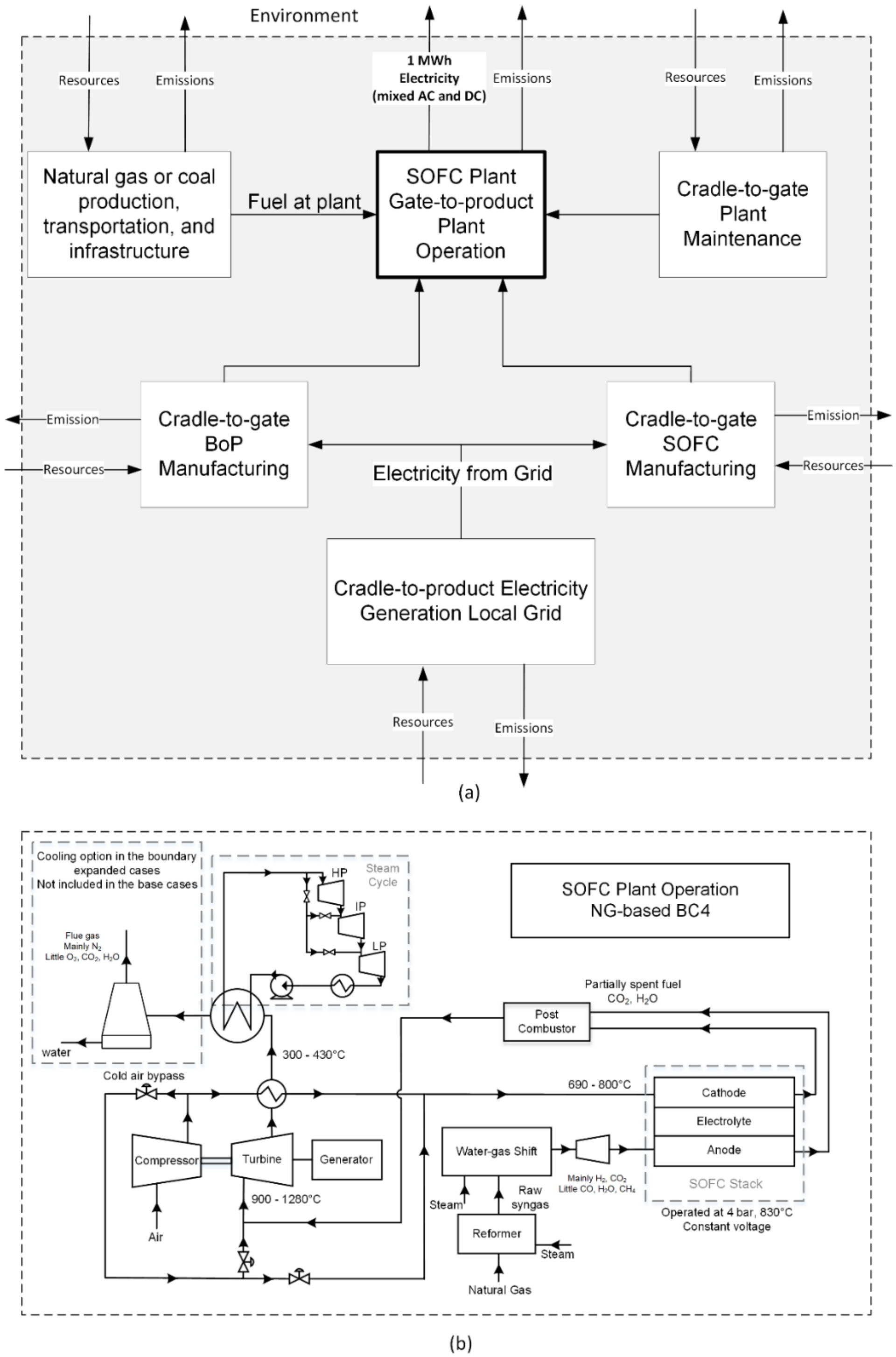

Figure 1. Life cycle boundary for SOFC plants and process flow diagram of the SOFC plant operation for NG-based BC4.

2.2. Plant operation

The boundary for the plant operation includes all species that are transferred between the plant and the natural environment for the production of 1 MWh of net electricity (mixed AC and DC). Figure 1 (b) shows a sample process flow diagram of the SOFC plant operation for NG-based BC4 and its additional cooling option included in boundary expanded cases (explained later in section 3.3). The data for plant operation of each case were obtained from our prior studies and are provided in the Supplemental Material [10,11].

2.3. SOFC manufacturing

A 1 cm^2 active membrane area was selected as the basis for the SOFC manufacturing inventory data. While a unit basis of 1 kW has been widely used in LCAs of SOFC manufacturing [13,14,23], this basis is specific only to situations in which SOFCs are operated under constant power production at nameplate capacity, and cannot be applied for SOFC stacks that are operated under different or transient conditions. Naeini et al. utilized Rillo et al.'s data and assumptions to construct an inventory basis of 1 cm^2 for SOFC manufacturing, which provides a more general reference point for use in LCAs of SOFCs with various operating conditions [13,20].

The SOFC stacks in the studied base cases varied in size due to the different system designs required to achieve a net power production of 550 MW. The SOFC model simulations considered long-term degradation, with the degradation rate changing according to the operating conditions in each case. Therefore, SOFC stack lifetime varied from case to case, as did the number of stacks used over the 30-year plant lifetime (Table 1). In this work, the SOFC manufacturing inventories were calculated based on the size and numbers of SOFC stacks in each case (Table 1) using the inventory basis per cm^2 presented by Naeini et al. [20]. The inventory accounts for the materials and energy used in SOFC manufacturing including, but not limited to, Nickel oxide (NiO), Yttrium stabilized zirconium (YSZ), Lanthanum strontium manganite (LSM), various solvents and binders, stainless steel, and electricity. The full inventory data and more detailed descriptions can be found in [14,20].

2.4. Balance-of-plant manufacturing

The balance-of-plant (BoP) manufacturing includes SOFC accessories, upstream treatment processes for fuel (NG or coal), gas turbines (in BC3 and BC4), and steam cycles (in BC2 and BC4). The different sub-processes included in the BoP manufacturing for each case are summarized in Table 1 above. The SOFC sub-processes mainly included steel production, stainless steel production, and energy for fabricating auxiliary equipment and running the SOFC assembly process [14,20]. The inventories for the manufacturing of syngas upstream processes, gas turbines, and steam cycles were estimated based on data collected from the literature [18,24,25].

2.5. Plant maintenance

The inventories for plant maintenance included the steel and stainless steel required for equipment maintenance, as well as the catalysts and chemicals consumed in the processes. The NG-based cases consumed Nickel-based and iron-based catalysts for reforming and water-gas-shift (WGS) processes. The coal-based cases consumed sulfur-impregnated activated carbon for Hg removal, iron-based catalyst for WGS reactions, Selexol for H_2S removal, and sodium hydroxide for HCl removal. All consumptions of catalysts and chemicals were estimated with their initial fills and daily makeups throughout the plant lifetime. For example, coal-based BC4 consumed an initial fill of 54.5×10^3 kg sulfur-impregnated activated carbon with a daily makeup of 74 kg/day, and the net consumption over the plant lifetime converted to the basis became 0.006 kg/MWh (Table 2). The inventories of these chemicals were estimated based on the following assumptions [26–30]:

- 1% of steel and stainless steel of the BoP would need to be replaced each year.
- Ni-honeycomb catalyst was used for the reforming process [26,28].
- Ferrite served as the iron-based catalyst for the water-gas-shift reactions [26,27,29].
- No initial fills of reforming catalyst for the NG-based cases and sodium hydroxide for the coal-based cases [26,27].

Table 2. Consumption of catalysts and chemicals in plant maintenance for NG-based and Coal-based BC4.

	Initial fill (10^3 kg)	Daily makeup (kg/day)	Net consumption (kg/MWh)
NG-based BC4			
Reforming catalyst	0	244	0.0185
WGS catalyst	73.8	235	0.0183
Coal-based BC4			
Sulfur-impregnated activated carbon	54.5	74	0.0060
WGS catalyst	258.5	177	0.0152
Selexol	1673.7	166	0.0242
Sodium hydroxide	0	7194	0.5450

2.6. Data Transparency

The original SimaPro files used in the analysis have been released to the public (See link at end of manuscript). The files contain the detailed gate-to-gate life cycle inventories used for all steps.

3. Results and discussion

3.1. Base cases

Figure 2 shows the midpoint characterization results of the base cases, which were obtained using ReCiPe 2016 (H). The results of the NG- and coal-based cases were normalized to the total midpoints of NG-based BC2 and coal-based BC2, respectively, in each category. For each case in each category, the contributions of plant operation, SOFC manufacturing, BoP manufacturing, and plant maintenance to the midpoint impact are shown as stack columns, with the legend shown in the figure. A more detailed overview of the results and data can be found in the Supplemental Material.

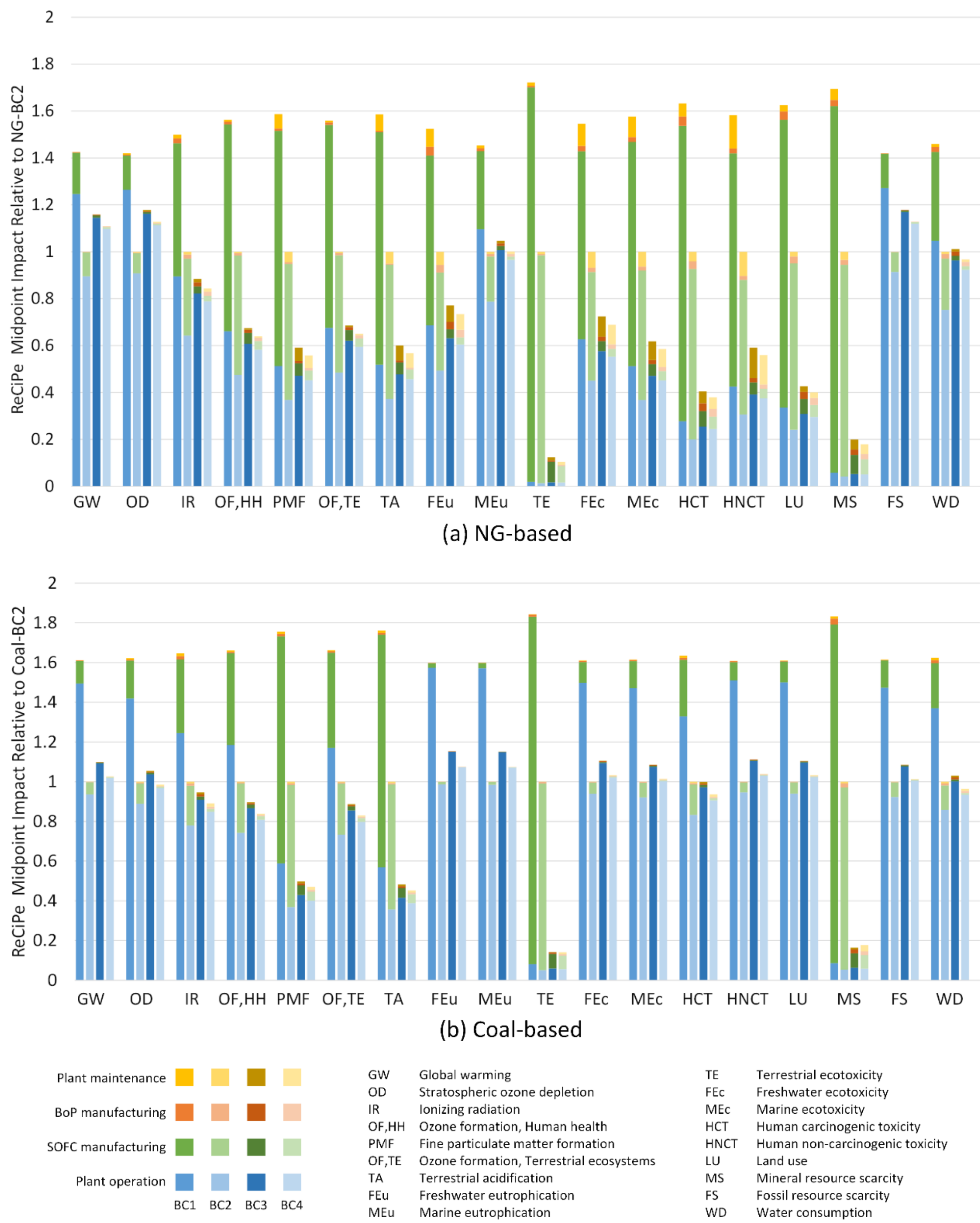

Figure 2. Normalized ReCiPe midpoint impact results (ReCiPe 2016 H) for the base cases. Subplots (a) and (b) show the four NG-based cases and four coal-based cases, respectively. The components' contributions to each impact category are shown as stacked columns.

For the NG-based cases, plant operation made the largest contribution to the total midpoint impacts in categories such as global warming, stratospheric ozone depletion, ionizing radiation, marine eutrophication, fossil resource scarcity, and water consumption. Since BC2 had the highest plant efficiency, it had the lowest midpoint impacts from plant operation among the four NG-based cases in every category. As the plant efficiency decreases from BC2→BC4→BC3→BC1 (Table 1), the midpoint impacts from plant operation in each category increased correspondingly. With regards to SOFC manufacturing, BC1 required the largest total active membrane area (around 24 times larger than BC4), followed by BC2 (around 14 times larger than BC4), BC3 (around 1.3 times larger than BC4), and BC4. Consequently, the midpoint impacts contributed by SOFC manufacturing decreased from BC1 to BC4. The midpoint impacts relating to terrestrial ecotoxicity and mineral resource scarcity were mostly from SOFC manufacturing. For BC1 and BC2, SOFC manufacturing also contributed a large amount of midpoint impacts in categories such as ozone formation, fine particulate matter formation, terrestrial acidification, freshwater ecotoxicity, marine ecotoxicity, human toxicity, land use, and mineral resource scarcity. The impacts from BoP manufacturing and plant maintenance were relatively small compared to plant operation and SOFC manufacturing in most categories. However, plant maintenance had noticeable impacts with respect to human toxicity, freshwater ecotoxicity, marine ecotoxicity, freshwater eutrophication, terrestrial acidification, and fine particulate matter formation, mainly due to the consumption of catalysts.

The comparison of BC2 (standalone SOFC with steam cycle) and BC4 (SOFC/GT with steam cycle) showed that BC2 had lower midpoint impacts in categories dominated by plant operation, such as global warming, stratospheric ozone depletion, and fossil resource scarcity, mainly due to its higher plant efficiency. However, the short SOFC stack lifetime (high degradation rate) in BC2 results in large impacts from SOFC manufacturing, which results in higher total midpoint impacts in almost all other categories compared to BC4. Similar results were observed in the comparison of BC2 and BC3, with one performing better in some categories and worse in other categories. BC4 had a lower impact than BC3 in all categories due to its higher plant efficiency and lower SOFC manufacturing.

For the coal-based cases, plant operation also contributed the highest midpoint impacts in the same categories as the NG-based cases, namely, in global warming, stratospheric ozone depletion, ionizing radiation, marine eutrophication, fossil resource scarcity, and water consumption. Besides these categories, plant operation in the coal-based cases also dominated the midpoint impacts in freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity, human toxicity, and land use. These results indicate that, in the coal-based case, plant operation contributed higher midpoint impacts in these categories compared to the NG-based cases. In addition, due to the higher midpoint impacts from plant operation in the coal-based cases, the relative total impacts for BC2 compared to BC4 with respect to freshwater eutrophication, freshwater ecotoxicity, marine ecotoxicity, human toxicity, and land use were much smaller than in NG-based cases. This implies that, in these categories, NG-BC2 is worse than NG-BC4, but coal-BC2 is about the same or even marginally better than coal-BC4. In the NG-based cases, SOFC manufacturing consistently contributed the greatest impacts in terrestrial ecotoxicity and mineral resource scarcity, while BoP manufacturing and plant maintenance had insignificant impacts in all categories.

3.2. Monte Carlo sensitivity analysis

A Monte Carlo sensitivity analysis was conducted to investigate how uncertainties in plant operation and SOFC manufacturing processes affected the ReCiPe midpoint impacts. Plant efficiency was assumed to fluctuate within ± 2% (two percentage points) to account for uncertainties in plant operation. The inventories for SOFC manufacturing were assumed to fluctuate within ±5% to account for uncertainties during the manufacturing process. Using SimaPro, we conducted Monte Carlo sampling with 1000 runs that followed two normal distributions, with the two uncertainty ranges of plant operation and SOFC manufacturing as the 95% confidence intervals simultaneously. The ReCiPe midpoint impact results are shown in Figure 3. The average total midpoint impact of the Monte Carlo runs for each case in each category was approximately the same as the corresponding base case. The standard deviation (represented as error bars in the figure) in each Monte Carlo case indicates that the uncertainties in plant operation and SOFC manufacturing did not have a large impact on the ReCiPe midpoint impact results.

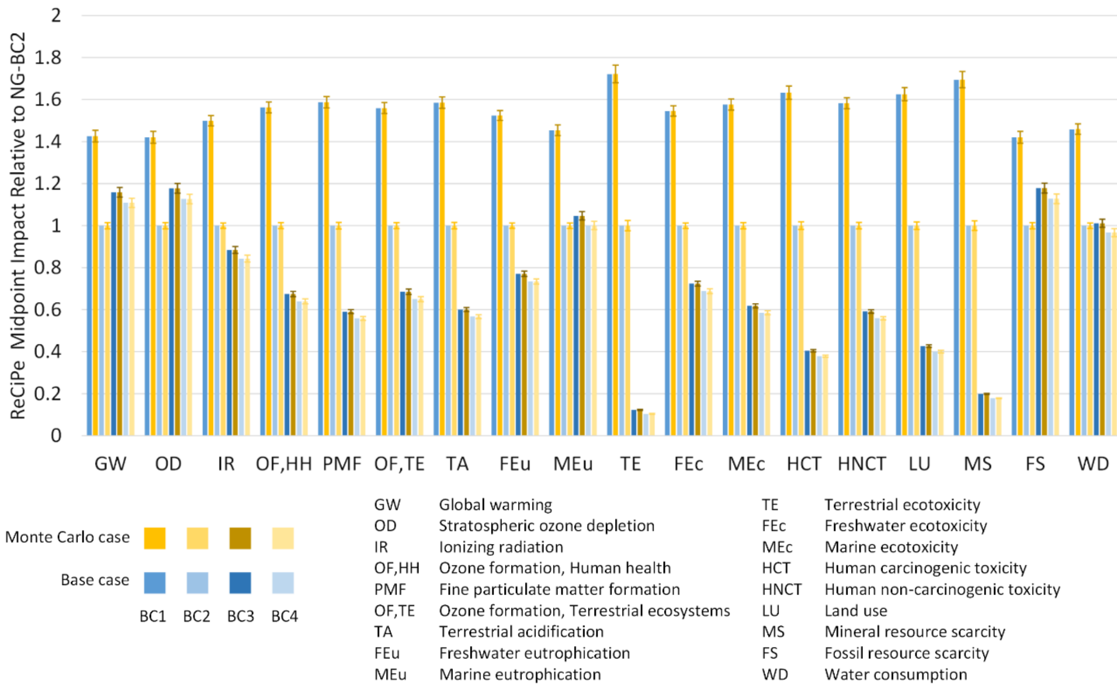

Figure 3. Normalized ReCiPe midpoint impact results (ReCiPe 2016 H) for the comparisons of the base cases and base cases with Monte Carlo sensitivity analyses.

3.3. Boundary expansion

The plant operation boundaries used in the previous section for the four NG-based cases and four coal-based cases were based on previous works, which did not include cooling towers for cooling the flue gas stream at the end of the processes; this deficiency could be addressed by including either wet cooling towers or dry cooling towers (air cooled). Furthermore, these base cases utilized mixed AC and DC electricity production, which could be converted to only AC grid-quality electricity with an inverter [10]. As such, we expanded the boundaries of the base cases to include two more cases for each category: (1) an expanded base case with wet cooling towers and AC grid-quality electricity as the output (e.g., BC1Wc), and (2) an expanded base case with dry cooling towers and AC grid-quality electricity as the output (e.g., BC1Dc). The boundary expansion was conducted using the following assumptions:

- A DC to AC conversion efficiency of 96% [31].
- The wet cooling towers consumed 0.42 L of water per MJ of electricity production and had 1% electricity penalty (of the gross power) compared to the base case [31–33].

- The dry cooling towers consumed no water for cooling purposes and had 7% electricity penalty (of the gross power) compared to the base case [31,32].

Figure 4 (a) shows the ReCiPe midpoint impact results for the expanded NG-based cases compared to those of the corresponding base cases. With regards to water consumption, the expanded NG-based cases with wet cooling towers and AC grid-quality electricity output (BC1Wc to BC4Wc) more than doubled the water consumption of the corresponding base cases, whereas water consumption was greatly reduced in the expanded NG-based cases with dry cooling towers and AC grid-quality electricity output (BC1Dc to BC4Dc). Not only did the dry cooling towers consume no water for cooling purposes, they also enabled the recovery of water from the cooled flue gas stream. Indeed, more water was produced than consumed during plant operation in these cases. Since the water was recovered from the flue gas stream, the plant operation in the NG-based cases resulted in negative water consumption, which is consistent with previous work on SOFC flue gas water recovery by Adams and Barton [31]. Nonetheless, the other LCA boundary components (mainly the SOFC manufacturing) did consume water, with consumption increasing from BC4 to BC1 in proportion to SOFC manufacturing. Therefore, BC1Dc and BC2Dc had positive net water consumption (combining negative water consumption from plant operation and positive water consumption from other components), while BC3Dc and BC4Dc had negative water consumption. In all other categories, the midpoint impacts of the expanded wet cooling cases were higher than the corresponding base cases due to the 1% electricity penalty; moreover, the midpoint impacts of the expanded dry cooling cases were even higher due to the higher electricity penalty (7%). As mentioned in the previous section, BC4 had lower midpoint impacts compared to BC2 in some categories and higher midpoint impacts in others. To further compare the two cases, ReCiPe endpoint impacts (ReCiPe 2016 H) were computed using SimaPro. The NG-based endpoint results are shown as the last category in Figure 4 (a). As can be seen, the endpoint impacts of BC4, BC4Wc, and BC4Dc were lower than those of BC2, BC2Wc, and BC2Dc, respectively. Although BC4 had lower plant efficiency than BC2, its environmental impacts were lower overall. It is also interesting that the endpoint impact of BC3 (or BC3Wc or BC3Dc) was slightly lower than that of BC2 (or BC2Wc or BC2Dc). This result indicates that the SOFC/GT hybrid plants (BC3 and BC4) are better alternatives to the standalone SOFC plants (BC1 and BC2), and that the SOFC/GT hybrid plant with a steam cycle (BC4) is the best option among the four.

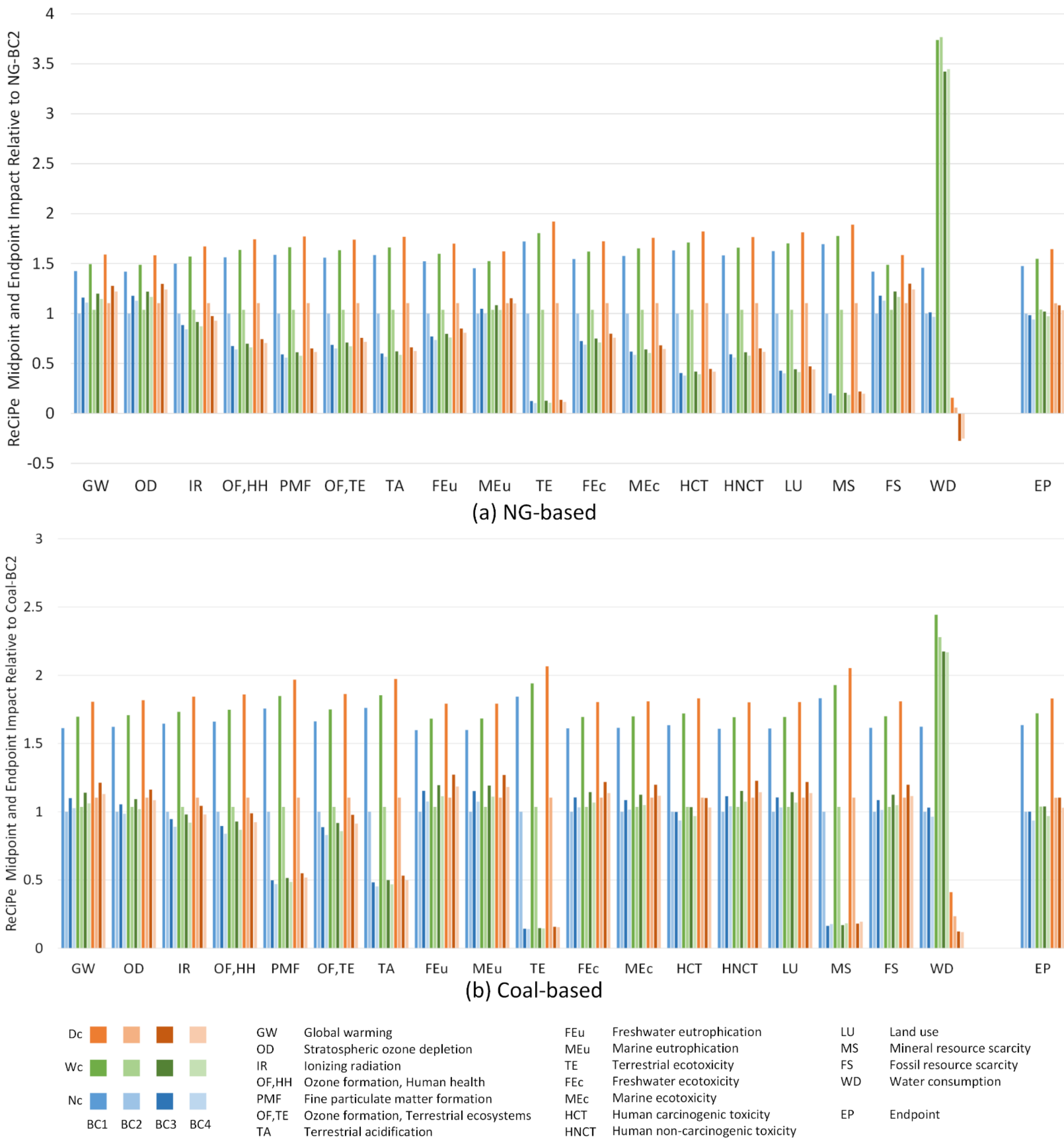

Figure 4. Normalized ReCiPe midpoint impact results (ReCiPe 2016 H) for the comparisons between base cases and base cases with the two boundary expansions. Nc: No cooling. Wc: Wet cooling. Dc: Dry cooling.

Similarly, the midpoint impacts in water consumption were higher in coal-based BC1Wc to BC4Wc and significantly lower in coal-based BC1Dc to BC4Dc compared to the corresponding base cases. Due to the water recovery from the flue gas stream and the lack of water consumption in the dry cooling method, the plant operation in the Dc cases had negative water consumption. However, the other components, especially SOFC manufacturing, still consumed water, resulting in positive net water consumption for the four coal-based Dc cases. Water consumption aside, the midpoint impact for BC1 to BC4 increased in other categories in the order of Nc, Wc, and Dc as the electricity penalty increased, respectively. The endpoint results for the coal-based cases also showed that BC4, which is a SOFC/GT system with steam cycle, had lower environmental impacts than BC2 (standalone SOFC with a steam cycle).

In addition to the ReCiPe method, TRACI 2.1 V1.05 was also applied to compute the LCA results of all cases (Figure 5). In every category for both the NG- and coal-based plants, BC1Dc had the highest midpoint impact, followed by BC1Wc and BC1(Nc) due to the above-noted electricity penalties. The same trend can be seen for BC1 through BC4. Since the TRACI midpoint method did not include water consumption—to the advantage of the Dc cases—the results do not reflect the reduction of water consumption. Similar to the ReCiPe midpoint results, BC2 had the lowest impact among all the cases for some TRACI categories, while BC4 had the lowest impact for others. Specifically, NG-BC2 outperformed NG-BC4 with respect to global warming, ozone depletion, and fossil fuel depletion, mainly due to its higher plant efficiency. In contrast, it was outperformed by NG-BC4 in all other categories, mainly due to the need for much more SOFC manufacturing. Coal-BC2 outperformed Coal-BC4 with respect to global warming and eutrophication, but was outperformed by Coal-BC4 in all other categories. These TRACI midpoint results are generally consistent with the ReCiPe midpoint results, with the exception of fossil fuel depletion for the coal-based cases. The TRACI midpoint in fossil fuel depletion decreased from Coal-BC1 to BC4 (Figure 5), while the ReCiPe midpoint in the same category showed that Coal-BC4 had slightly higher impact than Coal-BC2, and Coal-BC3 had higher impact than Coal-BC2 and BC4 (Figure 4). This inconsistency was due to the fact that TRACI method computed lower impact in plant operation and higher impact in SOFC manufacturing compared to ReCiPe method. For example, the midpoint impact ratio of plant operation and SOFC manufacturing in Coal-BC2 was 4:1 when computed using TRACI, and 12:1 when computed using ReCiPe.

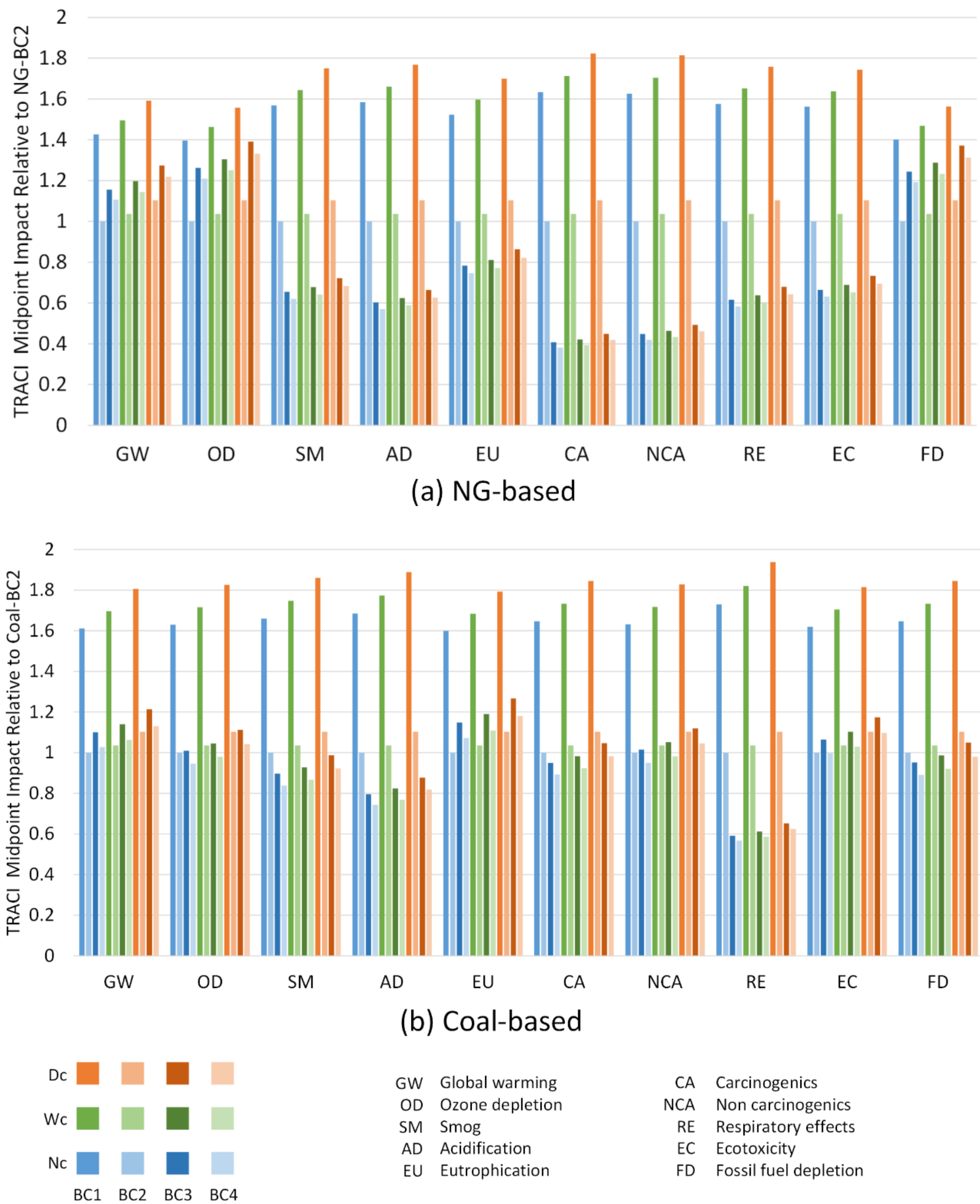

Figure 5. Normalized TRACI midpoint impact results for the comparisons between base cases and base cases with the two boundary expansions. Nc: No cooling. Wc: Wet cooling. Dc: Dry cooling.

3.4. Comparison with other SOFC systems in the literature

In addition to analyzing all the base cases and the expanded cases, we also compared the obtained LCA results with those of other SOFC systems in the literature. Compared to Nease et al.'s NG-based SOFC plant, (their case without considering carbon capture and transmission loss) which has a similar power scale as our cases, our NG-BC2 and NG-BC4 base cases had 20% and 33% higher ReCiPe midpoint impacts in global warming, respectively [16]. With regards to fossil resource scarcity, NG-BC2 and NG-BC4 had higher impacts of 9% and 23%, respectively, compared to Nease et al.'s NG-based SOFC plant [16]. The main reason for the higher midpoint impacts of our cases is that we used SOFC models that accounted for degradation effects, which not only reduced plant efficiency, but also the lifetime of SOFC stack. As a result, the midpoint impacts contributed by plant operation and SOFC manufacturing increased. Note that ReCiPe 2016 was used in this work, and ReCiPe 2008 was used in Nease et al. [16]. Overall these differences are reasonable, expected, and thus in good agreement with the literature.

We also compared our LCA results to Naeini et al.'s NG-based SOFC system, which featured the same power scale as ours, while also accounting for degradation effects (but with a different degradation model) [20]. The SOFC models used in our cases considered the overall degradation of the SOFC stack in relation to operating conditions, such as current density, fuel utilization, and temperature, based on experimental data. Unlike our SOFC model, Naeini et al. used an SOFC model that accounted for various degradation mechanisms in different components of the SOFC. At the system level, Naeini et al. focused more on the SOFC itself and did not combine it with other power systems, such as gas turbines or steam cycles. Instead, they designed an SOFC stack replacement schedule of every 5 years or 10 years for a 20-year plant lifetime by changing the operating conditions [20]. These SOFC replacement schedules are comparable to the ones we used for NG-BC3 and NG-BC4, wherein the SOFC stacks were replaced every 7.2 years and 8.2 years, respectively. The operating strategy in Naeini et al.'s 5- or 10-year plan was to allow the current density or power output decrease over time, which was similar to the approach used in BC3 and BC4, wherein the voltage was kept constant and the current density or power was allowed to drop as the SOFC degraded. Since they did not harness the waste heat from the SOFC stack for additional power generation, the overall electrical efficiency was lower compared to NG-BC2, NG-BC3, and NG-BC4 in our study [20], as expected.

Figure 6 shows the ReCiPe midpoint impact comparison for selected categories, with all midpoints being normalized relative to Naeini et al.'s SOFC case with a

10-year replacement schedule [20]. As can be seen, with the exception of BC1 (including BC1Wc and BC1Dc), all our NG-based cases had lower midpoint impacts with respect to global warming, mainly due to their higher plant efficiency. SOFC manufacturing contributed a large portion of midpoint impacts in the categories of fine particle matter formation and terrestrial acidification, therefore, BC3 and BC4 (including the Wc and Dc cases) had impacts close to those reported for Naeini et al.'s SOFC-5yr and SOFC-10yr cases [20]. Since BC1 and BC2 (including the Wc and Dc cases) required considerably more SOFC manufacturing due to frequent SOFC replacement, they had much higher impacts in these two categories. The comparison results showed good agreement between our findings and those for SOFC systems in literature that account for long-term degradation effects.

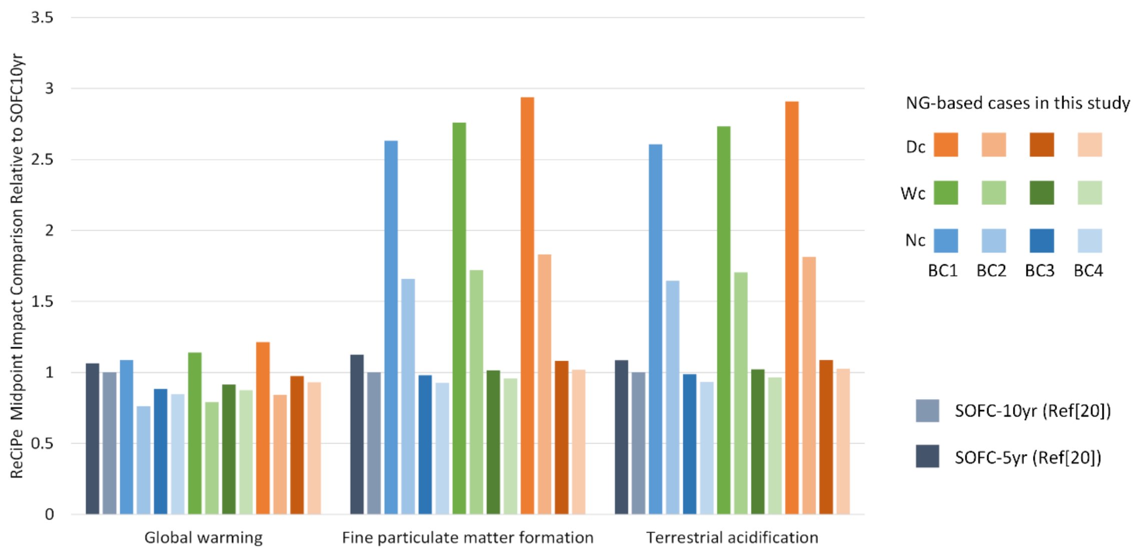

Figure 6. Normalized ReCiPe midpoint impact comparison (ReCiPe 2016 H) with other NG-based SOFC systems from [20].

4. Conclusion

In this study, we performed cradle-to-product life cycle analyses for four NG-based SOFC plant base cases and four coal-based SOFC plant base cases, as well as for two additional expanded boundary cases for each base case. The LCA results obtained via ReCiPe 2016 (H) in SimaPro showed that the standalone SOFC plants (NG-BC1 or Coal-BC1) had highest midpoint impacts in every category due to having the lowest plant efficiency (unused waste heat) and largest SOFC-stack manufacturing requirements (i.e., the shortest SOFC stack lifetime). The standalone SOFC plants with a steam cycle (NG-BC2 or Coal-BC2) outperformed the SOFC/GT hybrid plants with a steam cycle (NG-BC4 or Coal-

BC4) in some midpoint categories (e.g., global warming) due to their higher plant efficiency, but had worse (higher) environmental impacts in other categories (e.g., terrestrial ecotoxicity) due to the need for more SOFC manufacturing. Similar results can be seen between BC3 and BC2, while BC4 always had better (lower) environmental impacts than BC3 in either the NG-based or coal-based cases. The ReCiPe endpoint results indicated that NG-BC4 and Coal-BC4 had the lowest environmental impacts in their respective classes (i.e., natural-gas-based and coal-based designs).

For all NG-based cases, plant operation accounted for the largest ReCiPe midpoint contributions to global warming, stratospheric ozone depletion, fossil resource scarcity, and water consumption, while SOFC manufacturing contributed the most to terrestrial ecotoxicity and mineral resource scarcity. The midpoint impacts contributed by plant operation decreased as plant efficiency increased (i.e., BC1→BC3→BC4→BC2) for all categories, while the midpoint impacts contributed by SOFC manufacturing similarly decreased alongside the corresponding total number of SOFCs required over the 30-years plant lifetime (i.e., BC1→BC2→BC3→BC4). While balance-of-plant manufacturing and plant maintenance generally accounted for lower midpoint impacts than the other two components, plant maintenance had noticeable impacts in some categories, such as human toxicity and freshwater and marine ecotoxicity, mainly due to the use of catalysts.

The sensitivity analyses with Monte Carlo sampling showed that the ReCiPe midpoint impacts of the base cases were not sensitive to uncertainties in plant operation and SOFC manufacturing. The expanded boundary cases with wet cooling towers had higher ReCiPe midpoint impacts compared to the corresponding base cases in all categories, while the cases with dry cooling towers significantly reduced water consumption, but had higher overall impacts compared to the corresponding cases with wet cooling towers. The midpoint impacts results obtained using TRACI 2.1 were similar to the ReCiPe results. Finally, a comparison with other SOFC systems revealed that our findings agreed well with the those reported in the literature, and that including SOFC degradation in the model resulted in higher environmental impacts in relation to plant operation and SOFC manufacturing, thus increasing the midpoint impacts in every category.

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Simulation files

Models and codes related to this work have been released to the public in LAPSE (link: https://psecommunity.org/LAPSE:2023.0002).

Nomenclature

AC	Alternating Current
AD	Acidification
BoP	Balance-of-plant
CA	Carcinogenics
DC	Direct Current
EC	Ecotoxicity
eTEA	Eco-technoeconomic Analysis
EU	Eutrophication
FD	Fossil fuel Depletion
FEc	Freshwater Ecotoxicity
FEu	Freshwater Eutrophication
FS	Fossil resource Scarcity
FU	Fuel Utilization
GT	Gas Turbine
GW	Global Warming
HCT	Human Carcinogenic Toxicity
HNCT	Human Non-carcinogenic Toxicity
IR	Ionizing Radiation
LCOE	Levelized Cost of Electricity
LHV	Lower Heating Value
LSM	Lanthanum Strontium Manganite
LU	Land Use
MEc	Marine Ecotoxicity
MEu	Marine Eutrophication

MS	Mineral resource Scarcity
NCA	Non carcinogenics
NG	Natural Gas
OD	Stratospheric Ozone Depletion
OF, HH	Ozone Formation, Human Health
OF, TE	Ozone Formation, Terrestrial Ecosystems
PMF	Fine Particulate Matter Formation
RE	Respiratory Effects
SOFC	Solid Oxide Fuel Cell
SM	Smog
ST	Steam cycle (steam turbine)
TA	Terrestrial Acidification
TE	Terrestrial Ecotoxicity
WD	Water consumption (depletion)
WGS	Water-gas-shift reaction
YSZ	Yttria-stabilized Zirconia

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