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Environmental Impacts Analysis of Stationary Fuel Cell Combined Heat and Power Generation Systems

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The use of stationary fuel cell power systems for residential applications has been expanding owing to the characteristics of energy saving and environmental friendliness. Technical Committee 105 Working Group 14 (TC105 WG14) in the International Electrotechnical Commission (IEC) proposed assessment procedures for environmental impacts of stationary fuel cell systems using the life cycle assessment (LCA) methodology. In this study, the impact of the 700 W scale of a polymer electrolyte fuel cell combined heat and power generation system (PEFC-CGS) was tested based on the proposal document of the IEC TC105 WG14. In the estimation, the aurum (Au) in the circuit board, which is a precious metal, as well as platinum (Pt) contained in the cell stack, and differences in the hydrogen fuel production paths were considered. According to our results, the factors that contributed to the environmental impact were revealed. Therefore, to improve these factors for product differentiation from environmental aspects, differences in cell performance due to the cell manufacturing method were investigated. Then, it was confirmed that the multilayer electrode reduced the abiotic depletion potential (ADP) at manufacturing by 6 or 12%, and differentiation between products could be achieved by manufacturing the catalyst layers.

近年、我が国をはじめ、家庭用定置型燃料電池システムがその省エネルギー性や環境性から普及しつつある。このような状況に伴い国際電気標準会議技術委員会 105 分科会 14 (IEC/TC105/WG14) において、ライフサイクルアセスメント (LCA) 手法による定置用燃料電池システムの環境影響評価手法が提案され技術仕様書が発行された。本研究では、この IEC/TC105/WG14 にて提案された技術仕様書に基づき、現在、我が国で主に導入されている出力 700W の固体高分子形燃料電池コージェネレーションシステム (PEFC-CGS) について環境影響評価を実施した。評価は技術仕様書に基づき、運転性能だけでなく、環境影響指標の 1 つである非生物資源枯渇 (ADP) による機器の差別化の可能性を、運転性能と環境性の相互関係を考慮しつつ定量的に検討することが主な目的である。この結果、回路基板に含まれる金 (Au) やセルスタックに含まれる白金 (Pt) 等の希少金属の使用量、及び水素製造パスの違いを考慮した環境負荷の要因が明らかになった。また、これらの金属使用量と運転性能との相互関係を明らかにし、セルの電極製造法に起因するセル性能の差異を反映させた環境影響評価を行った。その結果、同じ運転性能の下、多層構造の触媒層を用いた電極は PEFC-CGS 製造時の ADP において 6%~12% の低減が見出され、運転性能との相互関係に基づき製造手法による差別化が図れることが示唆された。

Key Words

Stationary fuel cell, LCA, Circuit board, Electrospray Deposition

1. Introduction

Recently, the use of the stationary fuel cell system for residential applications has been expanding. This system is known in Japan as “Ene-farm.” As of November 2019, there were 0.3 million of these systems¹⁾. Based on the increased use of this system, in the International Electrotechnical

Commission (IEC) Technical Committee 105 Working Group 14 (TC105 WG14), the impact assessment procedure regarding general fuel cell combined heat and power generation system (FC-CGS) using the life cycle assessment (LCA) methodology is currently under consideration²⁾. The assessment procedure is a simplified evaluation method that focuses on global warming potential (GWP) and abiotic depletion potential (ADP), which are attributed to the operating performance and the component elements,

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respectively.

Sato *et al.*³⁾ pointed out that, during the manufacturing stage, the use of platinum (Pt) as a catalyst in the cells had the greatest impact on ADP. However, the current consumption of Pt (mg/cm²) in the electrodes has been greatly reduced while maintaining or improving the current density of the cell⁴⁾. Consequently, it was reported that the use in circuit boards of aurum (Au), which is a rare metal like Pt, has a significant impact on ADP⁵⁾. However, the amount of Au in the manufacture of circuit boards cannot be determined from the system specification. For instance, in previous studies, the amount could be roughly estimated using other electrical devices. However, it is not clear whether these are adequate for FC-CGS. Therefore, the proposed procedure for the current environmental impact assessment of FC-CGS may not be adequate.

Considering the recent development of pure H₂ type polymer electrolyte fuel cell combined heat and power generation systems (PEFC-CGSs)⁵⁾, it needs to be shown that the same assessment procedure can be performed for this novel type of system. That is, the environmental impacts including the interaction of the operating performance for various fuel types and the content of rare metals attributed to that should be clarified. In this study, we first evaluated the environmental impacts of PEFC-CGS in terms of ADP and GWP, following the method proposed by TC105 WG14. The aspects that had not yet been evaluated, such as a novel pure H₂ type PEFC-CGS and materials other than platinum, were considered. Finally, we indicate that various PEFC-CGSs can be differentiated due to the environmental impacts of GWP and ADP.

2. Methodology

2.1 Target PEFC-CGS and energy demand data

In this study, the impacts of three types of 700 W-scale PEFC-CGSs were estimated. Natural gas (Scenario 1), pure H₂ derived from natural gas steam reforming (NGSR) plants (Scenario 2), and pure H₂ derived from electrolysis with wind power (Scenario 3) were considered as the input fuel scenarios.

Table 1 shows the specifications of the FC-CGS evaluated in this study^{5) ~ 7)}, and Fig. 1 shows the system boundary. The functional unit (FU) is defined as the total demand for electricity and heat in a typical household for 10 years, including seasonal variations. For the electricity demand and hot water demand data, we referred to JISC 8851⁸⁾. These data target a standard Japanese household (a family of four). Fig. 2 shows the electricity and hot water demand patterns. Based on these energy patterns, the adequate operating condition of PEFC-CGS was selected. In this case, the FC-CGS was operated by the electric load-following method. Shortages against the demands was compensated for by the grid power and the supplementary heat generator (fueled by natural gas in all scenarios).

2.2 Inventory analysis

The inventory data of the FC-CGS were based on the annual project report of New Energy and Industrial Technology Development Organization (NEDO)⁵⁾. The inventory of the inverter, including Au in the circuit board, was based on the study by Nordelöf⁹⁾. Note that the inventory data of the inverter in the FC-CGS were assumed to be proportional to the weight of the electric vehicle parts. Regarding the GHG emission intensity of pure H₂, the document analyzed by Cetinkaya *et al.* was referred to⁷⁾.

Table 1 Specification of stationary FC-CGS^{5) ~ 7)}

Parameter	Unit	Scenario 1	Scenario 2	Scenario 3
FC type ⁵⁾	-	PEFC (Polymer electrolyte fuel cell)		
Rated output ⁵⁾	W	700		
Fuel type	-	Natural gas ⁵⁾	Pure H ₂ (NGSR plant) 0.0991 kg-CO ₂ eq./MJ-H ₂ ⁷⁾	Pure H ₂ (Wind power) 0.0081 kg-CO ₂ eq./MJ-H ₂ ⁷⁾
Presence of reformer in PEFC-CGS ⁵⁾	-	✓	-	-
Rated electric efficiency ⁵⁾ (Assuming degradation linearly by 10% in lifecycle)	%	39	55	55
Rated heat recovery efficiency ⁵⁾	%	56	35	35
Overall energy efficiency ⁵⁾ (Constant for the entire lifetime)	%	95	90	90
Minimum output ⁵⁾	W	210		
Hot water storage tank volume ⁵⁾	L	140		
Heat recovery efficiency of the supplementary heat generator ⁶⁾	%	95

Fig. 1 System boundary

(a) Electricity

(b) Hot water

Fig. 2 Energy demands in a standard Japanese household⁷⁾

Secondary data were based on Ecoinvent 3.6 and the CML-IA baseline, and they were used in the impact assessment method. The LCA software SimaPro 9.1.0.8 was used in this study.

3. Results

Fig. 3 shows the results of the environmental impact assessment. In the manufacturing of each type of FC-CGS, the stack accounted for approximately 18% of the ADP, while the inverter and the supplementary heat generator accounted for approximately 28% and 43%, respectively. The inverter and supplementary heat generator including the circuit board were considered to have a remarkable impact because of the Au consumed by the bonding wires in the integrated circuit (IC) and the Au plating on the connectors. In addition, the ADP of the natural gas reformer in PEFC-CGS (Scenario 1) was 4% and the difference in fuels fed to PEFC-CGSs did not appear.

In terms of ADP (fossil fuels), Scenario 2 had the largest impact, which was 7% higher than that of Scenario 1. Moreover, Scenario 2 showed the largest GWP of the three scenarios, which was 8% higher than that of Scenario 1. Additionally, the use of renewable energy resources in Scenario 3 resulted in the smallest ADP (fossil fuels) and GWP.

4. Discussions

4.1 Issues of differentiating by circuit boards

Although the ADP of the circuit boards was significant, it was difficult to quantify this value because of the variation in the amounts of rare metals used. To compare the differences between the literature, Nordelöf's⁹⁾ and

(a) ADP [kg-Sb eq./FU] (manufacturing stage)

(b) ADP [MJ-fossil fuels/FU] (manufacturing and use stages)

(c) GWP [kg-CO₂ eq./FU] (use stage)

Fig. 3 Results of the impact assessment

Tschümperlin's¹⁰⁾ inventory data on inverters were referred to. The inverter mass was calculated based on an output power of 700 W using equation (1)^{10) 11)}.

Fig. 4 ADP deviation on the inverter specification difference

$$M = 6.03 \times P^{0.68} \quad (1)$$

where M [kg] and P [kW] are the total mass of the inverter components and the output power through the inverter, respectively.

As shown in Fig. 4, the values were largely different. Thus, the superiority of the products cannot be indicated, because a quantitative comparison cannot be obtained. In addition, it is also difficult to determine the exact amount of Au used in the IC and connectors on circuit boards because of the difficulty in obtaining confidential information from manufacturers. Hence, treating the ADP of circuit boards as an index to differentiate between products from an environmental perspective may not be practical.

4.2 Differentiation by cell stacks manufacturing

Next, based on Section 4.1, we focused on the cells that make up the stack because the stack had the second largest impact on ADP at the manufacturing stage, after the components including the circuit board. In addition, this impact was related to electric efficiency and contributed to GWP. According to Arai *et al.*¹²⁾, although the amount of Pt consumption (mg/cm²) of the cell is the same, the cell performance can be improved by applying the catalyst ink in a gradation structure in the thickness direction (Fig. 5). These structures are formed on the catalyst layer of the cathode electrode via electrospray deposition.

In this study, three types of structures were considered and compared: one without a gradient structure (single layer) and two with a gradient structure (two layers and three layers). Although the Pt density of the cell was equal for these three types of structures (0.3 mg/cm²), the multilayer structure improved the cell performance by distributing more catalyst particles on the electrolyte membrane (upper part of Fig. 5). Fig. 6 shows a comparison of the I-V curves of the cells with different catalyst layer

Fig. 5 Structures of cathode electrode ¹²⁾ Fig. 6 The I-V curves in the three types of cathode cells ¹²⁾Table 2 Specification of the designed cell stack and auxiliaries ^{12) 13)}

	Case 1 (Single layer)	Case 2 (Two-layers)	Case 3 (Three-layers)
Minimum voltage of a cell [V]	0.649	0.648	0.651
Maximum current density of a cell [mA/cm ²]	300 ¹²⁾	320 ¹²⁾	340 ¹²⁾
Inverter efficiency		0.90 ¹³⁾	
Reforming efficiency		0.90 ¹³⁾	
Fuel utilization efficiency		0.85 ¹³⁾	
Number of cells in the stack		20	
Area of a cell [cm ²]	9.99	9.37	8.79
Pt loading (anode + cathode) [mg/cm ²]		0.600 ¹²⁾	
Total amount of Pt consumption [g]	0.120	0.112	0.105

Fig. 7 Comparison of ADP in the manufacturing stage and GWP in the use stage

structures.

Based on the I-V curves shown in Fig. 6, a stack was designed for each catalyst layer structure to match the power output of the PEFC system in this study (Table 2). The minimum operating voltage of a single cell was determined to be 0.65 V from the hearing.

For the three types of stacks shown in Table 2, we evaluated the environmental impacts per functional unit for the natural gas type PEFC-CGS. Fig. 7 shows the environmental impacts of ADP in the manufacturing stage and GWP in the use stage of the three different types of

cell stacks. Note that the environmental impact results are normalized (i.e., the result of Case 1 in each category is 1.0). The GWP value did not change because the cell voltages at the same output were almost identical. However, the ADP value of the multilayer stacks decreased with decreasing cell area.

5. Conclusions

In this study, we first followed the method proposed by TC105 WG14 to evaluate the environmental impacts of PEFC-CGSs in terms of ADP and GWP. In terms of ADP at manufacturing stage, the stack accounted for about 18%, while the inverter and the supplementary heat generator accounted for approximately 28% and 43%, respectively. We also evaluated the deviation of ADP in devices that included the circuit boards, based on two studies, and provided an explanation for the difficulty in differentiating products by Au. Therefore, we focused on the stack and confirmed that differentiation between PEFC-CGSs could be achieved in terms of ADP by examining the manufacture of the catalyst layers. That is, three layers cathode electrode type showed 12% lower ADP than conventional single layer electrode.

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Appendix

The total global warming potential (GWP) for the target duration (10 years) in the use stage was calculated as follows:

$$GWP_{\text{total}} = \sum_{i=1}^{10} \left[\frac{NEP_{\text{FC}}}{\eta_{\text{el FC } i}} \times GWP_{\text{fuel FC}} + NEI \times GWP_{\text{el G}} + \frac{STED_i}{\eta_{\text{th S}}} \times GWP_{\text{fuel S}} \right].$$

Where,

i : number of years of use;

NEP_{FC} : total annual net electricity production of the fuel cell, FC (kWh electricity per year);

NEI : net annual electricity imported from the grid (difference between total electricity demand and electricity generated by the fuel cell) (kWh electricity per year);

$STED_i$: annual supplementary thermal energy demand in year i (kWh thermal energy per year);

$\eta_{\text{el FC } i}$: electric efficiency of the fuel cell, FC, in year i (kWh electricity generation per kWh inlet fuel);

$\eta_{\text{th S}}$: heat recovery efficiency of the supplementary heat generator, S (kWh heat generation per kWh inlet fuel);

GWP_{fuel} : GWP of the fuel used in the fuel cell, FC, or the supplementary heat generator, S (kg-CO₂ eq. per kWh-fuel);

$GWP_{\text{el G}}$: GWP of the electricity grid, G, in the geographical region where the stationary fuel cell power system is operated (kg-CO₂ eq. per kWh-electricity);

GWP_{total} : total global warming potential (kg-CO₂ eq.)

The total abiotic depletion potential (ADP) for the target duration (10 years) in the manufacturing stage was calculated as follows:

$$ADP_{\text{total}} = \sum_k ADP_k \times m_k.$$

Where,

ADP_{total} : total abiotic resource depletion potential (ADP) (kg-Sb eq.);

ADP_k : abiotic resource depletion potential of resource k (kg-Sb eq. per kg-resource);

m_k : the quantity of resource k extracted (kg).

The total abiotic depletion potential of fossil fuels (ADP [fossil fuels]) for the target duration (10 years) in the manufacturing and use stage was calculated as follows:

$$ADP(\text{fossil fuels})_{\text{total}} = \sum_k ADP_k \times m_k.$$

Where,

$ADP(\text{fossil fuels})_{\text{total}}$: total abiotic resource depletion potential of fossil fuels (ADP fossil fuel) (MJ);

ADP_k : abiotic resource depletion potential of resource k ;

m_k : quantity of resource k extracted (MJ).