A region-specific environmental analysis of technology implementation of hydrogen energy in Japan based on life cycle assessment

Teruyuki Shimizu1 | Kei Hasegawa2 | Manabu Ihara2 | Yasunori Kikuchi1,3,4

1 Presidential Endowed Chair for “Platinum Society”, University of Tokyo, Bunkyo-ku, Tokyo, Japan
2 Department of Chemical Science and Engineering, Tokyo Institute of Technology, Meguro-ku, Tokyo, Japan
3 Department of Chemical System Engineering, University of Tokyo, Bunkyo-ku, Tokyo, Japan
4 Integrated Research System for Sustainability Science, University of Tokyo Institutes for Advanced Study, Bunkyo-ku, Tokyo, Japan

Correspondence
Yasunori Kikuchi, Presidential Endowed Chair for “Platinum Society,” University of Tokyo, Bunkyo-ku, Tokyo, Japan.
Email: ykikuchi@ifl.u-tokyo.ac.jp

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Abstract
Energy systems using renewables with adequate energy carriers are needed for sustainability. Before accelerating technology implementation for the transition to the new energy system, region-specific implementation effects should be carefully examined as a system. In this study, we aim to analyze an energy system using hydrogen as an energy carrier with the approach of combining life cycle assessment and a regional energy simulation model. The model calculates the emissions, such as CO$_2$, nitrogen oxides (NOx), sulfur oxides (SOx), and volatile organic compounds, and their impacts on human health, social assets, primary production, and an integrated index. The analysis quantitatively presented various environmental impacts by region, life cycle stage, and impact category. Climate change was dominant on the integrated index while the other impact categories were also important. Fuel cell vehicles were effective in mitigating local air pollution, especially in high-population regions where many people are adversely affected. Although technology implementation contributes to mitigating environmental impacts at locations of energy users, it also has possibilities to have negative impacts at locations of device manufacturing and raw material processing. The definition of the regional division was also an important factor in energy system design because the final results of life cycle assessments are highly sensitive to region-specific characteristics. The proposed region-specific analysis is expected to support local governments and technology developers in designing appropriate energy systems for regions and building marketing plans for specific targets.

KEYWORDS
fuel cell vehicle, hydrogen energy system, industrial ecology, life cycle impact assessment method based on endpoint modeling (LIME), region-specific characteristics, urban employment area

1 INTRODUCTION

Renewables-based energy systems are greatly needed for sustainability, mitigating global warming, resource depletion, and energy security. Photovoltaic (PV) and wind turbine power generation have been rapidly installed all over the world (IEA, 2017), although such power generations have issues of stable power supply because of their intermittent generation characteristics (Armaroli & Balzani, 2011). A wide range of measures to accommodate a large amount of intermittent renewable electricity has been studied (Lund, Lindgren, Mikkola, & Salpakari, 2015), for example, demand-side management, storage, thermal power plant response, curtailment of renewable-based electricity, and development of grid transmission capability. Energy carriers (ECs) can facilitate the storage and transport of renewable-based energy for applications in energy demands such as vehicles (International Energy Agency [IEA], 2015).
Region-specific characteristics have a strong influence on the implementation effects because regions in a country have different characteristics in terms of resource availability, climate conditions, existing equipment for energy use, current energy mix, and environmental conditions (Min, Azevedo, & Hakkarainen, 2015). Model-based simulations and optimizations have been applied to the analysis and design of energy systems considering region-specific characteristics (Agnolucci & McDowall, 2013), for example, industrial symbiosis with combined heat and power on the island of Tanegashima in Japan (Kikuchi, Kanematsu, Ugo, Hamada, & Okubo, 2016) and an energy system in an Italian Alpine valley (Mahbub, Viesi, & Crema, 2016). Scale and location designs of facilities by optimization models were performed in France (De-León Almaraz, Azzaro-Pantel, Montastruc, & Boix, 2015) and in the United Kingdom (Samsatli, Staffell, & Samsatli, 2016). The influence of region-specific characteristics (e.g., climate, technologies used for heating and cooling, electricity fuel mix, and electricity prices) on technology replacement was investigated in the United States (Min et al., 2015).

While many studies on ECs have performed environmental analysis focusing on greenhouse gas (GHG) emissions (e.g., Reuß et al., 2017), there has been insufficient research on the other emissions. The other emissions, such as nitrogen oxides (NOx), sulfur oxides (SOx), and nonmethane volatile organic compounds (NMVOCs) are also important for the power generation (Turconi, Boldrin, & Astrup, 2013) and transport sectors (Singh, Guest, Bright, & Strømman, 2014) because they cause site-specific damage not only to human health but also to resources and ecological systems. Life cycle assessments (LCAs) have been used to analyze a wide range of emissions from entire systems inside boundaries and to quantify their environmental impacts (Valente, Iribarren, & Dufour, 2017). However, data on emissions such as NOx from unit processes are often more difficult to obtain than for GHG emissions. The GHG emissions from many processes are available in journal papers and reports. In addition, foreground CO2 emissions can be estimated based on the mass balance of the carbon component in fuels. By contrast, other emission data have not been reported much, and they are often difficult to estimate from the mass balance; for example, NOx emissions include thermal NOx from the air and SOx is often partially removed by treatment processes, whereas the life cycle inventory databases (e.g., ecoinvent (ecoinvent, 2014) and IDEA (AIST & JEMAI, 2015)) can be used to learn about various emissions; emission data on emerging technologies tend to be insufficient. Inventories of such emerging technologies need to be organized through literature research or measurements on processes.

Hydrogen as an EC is at an emerging phase of its related technology implementation and infrastructure construction. For example, around 56,000 units (213.5 MW) and 12,000 units (455.7 MW) of fuel cell products were shipped around the world in 2016 in stationary and transport applications, respectively (E4Tech, 2017). In Japan, the Strategic Roadmap for Hydrogen and Fuel Cells (ANRE, 2014) and the Basic Hydrogen Strategy (MCRE, 2017) were presented. Some regions in Japan have visions or roadmaps to implement technologies and build infrastructure for their future energy systems (e.g., Aichi Prefecture (2018) and Fukushima Prefecture (ANRE, 2017)) and have taken actions to implement technologies and execute projects (e.g., Hokkaido Prefecture, 2018; Kanagawa Prefecture, 2017). While implementing technologies associated with hydrogen energy is under consideration or has already started in many regions, such technologies would have long-term influences on the regional environment, residents’ lives, and economy. Before accelerating technology implementation, sophisticated region-specific assessment is strongly needed.

This paper aims to analyze the region-specific implementation effects of emerging hydrogen-related technologies. Diverse values of technology implementation are explored by assessing various environmental impacts induced by multiple emissions, not just CO2. The implementation effects are examined based on the combination of LCA and a regional simulation model to calculate the life cycle inventories of systems configured with emerging technologies that vary between regions in Japan. A region-specific analysis for implementing technologies of fuel cell vehicle (FCV) and stationary fuel cell cogeneration systems for household use (FCCGh) combined with fuel gas steam reforming (FGSTR) and water electrolysis with PV electricity (PVWE) was performed with the previously developed model (Shimizu et al., 2019). The model was expanded to include other emissions such as NOx, SOx, and NMVOCs, which were obtained from the analysis of inventories of emerging technologies, to assess their impacts. Through LCA of such technology implementation, the relationship between region-specific characteristics and environmental impacts of the implementation are specified, which could help municipalities and technology developers to design appropriate energy systems for regions and build marketing plans for specific targets.

2 METHODS

2.1 The region-specific analysis

The region-specific analysis on technology implementation equipping hydrogen energy was performed by LCA combined with the expanded regional simulation model (Shimizu et al., 2019) (hereinafter, region energy model (REM)). This model was used because region-specific characteristics were considered in the simulation of energy systems in Japan and could be expanded to obtain inventories of emissions, which are then connected with an impact assessment. A region-specific environmental analysis was performed as presented in Figure 1. The inputs to the model were region-specific data and the setting parameters. From simulations with REM based on energy balance, the emissions from the processes, energy flows, and the scales of the implemented and replaced equipment were calculated as the output of the model. Life cycle impact analysis (LCIA) was performed based on the output inventory and the impact factor set of the life cycle impact assessment method based on endpoint modeling for Japan (LIME2), which is available in JLCA (2013). Finally, the LCIA results were visualized by region with bar charts and geographical maps. According to the results, the regions were colored on maps by the geographic information system (GIS), ArcGIS 10.4 for desktop.
Region-specific parameters presented on the left periphery in Figure 1 include generation patterns of renewables, use patterns of end-use equipment such as cars and electric devices, the maximum numbers of technology units to be implemented, and grid power inventories acquired from the literature with some estimations. Such regional differences can affect the energy use patterns and technology implementation scales, and would result in different emissions and impacts. Impact factors of urban area air pollution and the creation of photochemical oxidants were also treated as region-specific parameters because they are affected by site-specific conditions such as climate and demographics, while impact factors of climate change and acidification were not treated as region-specific but as setting parameters (Figure 1 depicts two kinds of impact factors as region-specific and setting parameters).

2.2 Goal and scope definition

Table 1 summarizes the goal and scope of this study. Four combinations of technology implementations associated with hydrogen as an EC were considered for this study; that is, FGSTR and PVWE for hydrogen production and FCCGh and FCV for hydrogen utilization. Life cycles of both EC and equipment were considered in the system boundary for LCA, as represented in Figure 2. The EC life cycle, which is also called well-to-wheel in the field of vehicle LCA (Nordelöf, Messagie, Tillman, Ljunggren Söderman, & Van Mierlo, 2014), includes production, transport, and utilization of hydrogen. Equipment life cycles include raw material processing, equipment manufacturing, and equipment utilization. At the transport stage, only emissions corresponding to energy inputs to compress hydrogen for storage were considered, assuming on-site hydrogen production (i.e., zero distance transport) because designing locations of hydrogen production and utilization was not the main aim of this study. The future situation, in which FCCGh and FCV are penetrated 10% instead of conventional technologies, was assumed although the current technological parameters were used because technological forecasts are out of the scope.

The prefectures and the urban employment areas (UEAs) of Japan were adopted as regional divisions that define the regional boundaries of the analysis. The prefecture is an administrative division in Japan, and UEAs are functional divisions proposed by Kanemoto and Tokuoka (2002) regarding municipalities, which are strongly connected with each other by commuting, as a region. A UEA consists of a core area with significant concentrations of employment and surrounding densely settled areas with close commuting ties with the core. Municipalities have been classified into UEAs in the previous study according to this definition (Shimizu et al., 2019). The UEAs cover about 88% of the population in Japan, whereas some municipalities are not classified into any UEA and were excluded from the UEA analysis in this study. In Japan, there are 247 UEAs with an average area of about 866 km$^2$ and 47 prefectures with an average area of 7,926 km$^2$. UEAs were adopted expecting to have intensive
**TABLE 1** Settings for life cycle assessment (LCA)

| Items                                      | Settings                                                                                                                                                                                                 |
|--------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Life cycle background inventory data       | IDEA v2 (AIST & JEMAI, 2015), ecoinvent v3.1 (ecoinvent, 2014). (See also Tables S1 and S3 in the Supporting Information for the cumulative environmental loads of main inventories) |
| Life cycle foreground inventory data       | Implementation amount and fuel consumption in each region are estimated by region energy model (REM)                                                                                                      |
| Life cycle boundary inventory data         |                                                                                                                                             |
|                                                                 | Cradle to grave for energy-carrier (EC) life cycle                                                                                           |
| Assumed time frame                         | The future, when the hydrogen-related technologies have penetrated to 10%, but the current status was used for technological parameter settings                                                                 |
| Functional unit                            | One-year use of alternative technologies with 10% replacement for the conventional technologies                                                                                                         |
| Technical information                      | Refer to Table S2 in the Supporting Information                                                                                              |
| Region-specific characteristics            | 47 prefectures and 247 urban employment areas (UEAs) in Japan (refer to Table S3 in the Supporting Information)                                                                                          |
| Emission substances                        | CO₂, CH₄, N₂O, NOₓ, SOₓ, HCl, NH₃, nonmethane volatile organic compounds (NMVOCs)                                                             |
| Life cycle impact factors                  | <midpoint>                                                                                                                                  |
|                                                                 | – Climate change                                                                                                                            |
|                                                                 | – Acidification                                                                                                                            |
|                                                                 | – Urban area air pollution                                                                                                                  |
|                                                                 | – Photochemical oxidant creation                                                                                                             |
|                                                                 | <endpoint>                                                                                                                                  |
|                                                                 | – Human health damage                                                                                                                       |
|                                                                 | – Social asset damage                                                                                                                       |
|                                                                 | – Primary production damage                                                                                                                  |
|                                                                 | – LIME index (integrated single index)                                                                                                      |
|                                                                 | Refer to (JLCA, 2018) for details of the LIME2 impact factors. See Table S3 in the Supporting Information for the region-specific impact factors. The specific values of the LIME2 impact factors are available in JLCA (2013). |
| Direct applications of LCA results         | – Strategy planning to develop a region-specific energy system                                                                            |
|                                                                 | – Design of the appropriate regional division for technology implementation                                                                |
| GIS software                               | ArcGIS 10.4                                                                                                                                  |

**FIGURE 2** Energy system boundary considered in this study
region-specific characteristics, while prefectures show averaged characteristics because they contain both urban and rural areas. The design of the appropriate regional division for technology implementation is discussed through the analysis of these two types of regional divisions.

### 2.3 Description of the region energy model

The previously developed model (Shimizu et al., 2019) was expanded for this study to calculate inventories of various emissions by acquiring information from the inventory database and literature. The REM is described with equations in this section, and the expanded part is further discussed in the next section.

Production, transport, and utilization of the EC are balanced in a region, according to:

\[
\theta_{i,r} \cdot P_{i,r}^{EC} = U_{i,r}^{EC} = T_{k,r}^{EC},
\]

where \(P_{i,r}^{EC}\), \(U_{i,r}^{EC}\), and \(T_{k,r}^{EC}\) represent the maximum annual EC production (in units of \(J/\text{year}\)), annual EC utilization (\(J/\text{year}\)), and annual EC transport (\(J/\text{year}\)), respectively, \(\theta_{i,r}\) is the ratio of the actual EC production to the maximum production (dimensionless), subscript \(r\) represents region, and subscripts \(i, j, \) and \(k\) represent production and utilization technology and transport mode of the EC, respectively. See Table 2 for the full nomenclature used in this article. The actual EC production is adjusted by \(\theta_{i,r}\) so as to match demand. The amount of EC utilization is derived from the numbers of implemented technologies, \(N_{i,r}\) (dimensionless), conversion efficiency of the technologies, \(\eta\) (dimensionless), and utilization rate of the technologies, \(\beta_{j,r}\) (dimensionless), according to:

\[
U_{j,r}^{EC} = f_j \left(N_{j,r}, \eta, \beta_{j,r}\right).
\]

The function \(f_j\) is different between FCCGh and FCV. FCCGh is assumed to be operated so as not to generate excess electricity or hot water to meet the region-specific demand for electricity and hot water in each household because many cogeneration systems in Japan are operated without transferring excess power and heat. The utilization ratio of FCV is determined by the region-specific annual travel distance per car. The number of implemented technologies, \(N_{j,r}\), is determined by specifying the implementation ratio, \(a_j\) (dimensionless), according to:

\[
N_{j,r} = a_j \cdot N_{j,r}^*.
\]

where \(N_{j,r}^*\) represents the potential implementation number of technology \(j\) in region \(r\) (dimensionless), for example, the numbers of owned normal passenger cars and of families for FCV and FCCGh implementation. For this study, \(a_j = 0.1\) was specified. With this implementation ratio, no limitation of resource availability was assumed because, in all regions, the demands are below the potential PV generation availabilities derived from MOE (2013).

Based on the EC balance, emission changes by technology implementation, \(E_{i,r}^{total}\) (kg-CO\(_2\)/eq/\text{year}) are calculated from life cycle emissions at each stage, according to:

\[
E_{i,r}^{total} = \theta_{i,r} \cdot E_{i,r}^{prod} + E_{i,r}^{util} + E_{i,r}^{trans},
\]

where \(E_{i,r}^{prod}\), \(E_{i,r}^{util}\), and \(E_{i,r}^{trans}\) represent emissions at production, utilization, and transport stages, respectively (kg-CO\(_2\)/eq/\text{year}). The emissions at production and transport stages are represented by the following equations,

\[
E_{i,r}^{prod} = \phi_{i,r}^{prod} \cdot P_{i,r}^{EC},
\]

\[
E_{i,r}^{trans} = \phi_{i,r}^{trans} \cdot T_{k,r}^{EC} \cdot TD + \phi_{i,r}^{trans,ND} \cdot T_{k,r}^{EC},
\]

where \(\phi_{i,r}^{prod}\) represents the coefficient of GHG emission per unit EC production (kg-CO\(_2\)/eq/J), and while both \(\phi_{i,r}^{trans}\) and \(\phi_{i,r}^{trans,ND}\) represent the coefficient of GHG emission per unit EC transport, the former is dependent on transport distance (kg-CO\(_2\)/eq/J/km) and the latter is independent of transport distance (kg-CO\(_2\)/eq/J). TD represents EC transport distance (km). For this study, \(TD = 0\) was specified assuming on-site EC production. At EC utilization stage, GHG emissions reductions by replacement of the existing or alternative technologies are considered, for example, gasoline-fueled internal combustion engine vehicle (ICEV) is replaced by FCV and use of grid power and fuel gas (i.e., city gas and liquefied petroleum gas) for the hot water supply are replaced by FCCGh. GHG emissions at the utilization stage are calculated as follows:

\[
e_{i,r}^{util} = E_{i,r}^{util,decrease} - E_{i,r}^{util,increase},
\]
TABLE 2 Nomenclature

| Parameter | (Unit) | Description |
|-----------|--------|-------------|
| $E_{i,r}^{U}$ | (kg-substance/year) | Annual emission of substance $s$ at energy-carrier (EC) production by technology $i$ in region $r$ |
| $E_{j,r}^{U}$ | (kg-substance/year) | Annual emission of substance $s$ at EC utilization by technology $j$ in region $r$ |
| $E_{j,r}^{U,\text{increase}}$ | (kg-substance/year) | Annual increase in emission of substance $s$ by implementation of technology $j$ in region $r$ |
| $E_{j,r}^{U,\text{decrease}}$ | (kg-substance/year) | Annual decrease in emission of substance $s$ by replacement of conventional technology with EC utilization technology $j$ in region $r$ |
| $E_{k,r}^{T}$ | (kg-substance/year) | Annual emission of substance $s$ at EC transport by transport mode $k$ in region $r$ |
| $N_{r,j}$ | (−) | Number of implemented devices on EC utilization technology $j$ in region $r$ |
| $N_{r,j}^*$ | (−) | Potential implementation number of technology $j$ in region $r$ |
| $\mu_{SC_j}$ | (J/year) | Amount of the maximum EC production from technology $i$ in region $r$ |
| $\tau_{EC_j}$ | (J/year) | Amount of EC transport by technology $k$ in region $r$ |
| $\mu_{EC_j}$ | (J/year) | Amount of EC utilization by technology $j$ in region $r$ |
| $TD$ | (km) | EC transport distance |
| $\eta_j$ | (−) | Implementation ratio of EC utilization technology $j$ |
| $\eta_j$ | (−) | Conversion efficiency of technology $j$ |
| $\delta_j$ | (−) | Utilization rate of technology $j$ in region $r$ |
| $\theta_j$ | (−) | Ratio of the actual EC production to the maximum EC production from technology $i$ in region $r$ |
| $\tau_j$ | (year) | Lifetime of technology $j$ |
| $\phi_{j,use}^{mfg}$ | (kg-substance/unit) | Emission coefficient of substance $s$ in manufacturing technology $j$ |
| $\phi_{j,use}^{TD}$ | (kg-substance/J) | Emission coefficient of substance $s$ per unit EC production by technology $i$ in region $r$ |
| $\phi_{j,use}^{TD}$ | (kg-substance/J/km) | Distance-dependent emission coefficient of substance $s$ per unit EC transported by transport mode $k$ in region $r$ |
| $\phi_{j,use}^{TD,ND}$ | (kg-substance/J) | Distance-independent emission coefficient of substance $s$ per unit EC transported by transport mode $k$ in region $r$ |
| $\phi_{j,use}^{use}$ | (kg-substance/J) | Emission coefficient of substance $s$ per unit EC utilized by technology $j$ in region $r$ |
| $f_j$ | (−) | Function of EC utilization by technology $j$ |

Additional characters

- $i$ EC production technology
- $j$ EC utilization technology
- $j^0$ Technology replaced by technology $j$
- $k$ EC transport mode
- $r$ The target region in which the technology is implemented
- $s$ Emission substance

where $E_{i,r}^{U,\text{increase}}$ and $E_{j,r}^{U,\text{decrease}}$ represent the emissions increase by the implemented technology and emissions decrease by replacement of the conventional technology, respectively (kg-CO$_2$eq/year). The emissions increase and decrease include emissions at the manufacturing and using technologies, according to

$$E_{j,r}^{U,\text{increase}} = \phi_{j,use}^{mfg} \cdot N_{j,r} / \tau_j + \phi_{j,use}^{use} \cdot f_j \left( N_{j,r}, \eta_j, \delta_j, \eta_j^0, \phi_{j,use}^{mfg}, \phi_{j,use}^{use}, \phi_{j,use}^{mfg} \right),$$

$$E_{j,r}^{U,\text{decrease}} = \sum_{j^0} \left( \phi_{j^0,use}^{mfg} \cdot N_{j^0,r} / \tau_{j^0} + \phi_{j^0,use}^{use} \cdot f_j \left( N_{j^0,r}, \eta_{j^0}, \delta_{j^0}, \eta_j, \phi_{j^0,use}^{mfg}, \phi_{j^0,use}^{use}, \phi_{j^0,use}^{mfg} \right) \right).$$

where $\phi_{j,use}^{mfg}$, $\phi_{j,use}^{use}$, and $\tau_j$ represent the coefficient of GHG emissions per unit production of technology $j$ (kg-CO$_2$eq/unit) and per unit EC utilization by technology $j$ (kg-CO$_2$eq/J), and lifetime of technology $j$ (year), respectively. The subscript $j^0$ means conventional technology replaced by implemented technology $j$ (e.g., ICEV, grid power, and water heater using fuel gas). The numbers and utilization rate of replaced conventional and implemented technologies are assumed to be the same. When FCCGh is implemented, two types of technologies, grid power and water heaters, are replaced. Because the power supply from the grid and the heat supply from water heaters are supposed to be only partially, not fully replaced.
by FCCGh, a decrease in GHG corresponding only to the usage stages of the grid power and water heaters is considered, excluding their manufacturing stages. The amount of power or heat provided by EC utilization technology is the same as the amount of replaced power or heat provided by conventional technology, for example, the total transport distances of implemented FCV and replaced ICEV are the same but the total fuel consumption depends on their specific efficiencies.

The specific values assigned in this study are summarized in Supporting Information S2 (Tables S2-1 through S2-3).

### 2.4 Model expansion for life cycle inventory analysis and impact assessment

As a model expansion, the emissions described in Equations (4)–(9) were changed to be calculated by substance, that is, emissions and coefficients of emissions were changed to obtain inventories of substances as \( \phi_{\text{total}}^{P}, \phi_{\text{total}}^{T}, \phi_{\text{total}}^{\text{increase}}, \phi_{\text{total}}^{\text{decrease}}, \phi_{\text{total}}^{\text{ND}}, \phi_{\text{total}}^{\text{mfg}}, \phi_{\text{total}}^{\text{use}}, \phi_{\text{total}}^{\text{f},s}, \phi_{\text{total}}^{\text{mfg},s} \), where the subscript \( s \) represents emission substance. The emissions of \( \text{CO}_2, \text{CH}_4, \text{N}_2\text{O}, \text{NOx}, \text{SOx}, \text{HCl}, \text{NH}_3, \) and \( \text{NMVOCs} \) were quantified. These emissions were selected based on the significance of the problems faced by the existing energy systems. NOx and SOx, which cause air pollution and acidification, are emitted from fossil-fuel thermal power plants. Automobiles had a contribution to emissions of NOx and NMVOCs, which leads to the creation of photochemical oxidants. CH\(_4\), N\(_2\)O, HCl, and NH\(_3\) were included because they also have impacts on global warming, air pollution, and acidification.

LIME2 (Itsubo & Inaba, 2012; JLCA, 2013) was used here as an impact assessment method. The midpoints, climate change, acidification, air pollution in urban areas, and photochemical oxidant creation were considered for quantifying the damage from substances to human health, social assets, and primary production, with the index of disability-adjusted life year (DALY), Japanese yen (JPY), and net primary production (NPP), respectively. The LIME single index as an external cost in JPY was also used to integrate the impacts of damages. To calculate the LIME index, the weight for each impact factor was specified based on the social preferences of the Japanese people (JLCA, 2018).

Site-specific impact factors of urban area air pollution and the creation of photochemical oxidants are provided in LIME2 (Itsubo & Inaba, 2012; JLCA, 2013) based on the analysis of the fate of and exposure to emission substances—concentrations of substances in air and the amounts of their damages are affected by the climate conditions and distributions of the protection objects (e.g., population distribution) at the emission sites. In this study, these site-specific impact factors were used for impact assessment as a region-specific parameter (see the left side of Figure 1), while the impact factors of global warming and acidification did not differ by region as a setting parameter (see top of Figure 1 and also Table S3 in the Supporting Information for the detailed settings of LIME2). The average impact factors for Japan were applied to the emissions at all stages of device manufacturing and raw material processing because the emissions did not always occur in the regions where the manufactured devices were used.

### 2.5 Life cycle inventory data acquisition

The coefficient of emissions by substance, for the model expansion, was acquired in each process from the inventory databases, journal papers, and relevant reports. The inventory database for environmental analysis in Japan (IDEA v2) (AIST & JEMAI, 2015) was used to analyze the inventories of equipment manufacturing and fuel use, including emissions in background processes such as the processing of raw materials, fuels, and electricity. Inventories of some processes, such as PVWE, fuel cell cogeneration system, and FCV, were partly obtained from the literature (Evangelisti, Tagliaferri, Brett, & Lettieri, 2017; NEEDS, 2008; Zhang, Bauer, Mutel, & Volkart, 2017). Only input and output inventories on the unit processes of PV (ecoinvent, 2014) and fuel cell (NEEDS, 2008) were used. Cumulative emissions induced by raw materials and utilities required for the unit processes were extracted from IDEA v2. Refer to Table S1 in the Supporting Information for the cumulative environmental loads of the main inventories.

### 3 RESULTS

#### 3.1 LCA results in the area of protection

The LCA results on human health damage are shown in Figure 3. Four combinations of technologies in four prefectures were assessed by different life cycle stages and impact categories. As a brief description of the prefectures in Japan, Hokkaido is the northernmost and coldest-climate prefecture with the largest area, Tokyo is the largest city with the largest population density, Fukuoka is a relatively urban prefecture (ninth-largest in population), and Okinawa is the southernmost and warmest-climate island prefecture and is located far from other prefectures (see Table S3 in the Supporting Information for detailed characteristics of these regions).

As the overall trend throughout the four technology combinations and four regions, the patterns of the net impacts and the breakdown structures by region were different. Climate change was the dominant impact category in every technology combination and in every region. The impact induced by GHG emissions was much larger than for other emissions due to a large volume of CO\(_2\) emission (two orders of magnitude larger than other emissions), whereas the impact factor of CO\(_2\) to human health damage was lower than that of NOx, SOx, and NMVOCs in all regions (from...
FIGURE 3  Life cycle assessment (LCA) results on human health damage for implementation of (a) fuel gas steam reforming (FGSTR) and stationary fuel cell cogeneration systems for household use (FCCGh), (b) water electrolysis with photovoltaic electricity (PVWE) and FCCGh, (c) FGSTR and fuel cell vehicle (FCV), and (d) PVWE and FCV implemented in four regions, that is, Hokkaido, Tokyo, Fukuoka, and Okinawa. The breakdown structures of impact changes in each life cycle stage and each impact category are represented by different colors and fill patterns. The positive side of the vertical axis means damage increase and the negative side means damage reduction by replacing the conventional technologies and their energy use. The net life cycle impacts are plotted with red-outlined diamonds. The values in the parentheses next to the region names represent 1/1,000 of the number of implemented FCCGh or FCV units, which is equal to 10% of the numbers of families or normal passenger vehicles in the regions. The underlying data for this figure are provided in Supporting Information S2.

About 1/1,000 to 1/10. This is partly because NOx and SOx are often removed to low concentration levels (e.g., by flue-gas treatment in power plants) and CO2 is often emitted directly. Air pollution in urban areas made the second-largest contribution to human health damage (about 30% at a maximum depending on regions and life cycle stages), while photochemical oxidant creation made little contribution. Air pollution in urban areas is mainly caused by SOx and NOx emissions from fuel gas and gasoline production in refinery plants, driven ICEV, power generation at thermal power plants, and fuel input in device manufacturing and raw material processing.

Comparing the systems with fossil-derived hydrogen (Figure 3a,c) with those with PV-derived hydrogen (Figure 3b,d), the damage increase in hydrogen production by FGSTR was larger than that by PVWE because of CO2 emission from fossil fuels. Damages were relatively small in manufacturing PV and electrolyzer. Air pollution in urban areas induced by hydrogen production with PVWE was larger than with FGSTR, partly because SO2 is emitted from heavy oil combustion as energy input in manufacturing and raw material processing, for example, production processes of glasses for PV panels, silicon carbide used for slicing silicon ingots in PV wafer production, and metallurgical silicon before purification for solar- or electronics-grade material. For PVWE implementation, the contribution of hydrogen compression, in which grid power was used, to hydrogen production was larger than that for FGSTR implementation.

Compared with FCV implementation (Figure 3c,d), FCCGh implementation (Figure 3a,b), which has a different axis scale, shows the effect of positive implementation in terms of human health damage. The net changes in life cycle damage were near zero in all regions for the FGSTR and FCCGh combination, as observed in Figure 3a. FCCGh implementation reduced the damage attributed to the replacement of grid power utilization...
more than that of fuel gas utilization. FCV implementation reduced damages mainly by replacing gasoline use. Damage increase by FCV manufacturing was larger than damage reduction by replacing ICEV manufacturing, while the damage increase by FCCGh manufacturing was small.

Figure 3d shows that the implementation of PVWE and FCV caused fewer changes in net damage. There are four possible reasons why PVWE and FCV implementation did not lead to damage reduction despite renewable-derived energy use. First, the car utilization ratios are low, which made the contribution of the manufacturing stage large. Second, replaced gasoline is not large because replacing the latest high-fuel-economy ICEV was assumed in this study. Third, the environmental impact in FCV manufacturing is larger than that in ICEV manufacturing because of energy-intensive fuel cell stacks and hydrogen tanks. Fourth, hydrogen compression consumes substantial electricity, which is supplied from the grid power.

In the simulation, the LCA results can be varied by the assigned value for each parameter, which is further examined in the Discussion.

Focusing on the difference between regions in PVWE and FCCGh implementation in Figure 3b, Tokyo damage reduction was the largest, followed by that in Hokkaido, Fukuoka, and Okinawa. This is consistent with the order of the implementation amounts by region (the values in the parentheses next to the prefecture names in Figure 3), which indicates that damage reduction depends on the demand sizes in the region. Damage reductions per unit FCCGh were 0.24, 0.16, 0.19, and 0.31 DALY/(year⋅10^3 unit) in Hokkaido, Tokyo, Fukuoka, and Okinawa, respectively. GHG emission factors of the power grid in Hokkaido and Okinawa are 1.3 and 1.5 times as high, respectively, as the average emission factor of the 10 representative electric power companies in Japan, which incentivize low carbon generation.

In Figure 3d, for PVWE and FCV implementation, the area ratio of gasoline use reduction to the total area in Okinawa is larger than that in other regions because it has the longest annual travel distance per car—13, 9.3, 16, and 27 (10^3 km/year/car) in Hokkaido, Tokyo, Fukuoka, and Okinawa, respectively—and the highest utilization ratio of a car among regions. In descending order, Hokkaido, Fukuoka, and Tokyo had large damage at hydrogen compression, while the damage reductions at replaced gasoline utilization were within 1% of each other. This corresponds to the descending order of GHG emission factors of the grid powers in the three regions because substantial electricity is used to compress hydrogen.

Despite its short annual travel distance per car, only Tokyo reduced net damage, while other regions increased damage. This is attributed to large damage reduction in air pollution in urban areas by gasoline use reduction in addition to the comparatively small damage at hydrogen compression. Damage to human health by air pollution is more severe in Tokyo because it has the highest population density among all prefectures in Japan and many people suffer damage. This is why the impact factors of SOx and NOx in air pollution in urban areas of Tokyo are larger than those of other regions.

Social assets damage was also analyzed to understand the difference in factors influencing LCA results, which is shown in Figure 4. The observed patterns of the graphs are similar to those in human health damage because climate change was the dominant category in both types of damage. Impacts due to acidification accounted for a small fraction of damage to social assets. Impacts in photochemical oxidant creation were negligible for all technology combinations and regions. Because site-specific impact factors were not used for climate change and acidification, in Figure 4d, the net damage to social assets in Tokyo was increased, although that to human health was decreased because of local pollutant reductions at the gasoline utilization stage.

The LCA results on primary production damage are also shown in Figure 5. Different graph patterns from results on human health and social assets were observed because photochemical oxidant creation and acidification have impacts associated with primary production damage. NMVOCs at hydrogen production were major contributors to the increases in damage for PV-implemented cases, which are emitted from the lamination process of PV panel production (ecoinvent, 2014). Damage reductions of acidification and photochemical oxidant creation by replacing grid power and gasoline were larger than those by replacing fuel gas for hot water and ICEV. The reductions in Fukuoka were larger than in other regions because the number of cars in Fukuoka is not too small, that is, more than half of that in Tokyo, with about 14,000 (km/year/car) of annual travel distance per car, which is almost twice the distance per car in Tokyo. It is also because the Kyushu area, which includes Fukuoka and Okinawa, has the largest impact factors in Japan because of its specific ecosystems.

### 3.2 LCA results represented by the LIME index

The LCA results represented by the LIME index showed almost the same patterns as those in human health damage, which means that impacts on human health were dominant rather than impacts on social assets and primary production (see also Figure S1-1 in Supporting Information S1).

The net reduced LIME indexes in the prefectures are represented in Figure 6. All regions are compared to demonstrate which region-specific characteristics have a strong influence on the implementation effects. Different implementation impacts were observed for the four types of technology combinations. When hydrogen production with FGSTR was implemented (see Figure 6a,c), the LIME index increased in most regions. All regions caused increases in the LIME index when FCV was implemented together with FGSTR. When FCCGh was implemented, the LIME index reduced in regions where the grid powers have relatively higher GHG emission factors. In fact, the ratios of coal- and oil-fired power plants in the power mixes are more than 60% in the major electricity supply companies in Hokkaido (HEPCO, 2017), Hokuriku (Hokuriku-EPCO, 2017), Chugoku (Chugoku-EPCO, 2018), Shikoku (Shikoku-EPCO, 2018), and Okinawa (OEPCO, 2017).

Figure 6b indicates that the LIME index was reduced in higher-populated regions, that is, Fukuoka, Osaka, Aichi, and Tokyo, which have 5.1, 8.9, 7.4, and 13.2 million citizens, respectively. This result could be due to the relatively large energy demand and site-specific impact factors compared with the other areas.

Figure 6c indicates that the LIME index was reduced in higher-populated regions, that is, Fukuoka, Osaka, Aichi, and Tokyo, which have 5.1, 8.9, 7.4, and 13.2 million citizens, respectively. This result could be due to the relatively large energy demand and site-specific impact factors compared with the other areas.
FIGURE 4  Life cycle assessment (LCA) results on social assets damage for (a) fuel gas steam reforming (FGSTR) and fuel cell cogeneration systems for household use (FCCGh), (b) water electrolysis with photovoltaic electricity (PVWE) and FCCGh, (c) FGSTR and fuel cell vehicle (FCV), and (d) PVWE and FCV implemented in four regions, that is, Hokkaido, Tokyo, Fukuoka, and Okinawa. The breakdown structures of impact changes in each life cycle stage and each impact category are represented by different colors and fill patterns. The positive side of the vertical axis means damage increase and the negative side means damage reduction by replacing the conventional technologies and their energy use. The net life cycle impacts are plotted with red-outlined diamonds. The values in the parentheses next to the region names represent 1/1,000 of the number of implemented FCCGh or FCV units, which is equal to 10% of the numbers of families or normal passenger vehicles in the regions. The underlying data for this figure are provided in Supporting Information S2.

When PVWE and FCV were implemented (Figure 6d), the LIME index was increased in gray-colored prefectures or less reduced in red- and orange-colored ones, where the contribution of compression to the total results was larger than the other areas because of the high emission factors of their grid powers. Effective implementations are observed in the suburban areas where annual travel distances per car are long, emission factors of the grid powers are low, and impact factors of NOx and SOx are high.

The net reduced LIME index per capita in the prefecture is shown in Figure 7, which can be regarded as implementation effects not directly related to the population size. Figure 7a,c shows that the LIME index was increased in more than half of all regions for FGSTR and FCCGh implementation and in all regions for FGSTR and FCV implementation. In Figure 7b, the reductions in the LIME index by PVWE and FCCGh were relatively large in Hokkaido, Hokuriku, Chugoku, Shikoku, and Okinawa because of their high emission factors in the power grid. LIME index reductions were smaller in Kanto, Kansai, and Kyushu because of the capacity factors of FCCGh in these areas were roughly 70% of those of the Tohoku area because of warmer climates, that is, smaller hot water demand. For FCV implementation depicted in Figure 7d, the LIME index was less reduced in regions that have short annual travel distances per car, such as Tokyo, and the grid powers for compression had high emission factors. Reduction effects in SOx and NOx were high in Kanto, Chubu, and Kansai because of their higher impact factors in air pollution in urban areas.

The net reduced LIME index in the UEAs is shown in Figure 8. UEAs in the same prefecture showed different implementation effects. In Figure 8b, for instance, while many UEAs in Hokkaido showed comparatively small reduction effects in the LIME index by PVWE and FCCGh, Sapporo UEA
FIGURE 5 Life cycle assessment (LCA) results on primary production damage for (a) fuel gas steam reforming (FGSTR) and fuel cell cogeneration systems for household use (FCCGh), (b) water electrolysis with photovoltaic electricity (PVWE) and FCCGh, (c) FGSTR and fuel cell vehicle (FCV), and (d) PVWE and FCV implemented in four regions, that is, Hokkaido, Tokyo, Fukuoka, and Okinawa. The breakdown structures of impact changes in each life cycle stage and each impact category are represented by different colors and fill patterns. The positive side of the vertical axis means damage increase and the negative side means damage reduction by replacing the conventional technologies and their energy use. The net life cycle impacts are plotted with red-outlined diamonds. The values in the parentheses next to the region names represent 1/1,000 of the number of implemented FCCGh or FCV units, which is equal to 10% of the numbers of families or normal passenger vehicles in the regions. The underlying data for this figure are provided in Supporting Information S2.

showed higher reduction effects. A large reduction in Sapporo UEA, in which about 40% of the population of Hokkaido lives, resulted in a larger reduction in Hokkaido Prefecture, as shown in Figure 6b. The region-specific characteristics of UEAs are more intensive than those of prefectures, which clearly showed the differences inside the prefecture. Other factors such as utilization ratios of implemented technologies were not well reflected because of the low regional resolution of the available data (e.g., data by prefecture or by broader area), even though they should influence the implementation. In fact, the net reduced LIME index per capita in the UEAs shows almost the same pattern as in the prefectures (see Figure S1-2 in Supporting Information S1).

Damages to human health, social assets, and primary production were also represented on GIS, as shown in Figures S1-3 through S1-14 in Supporting Information S1. Differences in regional variations of damages among different endpoints were visualized. These maps can be used to identify what positive and negative effects in terms of various environmental impacts are caused by the implementation.

4 DISCUSSION

4.1 Assessment of the emerging technologies
The main difference caused by technology implementation of hydrogen energy is that the main emission sources changed from energy users to device manufacturers or material processors. Especially for implementation of FCV and PVWE, nonpoint-source emissions from ICEV driving were
reduced, while point-source emissions from manufacturers of PV, electrolyzer, and FCV and their upstream material processors were increased. FCV implementation would be preferable in urban regions suffering from air pollution caused by heavy traffic. LCA results in Figure 3d showed that gasoline use reduction in Tokyo mitigated 4 times and 20 times as much human health damage from air pollution as Fukuoka and Hokkaido, respectively, while mitigations of human health damage from climate change were almost the same level among the three regions (below 1% differences). It would be an advantage for FCV implementation that direct emissions from a vehicle can be negligible for FCV because thermal NOx and NMVOCs emissions directly from internal combustion engines would not be completely prevented.

To the contrary, technology implementation can cause negative impacts in locations of device manufacturing and material processing. The life cycle emission and impacts induced by manufacturing devices and raw material processing for implementation of PVWE and FCV became larger than those for the gasoline-fueled ICEV system. These emerging technologies require highly functional cutting-edge materials, which tend to be energy intensive. For instance, processing silicon for PV consumes a lot of energy for its purification (Pellow, Emmott, Barnhart, & Benson, 2015), and the production of carbon fiber used for both the fuel cell stack and hydrogen tank of FCV needs high-temperature energy for oxidation and carbonization (Evangelisti et al., 2017). While the direct emissions from FCCGh and FCV are reduced in the location of technology implementation, the indirect emissions from device manufacturing and raw material processing can be increased. Around two-thirds of PV modules and PV cells in the world were manufactured in China in 2015 (IEA, 2016), while in this study, PV manufacturing in Japan was assumed. High environmental impacts of PV manufacturing in China were reported because of its high emission factor in the grid system (Nian, 2016). The environment could become worse in manufacturing locations even if the environment in the device-using location is improved. Decarbonization, desulfurization, denitration, and NMVOCs removal in manufacturing processes should also be considered along with environmental improvement in the user-side locations.

Sensitivity analysis can be used not only to provide information on the uncertainty of a planned energy system for decision-makers but also to know the potential impact changes by technology development on the implemented system. Both technology development and system analysis should be done simultaneously for mutual improvement. To examine the sensitivity of the change in damage by PVWE and FCV implementation, in
Figure 7 Net reduced life cycle impact assessment method based on endpoint modeling (LIME) index per capita for (a) fuel gas steam reforming (FGSTR) and fuel cell cogeneration systems for household use (FCCGh), (b) water electrolysis with photovoltaic electricity (PVWE) and FCCGh, (c) FGSTR and fuel cell vehicle (FCV), and (d) PVWE and FCV implemented in the prefectures in Japan. Okinawa Prefecture is enlarged in the upper-left corner to improve visibility. The underlying data for this figure are provided in Supporting Information S2 Figure S1-15 in Supporting Information S1, the LIME index in Tokyo (the base case, corresponding to Figure S1-1 in Supporting Information S1(d)) was compared with four different cases; that is, compression with PV electricity, 2.5 times more efficient compression, 1.5 times higher FCV fuel economy, and FCV–ICEV equal manufacturing emission. All four cases showed a higher damage reduction than the base case. The LCA results should be carefully interpreted because such emerging technologies have much uncertainty in their inventories due to lack of information and to improvement potential.

Information on emerging technologies is often insufficient in terms of inventories and technological specifications. Moreover, information on the system in which they are implemented is unknown because the system has not been built and system configurations are not determined. The LCA for such systems with little information is difficult. The results of the study showed that the simulation of energy systems can be used to evaluate the energy flow and the scale of implementation, which is used as inventory for LCA.

4.2 Application of the obtained LCA results

Various quantitative environmental analyses can support decision-makers such as local governments and technology developers. For example, the quantitative analysis can be used as evidence that FCV will mitigate local air pollution, which would incentivize implementation in urban regions. Diverse values (not only CO₂ mitigation) should be sought for implementing emerging technologies. Comparison among regions showed visually the appropriate regions for implementation and the influences of multiple region-specific characteristics, such as emission factors of the power grids, energy use patterns, demand sizes, and impact factors. The analysis would motivate technology implementation in regions with positive results, for example, FCCGh implementation in Hokuriku, Chugoku, and Shikoku areas as presented in Figure 7b. Decision-makers such as local governments in the Kyushu area can use the same results to determine whether to stop implementation. They can also take alternative system options; for example, fuel cell cogeneration use in food factories that need much heat.

Implementation effect representation with GIS for prefectures and UEAs demonstrated that the regional boundary strongly affects the region-specific characteristics. The regional division based on prefectures homogenizes intensive regional characteristics, whereas a prefecture can contain urban and rural, resource-rich and -lean, and industrial and residential areas. UEAs with higher implementation effects than other UEAs in the common prefectures tend to have a higher population, as observed in Hokkaido Prefecture and its contained UEAs in Figure 8b because they have
FIGURE 8  Net reduced life cycle impact assessment method based on endpoint modeling (LIME) index represented as logarithmic values for (a) fuel gas steam reforming (FGSTR) and fuel cell cogeneration systems for household use (FCCGh), (b) water electrolysis with photovoltaic electricity (PVWE) and FCCGh, (c) FGSTR and fuel cell vehicle (FCV), and (d) PVWE and FCV implemented in the UEAs in Japan. Okinawa Prefecture is enlarged in the upper-left corner to improve visibility. When the logarithmic values are negative, in other words, the LIME index is increased by technology implementation, they are represented in gray. The underlying data for this figure are provided in Supporting Information S2.

The socioeconomic aspect is also important for technology implementation. Although 10% implementation was assumed in this study, whether regions actually have the potential to implement technologies to such an extent was not examined. The prioritization of regions in technology implementation is needed considering both implementation effects and the ability of regions. Technology developers and energy suppliers should concentrate on the prioritized region for making connections with stakeholders in the regions and designing suitable energy systems.

4.3 Limitations in data availability

Three limitations were identified in data availability for this region-specific analysis approach. First, inventory data for substances other than CO$_2$ are limited. The inventory databases IDEA v2 and ecoinvent v3.1 were used in this study for inventory analysis of a wide range of emissions. The uncertainty of emissions such as NOx, SOx, and NMVOCs seems to be larger than for CO$_2$ emission because of difficulties of measurement and assumptions made in the databases. Compared with the inventory of electricity generation in Japan in IDEA v2, for example, that in ecoinvent v3.1 presents about 2–10 times higher emissions of NOx, SOx, and NMVOCs, while CO$_2$ emissions are almost the same in the two databases. This is partly because conditions of fuel compositions and flue-gas-treatment abilities are different. It should be considered that the analysis results also have uncertainty attributed to the uncertainty included in the databases.

Second, inventories of emerging novel technologies are not contained in the databases. Inventories of PV, fuel cell, and electrolyzer are not provided in IDEA v2. While some of these are found in ecoinvent v3.1, FCV is not. For these technologies, in the present study, inventories were assumed by combining the two databases and using data from the literature. The uncertainty in the inventories potentially has a considerable influence on LCA results because of the large contributions of such device manufacturing and raw material processing, as shown in Figures 3–5.
Materials used in novel technologies tend to be energy intensive and to have high and multiple functions. Methodologies to estimate the inventories of such emerging technologies that are not fully available need to be established.

Third, the regional resolution of some data was not always sufficient for the analysis. Region-specific data for the UEA were not available and were derived from those for the municipality, which is the minimum constituent element of the UEA. However, many data are provided for prefectural and broader areas. For example, region-specific characteristics of energy use patterns were obtained from the data for prefectures and broader regions (MLIT, 2016; MRI, 2013). Site-specific impact factors of emissions have a low regional resolution for the broad areas, which divide Japan into seven areas. Such low spatial resolution and lack of data would lower the reliability of the assessment and weaken the intensity of region-specific characteristics by applying the same data within wider areas. Data availability with high regional resolution could improve analysis accuracy, especially for a UEA.

5 | CONCLUSIONS

We performed a region-specific environmental analysis of technology implementation in Japan by combining LCA with the model for simulating energy systems. The analysis quantitatively presented the implementation effects by region, by life cycle stage, and by impact category. While climate change was the dominant impact category of impacts on human health, social assets, and LIME index, photochemical oxidant creation had dominant impacts on primary production. Air pollution in urban areas also had considerable impacts on human health and the LIME index. Because, by gasoline use reduction, human health damage from air pollution in Tokyo was mitigated 4 times and 20 times as effectively as in Fukuoka and Hokkaido, respectively, urban regions can be motivated to implement FCV. Reduction in nonpoint-source emissions in urban region is valuable because of the difficulty of removing such emissions by other technology options. Comparison among regions showed visually a variety of implementation effects that reflected multiple region-specific characteristics, such as existing power grid systems, energy use patterns, demand sizes, and impact factors. The visualized results can justify effective FCCGh implementation in Hokuriku, Chugoku, and Shikoku areas while decision-makers in Kyushu area have a disadvantage in the implementation and they would consider alternative system options. The definition of the regional division was also an important factor because region-specific characteristics were largely dependent on and sensitive to the results. An appropriate regional division needs to be discussed for region-specific implementation.

The analysis also brought attention to the possibility of environmental deterioration in locations of device manufacturing and material processing due to the increase of emissions associated with such production. The life cycle emissions and impacts induced by manufacturing devices and raw material processing FCV are larger than for ICEV because of high energy input in material production for the fuel cell stack and hydrogen tank. PV modules also use energy-intensive materials, which may cause the environment to deteriorate in the locations of material processing. Both positive and negative impacts of emerging technology implementation should be discussed carefully in decision-making based on the quantitative analysis.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Teruyuki Shimizu https://orcid.org/0000-0003-1043-5860

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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