Concept of Carbon-related Energy to Connect Energy Consumption with \( \text{CO}_2 \) Emissions

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Reducing carbon dioxide (\( \text{CO}_2 \)) emissions from energy consumption is an urgent requirement to address climate change. The difficulty for energy consumers to consciously perceive \( \text{CO}_2 \) emissions largely hinders the reduction of \( \text{CO}_2 \) emissions. The purpose of this study is to develop new indicators to help \( \text{CO}_2 \) emissions to be perceived intuitively and to show the applications of the new indicators. The main results of this study are as follows. (1) The authors introduce the new concept of CE (carbon-related energy) that shows a very strong correlation with \( \text{CO}_2 \) emissions based on heating values and the element contents of fuels. The authors introduce CE-derived concepts such HE (hydrogen-related energy), RE (renewable energy), and CE ratio. (2) The CE ratio that is defined as CE per energy is the index of \( \text{CO}_2 \) emissions intensity per energy. The CE ratio that is expressed as a normalized index ranging between 0.0 and 1.0 would intuitively be perceived by energy consumers. (3) Using the modified Kaya identity that the authors derived using the CE-derived concepts, an increase and decrease in \( \text{CO}_2 \) emissions can be explained by the factors concerning CE-derived concepts and GDP. Using the CE-derived concepts, energy and CE as the indices of \( \text{CO}_2 \) emissions can be described in one unit in a table or a figure instead of separately.

Key Words
Carbon-related energy, \( \text{CO}_2 \) emissions reduction, H/C ratio, Kaya identity

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1. Introduction

Global CO₂ emissions from the consumption of fossil fuels exceed 30 Gt-CO₂ per year and continued to increase throughout 2010s [1]. One of the factors hindering the efforts to reduce CO₂ emissions is the fact that they are not consciously or intuitively perceived by energy consumers.

CO₂ emissions from energy consumption are calculated as the energy consumption multiplied by the CO₂ emissions intensities of the fuels used. However, the intensity of CO₂ emissions varies depending on the fuel type and is expressed in units of mass per energy, such as kg-CO₂ per joule. Thus, the available CO₂ emissions intensities can obscure the understanding of the relationship between CO₂ emissions and energy consumption.

In this study, the authors propose the concept of carbon-related energy (CE), based on the ratios and heating values of carbon in fuels, to better understand the relationship between energy consumption and CO₂ emissions.

Previous studies have discussed the ratios of carbon and hydrogen in fuels. Preceding studies [2, 3] analyzed the hydrogen over carbon (H/C) ratio in various fuels and showed that this ratio has increased over time and will continue to increase in the future. Various formulas that express the heating values of fuels have been proposed, such as the Dulong formula, using ratios of carbon, hydrogen, and oxygen in fuels [4 – 7]. However, these aforementioned studies [2, 3] did not discuss the heating values of fossil fuels, and the previous research [4 – 7] has not evaluated the relationship between heating values related to carbon contents and CO₂ emissions from fossil fuels.

The purpose and aims of this study are as follows. (1) To develop a new indicator of the carbon-related energy (CE) that can help in determining the relationship between energy consumption and CO₂ emissions intuitively; CE implies carbon-related heating values in fuels and is strongly correlated to CO₂ emissions from the fuels. (2) To propose a CE ratio as an index to express CO₂ emissions intensity per energy that could be recognized more easily by energy consumers; this ratio can be expressed as a normalized index ranging between 0.0 and 1.0, which is defined as the heating value of the carbon in the fuel to the sum of the lower heating value of all elements within the fuel. (3) To describe figures using the CE and the CE-derived concepts that help to grasp information concerning energy and CO₂ emissions.

2. Definition of CE and CE-derived concepts

We define carbon-related energy (CE) as

\[
CE = \frac{HVC}{(HVC + HVH)} \cdot HVF, \tag{1}
\]

where HVC is the heating value of the carbon in the fuel, and HVH is the heating value of all the other elements, i.e., hydrogen and minor sulfur. HVF is the heating value of the fuels (e.g., oil, natural gas, or coal). The HVFs are the lower heating values on a bone-dry basis. When a unit of energy consumption is assumed, the CE consumption shows a strong, linear correlation with the CO₂ emissions from the consumption of fossil fuels (Fig. 1). The determination factor between CE consumption and CO₂ emissions from fossil fuel consumption is over 0.99. Therefore, the authors propose CE consumption as an index to express the quantity of CO₂ emissions produced from fossil fuels.

Analogous to the definition of CE, hydrogen-related energy (HE), as well as nuclear energy (NE), renewable energy (RE), and electric energy (EE) can be defined. HE is equal to HVF minus CE. NE is the primary energy; RE, including bioenergy, can be primary energy as well as secondary energy. EE is secondary energy generated from primary energy, such as sum NE and parts of CE, HE, and RE.

The approximation formula used for the fossil fuels (natural gas, oil, and the average of the seven types of coal) and for hydrogen, indicates that the CO₂ emissions (in kg-CO₂) have values of approximately 115 multiplied by CE (in GJ).

The ratio of CE to the heating value of the fuel amounts to 0.0 for hydrogen, 0.46 for natural gas, 0.64 for crude oil, and 0.81 for averaged coal.

The approximation formula is not applied for bioenergy, because it contains a high ratio of oxygen (for...
example, the ratio of oxygen in cellulose is approximately 49%-weight). It is assumed that bioenergy is categorized as a type of renewable energy that discharges net zero CO₂ emissions. Modifying the formula of CE for bioenergy by considering the oxygen content should be a focus of future research.

In addition, the approximation formula cannot be applied to elemental carbon, which discharges approximately 108 kg-CO₂ per GJ, that is, about 6% less than the approximation formula, as elemental carbon is not a common energy carrier. The concept of CE is a pragmatic index that can be applied for fossil fuels. Modifying the formula of CE for elemental carbon should receive research attention in the future.

3. Uses of CE-derived concepts

3.1 Terms related to CO₂ emissions and CE in energy policies

The terms related to CO₂ emissions and CE in energy policies are listed in Table 1, emphasizing how both concepts are interrelated.

While CO₂ emissions are shown in mass units, CE consumption is shown in energy units, which enables energy consumers to recognize the relationship between CE and energy consumption without the need to convert the units. A reduction in CO₂ emissions can be translated to CE savings that are better recognized by energy consumers. As such, the concept is linked to energy savings, which is one of the most popular policies with which to manage energy.

CO₂ emissions intensity per energy corresponds to the CE ratio, which is defined as the ratio of the heating value of the CE to that of the fuel. This CE ratio is considered more recognizable by energy consumers, especially when it is expressed as a normalized index ranging between 0.0 and 1.0, as opposed to CO₂ emissions intensity per energy.

A CO₂ emissions trading system could work under a cap and trade system of CE, representing a combination of a cap and permit trading of CE consumption. A CO₂ pricing and a CO₂ budget could correspond to a CE pricing and CE consumption budget, respectively. Carbon capture and storage, then, corresponds to the offset of the CE consumption that can loosen the cap of CE consumption.

3.2 Modified Kaya identity using a concept of CE

The Kaya identity is described as follows:

$$\text{CO}_2E = (\text{CO}_2E/\text{ENE}) \cdot (\text{ENE}/\text{GDP}) \cdot \text{GDP}. \quad (2)$$

Nomenclature is shown at the end of the paper. The original Kaya identity (2) can be converted as follows without ENE:

$$\text{CO}_2E = (\text{CO}_2E/\text{GDP}) \cdot \text{GDP}. \quad (3)$$

However, as equation (3) does not include ENE, it cannot explain the relationship between ENE and CO₂E. On the other hand, the following equations (4) to (10) can explain the relationship between ENE and CE as the index of CO₂E.

Using the concept of CE, the Kaya identity can be described as follows:

$$\text{CE} = (\text{CE}/\text{ENE}) \cdot (\text{ENE}/\text{GDP}) \cdot \text{GDP}. \quad (4)$$

When ENE is omitted, equation (4) is written as follows:

$$\text{CE} = (\text{CE}/\text{GDP}) \cdot \text{GDP}. \quad (5)$$

ENE can be described using the CE-derived concepts such as HE, NE, and RE.

$$\text{ENE} = \text{CE} + \text{HE} + \text{RE} + \text{NE}. \quad (6)$$

The CE ratio of (CE/ENE) in equation (4) is explained by the HE, NE, and RE ratios.

$$(\text{CE}/\text{ENE}) = 1.0 - (\text{HE}/\text{ENE}) - (\text{RE}/\text{ENE}) - (\text{NE}/\text{ENE}). \quad (7)$$

This equation shows that the CE ratio as the index of CO₂ intensity per energy can be reduced by an increase in the HE, NE, and RE ratios.

The differential form of equation (7) is described as follows:

$$\frac{d(\text{CE}/\text{ENE})}{dt} = -\frac{d(\text{HE}/\text{ENE})}{dt} - \frac{d(\text{RE}/\text{ENE})}{dt} - \frac{d(\text{NE}/\text{ENE})}{dt}. \quad (8)$$

This equation shows that the increase and decrease in the CE ratio as the index of CO₂ intensity per energy can

| CO₂ emissions                   | CE (carbon energy)               |
|--------------------------------|----------------------------------|
| CO₂ emissions reduction        | CE saving                        |
| CO₂ intensity (=CO₂/Energy)    | CE ratio (=CE/Energy)            |
| CO₂ emissions permit           | CE consumption permit            |
| Cap and trade of CO₂ emissions permit | Cap and trade of CE consumption permit |
| CO₂ emissions trading system   | CE consumption permit trading system |
| CO₂ pricing                    | CE pricing                       |
| CO₂ budget                     | CE consumption budget            |
| CO₂ emission reduction by CCS  | CE consumption offset by CCS     |
be explained by the respective increase and decrease in the HE, NE, and RE ratios.

Equation (5) can be described as follows using equation (6):

$$CE = \frac{(ENE/GDP - HE/GDP - RE/GDP - NE/GDP)}{GDP} \cdot GDP. \ (9)$$

The differential form of equation (9) is described as follows:

$$d \ CE/dt / CE = d(CE/GDP)/dt \cdot (CE/GDP) + d GDP/dt / GDP$$

$$= d(ENE/GDP)/dt \cdot (ENE/GDP) \cdot (ENE/CE)\ + \ d(HE/GDP)/dt \cdot (HE/GDP) \cdot (HE/CE)\ - \ d(RE/GDP)/dt \cdot (RE/GDP) \cdot (RE/CE)\ - \ d(NE/GDP)/dt \cdot (NE/GDP) \cdot (NE/CE)\ + \ d GDP/dt / GDP. \ (10)$$

Equation (10) is approximated by equation (11), where $dt$ is replaced by $\Delta t$ to represent a period such as a year or a decade. For example, $\Delta CE$ in equation (11) is defined as the change in CE between the period of $\Delta t$. Equation (11) is a pragmatically useful equation for numerical analyses using statistical data.

$$\Delta CE / CE = \frac{\Delta (CE/GDP) \cdot (CE/GDP) + \Delta GDP / GDP}{\Delta (ENE/GDP) / (ENE/GDP) \cdot (ENE/CE)} - \frac{\Delta (HE/GDP) / (HE/GDP) \cdot (HE/CE)}{\Delta (RE/GDP) / (RE/GDP) \cdot (RE/CE)} - \frac{\Delta (NE/GDP) / (NE/GDP) \cdot (NE/CE)}{\Delta GDP / GDP}. \ (11)$$

Equations (10) and (11) show that the rate of change of CE can be explained by the weighted rates of change of (ENE/GDP), (HE/GDP), (RE/GDP), (NE/GDP) and GDP. The weights for the rates of change of (ENE/GDP), (HE/GDP), (RE/GDP), (NE/GDP), and GDP are (ENE/CE), (HE/CE), (RE/CE), (NE/CE), and 1.0, respectively, which are the weights of the energy amounts in those energy types. Using equations (11), the rate of change of CE ($\Delta CE / CE$) can be decomposed into factors of the weighted rates of changes of (ENE/GDP), (HE/GDP), (RE/GDP), (NE/GDP), and GDP.

The electricity generated by variable renewable energies (VREs) is converted to primary energy using the average energy efficiency of thermal power as stated in the statistic rule in Japan 16 as well as in the United States 15. On the other hand, the electricity generated by VREs is converted to primary energy using the conversion rate of 1.0 as presented in the statistics rule by the International Energy Agency (IEA) 16. In the former case, electrification that changes over from fossil fuels to VRE-dominant electricity generation often causes an increase in primary energy consumption with regards to the statistics rule used in Japan and the US. In such instance, a reduction in CO$_2$ causes an increase in ENE of primary energy including RE. In this case, equations (10) and (11) would be useful in determining the increase and decrease in CE as the index of CO$_2$ emissions using not only the weighted rate of (ENE/GDP) but also the weighted rates of changes of (HE/GDP), (RE/GDP), (NE/GDP), and GDP.

On the other hand, the original Kaya identity in equation (2) uses ENE as the total primary energy and does not identify the types of energy, such as CE, HE, RE, and NE.

The GDP in the modified Kaya identity in equations (9), (10), and (11) can be replaced by various parameters of energy-related activities (EA). Examples of EA are shown as follows: sales amounts of companies, amounts of industrial production, generated electrical energy (see section 4.2 and Fig. 5), amount of heat supplied from water heaters, and travel distances of vehicles.

The CE-derived concepts explained in this section could be pragmatic tools for simply determining the terms related to CO$_2$ emissions. In particular, equations (7), (8), (9), (10), and (11) are pragmatically useful equations for explaining the increase and decrease in CE and the CE ratio using the CE-derived concepts such as HE, RE, NE, and ENE.

4. Applications of CE and CE-derived concepts

4.1 Historical and future global primary energy supply

Historical and future global primary energy supply from different sources including CE supply, as the index for CO$_2$ emissions, is described in Fig. 2 (a) 17 using the concept of equation (6).

As shown in Fig. 2 (a), the CE-derived concepts can show not only CE as the index of CO$_2$ emissions but the other primary energy that consists of HE, trad. RE as traditional bioenergy, RE, and NE as well. The figure can show the CE as an index of CO$_2$ emissions and the primary energy in an energy unit in a figure, although the CO$_2$ emissions and the primary energy are usually shown in separate units in separate figures.

CE consumption continues to increase, and HE and RE consumption have increased since the middle of the 20th century. In relation to the scenarios of the World Energy Outlook 2018 of the IEA 18, the values of CE supply in the Current Policies (CP) and New Policies (NP) scenarios for 2040 will be higher than those for 2017, but for the Sustainable Development (SD) scenario the values will be lower than that for 2017.

The historical and future CE ratio for the world, as the index for CO$_2$ emissions intensity per energy, is described in Fig. 2 (b) using equation (7). Fig. 2 (b) uses the
CE-derived concepts and can explain not only the CE ratio as the index for CO₂ emissions intensity per energy but also the other energy ratios, such as the HE, RE, and NE, that can explain the increase and decrease in the CE ratio using equation (7).

In Fig. 2 (b), the CE ratio was almost constant at nearly 50% between 1940 and 2017. During that period, the increase in the ratios of modern RE and NE is offset by the decrease of the traditional RE. The ratio of HE has leveled off, implying that the switch from high-carbon fossil fuels to low CE sources has stagnated. As stated above, the CE-derived concepts help to recognize the factors of variation in the CE ratio as the index of CO₂ emissions intensity per energy.
Fig. 3 shows that the change in the CE ratio as the index of the CO₂ emissions intensity per energy is explained by the changes in the HE, RE, and NE ratios. Fig. 3 is described based on equation (8) using the global total data in and after 1960.

In Fig. 3, the CE ratio increased between 1960 and 1970. This is mainly because the trad. RE ratio decreased more than the HE ratio increased during this period. Contrarily, the CE ratio decreased between 1970 and 2000. During this period, the largest factor causing the decrease in the CE ratio was the increase in the NE ratio. In addition, the continuous increase in the RE ratio contributed to the decreases in the CE ratio. The CE ratio increased between 2000 and 2010, mainly because the trad. RE ratio decreased more than the RE ratio increased during this period. In addition, the decrease in the NE ratio contributed to the increase in the CE ratio. The CE ratio decreased between 2010 and 2017, which is mainly because the RE ratio increased more than the trad. RE ratio decreased during this period.

Fig. 4 shows that the rates of increase and decrease of CE is explained by the weighted rates of change of (CE/GDP), (ENE/GDP), (HE/GDP), (RE/GDP), (NE/GDP), and GDP. Fig. 4 is described based on equation (11) of the modified Kaya identity using the global total data in and after 1960.

In Fig. 4, the rate of decrease in (CE/GDP) is less than the rate of increase in (ENE/GDP) weighted by (ENE/CE) in and after 1960 continuously. This is mainly because the rate of change of (Trad. RE/GDP) is negative continuously and the rates of change of (HE/GDP), (RE/GDP), and (NE/GDP) are negative or slightly positive during this period. To decrease the rate of change of (CE/GDP) in future, not only a reduction in the rate of change of (ENE/GDP) but also an increase in the rates of change of (HE/GDP), (RE/GDP) and (NE/GDP) are needed.
4.2 Energy and CE intensities per generated electric energy using CE-derived concepts

Fig. 5 displays the energy intensity per generated electric energy as the inverse of the energy efficiency and the CE intensity per generated electric energy as the index of CO2 intensity per generated electric energy in one unit in one figure; this is different to the usual method of display in separate units in separate figures.

Natural gas power generation, which has a high generation efficiency and a low CE ratio, causes a low CE intensity. Biomass power generation has a low generation efficiency but generates net-zero CO2 emissions, as it is categorized as an RE.

4.3 Energy balance table and energy chains

An energy balance table [16) and a figure of energy chains [19) serve as powerful tools for numerically describing the overall energy chains; however, they cannot explain the CO2 emissions that are usually listed in different tables of statistics [14) [16).

Using the concepts of CE, HE, RE, NE, and EE (see section 2), the energy balance table and the figure of energy chains can be described, as shown in Table 2 and Fig. 6. These illustrate not only the energy balances but include the CE balances that are the indexes of the CO2 balances. In addition, the net decrease in CE in each process is proportional to the locational CO2 emissions in each process with electricity separated [1]. The table and figure show that the net decrease in the CE as...
the indexes of locational CO2 emissions are considerable in the industrial, transportation, and power generation sectors.

The IEA describes CO2 emissions in different sectors in two ways: CO2 emissions with electricity and heat separated and those with electricity and heat reallocated. The CO2 emissions with electricity and heat reallocated means that the emissions at power and heat generation are reallocated to final sectors such as industry, commercial, residential, and transportation. Because Table 2 and Fig. 6 use the concept of EE, they describe the indexes of the locational CO2 emissions with electricity separated, and do not show the index of CO2 emissions with electricity reallocated.

Table 3 and Fig. 7, where the primary energy of input of power generation is reallocated to the final sectors, show energy flows of CE, HE, RE, and NE with electricity reallocated. The CE in the table and the figure is the index of CO2 emissions in the final sectors with electricity reallocated. Table 3 and Fig. 7 show the ratios of CE, HE, RE, and NE to the total input of power generation at approximately 0.41, 0.22, 0.04, and 0.32, respectively. The CE ratio at 0.41 is the largest among those of CE, HE, RE, and NE, although it is smaller than those of fossils such as 0.46 for natural gas, 0.64 for crude oil, and 0.81 for coal (see section 2). In Table 3, the absolute value of the total of CE, as the index of CO2 emissions with electricity reallocated, in the industry sector is the largest among those in the final sectors; specifically, the CE contained in coal is the largest in the industry sector. The total of CE in the transportation sector is the second largest among those in final sectors; the CE contained in oil is the largest in the transportation sector. The CE contained in electricity is the largest in the commercial and residential sectors.

5. Conclusions

One of the main factors hindering the reduction of CO2 emissions is the difficulty for energy consumers to consciously perceive CO2 emissions. The purpose of this study was to develop new indicators to demonstrate CO2 emissions intuitively and show the applications of the new indicators. The main results of this study are as follows.
(1) The authors introduced a new concept of CE (carbon-related energy).
Table 3  Energy flows with electricity reallocated using the CE-derived concept in Japan in 2010 (unit: PJ/year)

| Primary energy supply | Coal | Oil | Natural gas | Nuclear | Renewable | Primary energy of input of power generation with electricity-reallocated | Total | Total of CE | Total of HE |
|-----------------------|------|-----|-------------|---------|-----------|-------------------------------------------------------------|-------|-------------|-------------|
| 4319                  | 1000 | 5490| 2995        | 1668    | 1927      | 3144                                                        | 446   | 0           | 0           |
| -2387                 | -553 | -536| -293        | -1212   | -1295     | -3144                                                       | -424  | 0           | 0           |
| -267                  | -62  | -427| -233        | 16      | 19        | 0                                                          | 0     | -47         | -236        |
| -1665                 | -385 | -4527| -2470       | -563    | -650      | 0                                                          | -22   | -3398       | -1904       |
| -1572                 | -364 | -765| -417        | -210    | -243      | 0                                                          | -1    | -1326       | -702        |
| -49                   | -11  | -350| -191        | -165    | -191      | 0                                                          | -3    | -1168       | -618        |
| -9                    | 0    | -396| -216        | -178    | -206      | 0                                                          | -39   | -1040       | -550        |
| -7                    | -2   | -2079| -1134       | -2      | -2        | 0                                                          | 0     | -63         | -34         |
| -36                   | -8   | -396| -511        | -7      | -8        | 0                                                          | 0     | 0           | 0           |
| 0                     | 0    | 0   | 0           | 0       | 0         | 0                                                          | 0     | 0           | 0           |
| 0                     | 0    | 0   | 0           | 0       | 0         | 0                                                          | 0     | 0           | 0           |

Note: Electricity (EE) is reallocated by inputs of primary energy at power generation 1). The data was taken from the Energy Data and Modeling Center (EDMC) 23) based on the IEA 16) and Fig. 1. The negative values in the total of CE in each process are proportional to the CO2 emissions with electricity reallocated 1) in each process.

Fig. 7  Energy flows with electricity reallocated using the concept of CE in Japan in 2010 (unit: PJ/year)

Note: Electricity (EE) is reallocated by inputs of primary energy at power generation 1). The net decrease of CE in each process is proportional to the CO2 emissions with electricity reallocated in each process 1). The data was taken from the Table 3 23) based on the IEA 16). Very small flows are not displayed in the figure.
related energy) based on heating values and element contents of fuels, and it shows a very strong correlation with CO₂ emissions. The determination factor between CE consumption and CO₂ emissions from fossil fuel consumption is over 0.99. The authors introduced CE-derived concepts such as HE (hydrogen-related energy), RE (renewable energy), and the CE ratio. (2) The CE ratio that is defined as CE per energy is the index of CO₂ emissions intensity per energy. The CE ratio expressed as a normalized index ranging between 0.0 and 1.0 would intuitively be perceived by energy consumers. (3) Using the CE-derived concepts such as the CE ratio and the modified Kaya identity, an increase or decrease in CO₂ emissions can be explained by the factors involving HE, RE, NE, and GDP. For example, the global CE ratio was almost constant at nearly 50 % between 1940 and 2017. During that period, the increase in the ratios of modern RE and NE were offset by the decrease in the traditional RE. The ratio of HE has leveled off, implying that the switch from high-carbon fossil fuels to low-CE sources has stagnated. Using the CE-derived concepts, energy and CE as the indices of CO₂ emissions can be described in one unit in a table or a figure; unlike how they are usually shown in separate units in tables or figures.

This concept could be an aid to overcome the lack of clarity among consumers regarding energy consumption and CO₂ emissions and the relationships between them. CE-derived concepts such as the CE ratio, modified Kaya identity, and energy balance tables using CE, are considered powerful tools to better understand and perceive the relationship between energy and CO₂ emissions. It is expected that these tools will be put into practice to achieve a reduction in CO₂ emissions on a national and global scale.

References
1) International Energy Agency (IEA), https://www.iea.org/reports/co2-emissions-from-fuel-combustion-overview (Last access: January 15, 2021)
2) Ausubel, J. H., *Am. Sci.*, 84, 166-178 (1996)
3) Nakicenovic, N., *Daedalus*, 125, 95-112 (1996)
4) Jenkins, B. M.; Baxter, L. L.; Miles Jr T. R.; Miles T. R., *Fuel Process. Technol.*, 54, 17-46 (1998)
5) Demirbaş, A., *Energy Convers. Manage.*, 42, 183-188 (2001)
6) Channiwala, S. A.; Parikh, P. P., *Fuel*, 81, 1051-1063 (2002)
7) Hosokai, S.; Matsuoka, K.; Kuramoto, K.; Suzuki, Y., *Fuel Processing Technology*, 152, 399-405 (2016)
8) Ichimatsu, T., Kogyo Netsurikigaku, Shokabo, 1981 (in Japanese)
9) Central Research Institute of Electric Power Industry (CRIEPI), CRIEPI Review No. 46, CRIEPI, 2002
10) Idemitsu, http://www.jcoal.or.jp/coaldb/shiryo/material/01ando.pdf (Last access: July 26, 2020)
11) JXTG Energy, https://www.noczjxtg-group.co.jp/binran/part01/chapter01/section01.html (Last access: July 26, 2020)
12) North American Energy Standard Board, https://www.naesb.org/pdf2/wgg_bpa100605w2.pdf (Last access: July 26, 2020)
13) Kaya, Y.; Yamaji, K.; Matsuhashi, R., paper presented at Tokyo Conference on the global environment and human response toward sustainable development. Tokyo, September 11-13, 1989
14) Ministry of Energy, Trade, and Economy (METI), https://www.enecho.meti.go.jp/statistics/total_energy/xls/stte_2010.xlsx (Last access: July 26, 2020)
15) Energy Information Center, https://www.eia.gov/totalenergy/data/annual/index.php (Last access: July 26, 2020)
16) International Energy Agency (IEA), World energy balances and statistics, IEA, 2019
17) Ritchie, H.; Roser, M., https://ourworldindata.org/energy (Last access: July 26, 2020)
18) International Energy Agency (IEA), World energy outlook 2018, IEA, 2018
19) Yamamoto, H., *J. Jpn. Soc. Energy Resour.*, 40, 220-23 (2019)
20) Nierop, S., Humperdinck, S., International comparison of fossil power efficiency and CO₂ intensity, ECOFYS, 2018
21) World Bank, https://data.worldbank.org/indicator/NY.GDP.MKTP.KD (Last access: December 8, 2020)
22) Ministry of Energy, Trade, and Economy (METI), https://www.meti.go.jp/english/press/2015/pdf/0716_01b.pdf (Last access: July 26, 2020)
23) Energy Data and Modeling Center (EDMC), https://edmc.ieej.or.jp/index_e.html (Last access: January 15, 2021)

Nomenclature

| Symbol | Description |
|--------|-------------|
| CE     | Carbon-related energy (Unit: J), as the index of CO₂ emissions |
| CE/ENE | CE ratio (-), as the index of CO₂ emissions intensity per energy |
| CE/GDP | CE intensity per GDP (J per JPY), as the index of CO₂ intensity per GDP |
| CO₂E   | CO₂ emissions (t-CO₂) |
| CO₂E/ENE | CO₂ intensity per primary energy (t-CO₂ per JPY) |
| CO₂E/GDP | CO₂ intensity per GDP (t-CO₂ per JPY) |
| EA     | Energy-related activities (various units) |
| Symbol | Description |
|--------|-------------|
| EE     | Electric energy (J) |
| ENE    | Primary energy (J) |
| ENE/GDP| Energy intensity per GDP (J per JPY) |
| GDP    | Gross Domestic Product (GDP) (JPY) |
| HE     | Hydrogen-related energy |
| HE/ENE | HE ratio (-) |
| HE/GDP | HE intensity per GDP (J per JPY) |
| HVC    | Heating value of the carbon element in a fuel (J) |
| HVH    | Lower heating value of all the other elements, i.e. hydrogen and minor sulfur in a fuel (J) |
| HVF    | Lower heating value in a fuel on a bone-dry basis |
| NE     | Nuclear energy (J) |
| NE/ENE | NE ratio (-) |
| NE/GDP | NE intensity per GDP (J per JPY) |
| RE     | Renewable energy (J) |
| RE/ENE | RE ratio (-) |
| RE/GDP | RE intensity per GDP (J per JPY) |
| Trad. RE | Traditional renewable that is traditional bioenergy (J) |