Hybrid input-output table method for socioeconomic and environmental assessment of a wind power generation system[1]

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HIGHLIGHTS

-The economic and environmental performance of a wind power generation system is assessed via input-output analysis.

-Existing input-output tables are improved to undertake a detailed analysis of a wind power generation system.

-Installation of a wind power generation system increases production and added value in various industries.

-The net value of production and added value is positive, but there are some negative effects in the conventional power sector.

-Installation of a wind power generation system supports reductions in energy consumption and CO2 emissions.

ABSTRACT

Input-output (I-O) analysis, an economic approach using an industrial commodity table, can be applied to analyze the inventories of energy and environmental burdens associated with a given product. The study thus uses I-O analysis to examine the effect of a wind power generation system on the environment, the energy sector, and the economy. New I-O table sections are developed based on actual data on wind turbine production processes. They cover wind power generation-related technology sectors such as manufacturing for system parts and construction. Both energy savings and CO_2 emissions reductions are estimated under constant electricity demand, including the demand for wind power, by adding these seven sectors to a Japanese I-O table for 2005. The study also examines the resulting production and added value for all sectors related to wind power generation via lifecycle I-O analysis. The positive production and added value effects outweigh the negative effects of partially substituting electricity from wind power for conventionally generated electricity.

Keywords:

Wind power generation system

Life cycle assessment

Input-output table

Economic impact

Energy consumption

CO_2 emissions

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[1] This paper was presented at the 7th International Conference on Applied Energy (ICAE2015), March 28-31, 2015, Abu Dhabi, UAE (Original paper title: “Environment, energy and economic analysis of wind power generation system installation with input-output table,” No. 566).

Nomenclature

X	Vector of domestic production
I	Unit matrix
A	Matrix of input coefficients
$\mathbf{F}^d$	Vector of domestic final demand
E	Vector of exports
M'	diagonal matrix with diagonal elements being import coefficients
b_{ij}	An element of the Leontief inverse matrix
e_j	Backward linkage of sector *j*
r_i	Forward linkage of sector *i*
R	Vector of added value
P	Matrix of added value coefficients
$\mathbf{R}_{energy}$	Vector of energy consumption
$\mathbf{P}_{energy}$	Matrix of energy consumption coefficients
$\mathbf{R}_{CO2}$	Vector of CO_2 emissions
$\mathbf{P}_{CO2}$	Matrix of CO_2 emissions coefficients
$\mathbf{A}^{hybrid}$	Matrix of input coefficients in hybrid model
A*	Matrix of commodity-by-commodity I-O technology coefficients
$\mathbf{C}^u$	Matrix representing upstream cut-off flows to the process data
$\mathbf{C}^d$	Matrix representing downstream cut-off flows to the I-O table from process data

1. Introduction

In recent years, installation of renewable energy infrastructure has been encouraged in many countries as a way to respond to problems of global warming, environmental pollution, resource depletion, and energy security, which also affects the economy [1-5]. Wind power, one renewable energy option, is an attractive and clean source of energy, with environmentally friendly production yielding “green” power, so many institutions promote the use of wind power [2][6]. However, manufacturing and constructing wind power generation systems have an indirect environmental burden [7-14]. As such, it is necessary to investigate the environmental impacts of the entire lifecycle of this renewable power generation system: manufacturing, construction, operation, maintenance, and disposal.

Lifecycle assessment (LCA) is a useful method for analyzing the full environmental burden of a product or technology [15-19]. Lifecycle inventory analysis (LCI) is the primary constituent of LCA and involves collecting and organizing the required data as the basis for evaluating comparative environmental impacts or potential improvements. There are several LCAs performed using data from existing wind power generation systems. For example, Ardente et al. implemented LCA in a wind power plant in Italy [20]. Two different methods, process analysis and input-output (I-O) analysis, are used for an LCI of energy supply systems. A hybrid LCI approach is a useful way to cover an entire lifecycle by combining process analysis methods with I-O analysis. Mizumoto et al. developed the hybrid LCI method to analyze the economic and environmental inventories associated with photovoltaic (PV) systems [21]. Lenzen et al. provided an example of this geographical variability by examining the energy and CO_2 embodied in a particular wind turbine manufactured in Brazil and in Germany using the hybrid LCI approach [22]. The present study aims to apply this methodology to undertake an inventory analysis of wind power generation systems.

The purpose of this study is to provide a comprehensive analysis of the environmental, energy, and economic impacts of installing a wind power generation system. I-O analysis is used to analyze the direct and indirect effects on each industry within a given society over all lifecycle stages of the system. A number of previous studies into LCAs of wind power generation focus only on environmental burdens including energy consumption. Therefore, we evaluate socioeconomic and environmental impacts of a wind power generation system using our proposed hybrid I-O analysis. As the existing I-O table is not well adapted for analyzing a specific power generation system, the table is improved by including process data for the system. The following section describes the method, and Section 3 presents the data. Section 4 provides the results, and Section 5 concludes.

2. Methodology

In I-O analysis, all material requirements for the different processes of lifecycle stages are conceived of as elements of a matrix. Lifecycle processes in the matrix represent hypothetical sectors, like the final demand vector, in an I-O table. To analyze the economic impacts of installing a wind power generation system, this study adds new sectors related to wind power generation to an existing I-O table. Then, the energy consumption and CO_2 emissions associated with the installation are calculated according to their economic impacts.

2.1 Input-output analysis

I-O analysis is a top-down, economic LCI method using an I-O table [23, 24] representing the industrial structure of one country or region and is composed of a technical coefficient matrix expressing the input and output configurations of each industrial sector based on activities related to the production of goods and services in a certain area at a certain time. This paper uses a basic I-O table for Japan in 2005 [25] compiled by relevant government ministries and agencies as a joint project every five years. These tables are used for the country's foundational statistics to illustrate the national economic structure and occupy an important position as a reference value of economic statistics. The total amount of industry output **X** required to meet an arbitrary final demand for output is calculated by equation (1). This equation is an advanced version of a basic model [23-27] that incorporates production increases or decreases caused by imports and exports. In this equation, the inverse matrix is described as a Leontief inverse matrix.

$$\mathbf{X}=\left[\mathbf{I}-\left(\mathbf{I}-\mathbf{M}'\right)\mathbf{A}\right]^{-1}\left[\left(\mathbf{I}-\mathbf{M}'\right)\mathbf{F}^{d}+\mathbf{E}\right] \qquad (1)$$

In this equation, **I** is an unit matrix, **M’** is a diagonal matrix with diagonal elements as import coefficients, **A** is a matrix of input coefficients, $\mathbf{F}^d$ is a vector of final domestic demand, and **E** is a vector of exports. A polynomial of **I-M’** represents a diagonal vector of the self-sufficiency rate. It is noted that import coefficients are defined as the proportion of imports of the domestic aggregate demand for each sector.

It is possible to analyze linkage effects between industries using a Leontief inverse matrix. The linkage effects are defined with reference to [28] and are used to examine industry characteristics with an I-O analysis in previous studies [29-34]. The sum of the *j* column elements in the Leontief inverse matrix represents the production-induced effects on all industrial sectors, including its own sector, when there is an increase in final demand of one unit in sector *j*. A backward linkage exists in any influential industry, e_j is developed to identify which industrial final demand increases affect induced production, as represented by equation (2).

$$e_j = \sum_{i=1}^{n} b_{ij} \Bigg/ \left(\sum_{i=1}^{n}\sum_{j=1}^{n} b_{ij} \Big/ n \right) \quad \text{with } j=1, 2, \cdots n \qquad (2)$$

On the other hand, the sum of the *i* row elements in the Leontief inverse matrix represents the total production-induced effects supplied by sector *i* when there are increases in final demand of one unit per sector. A forward linkage contained in a high-sensitivity industry, r_i is developed to identify which industrial sectors are susceptible to other industrial production activities and is defined in equation (3).

$$r_i = \sum_{j=1}^{n} b_{ij} \Bigg/ \left(\sum_{i=1}^{n}\sum_{j=1}^{n} b_{ij} \Big/ n \right) \quad \text{with } i=1, 2, \cdots n \qquad (3)$$

In equations (2) and (3), b_{ij} is an element of the Leontief inverse matrix.

By plotting the backward linkage on the x axis, the forward linkage on the y axis, and 1 at the origin, it is possible to visualize the characteristics of each industry, as shown in Fig. 1.

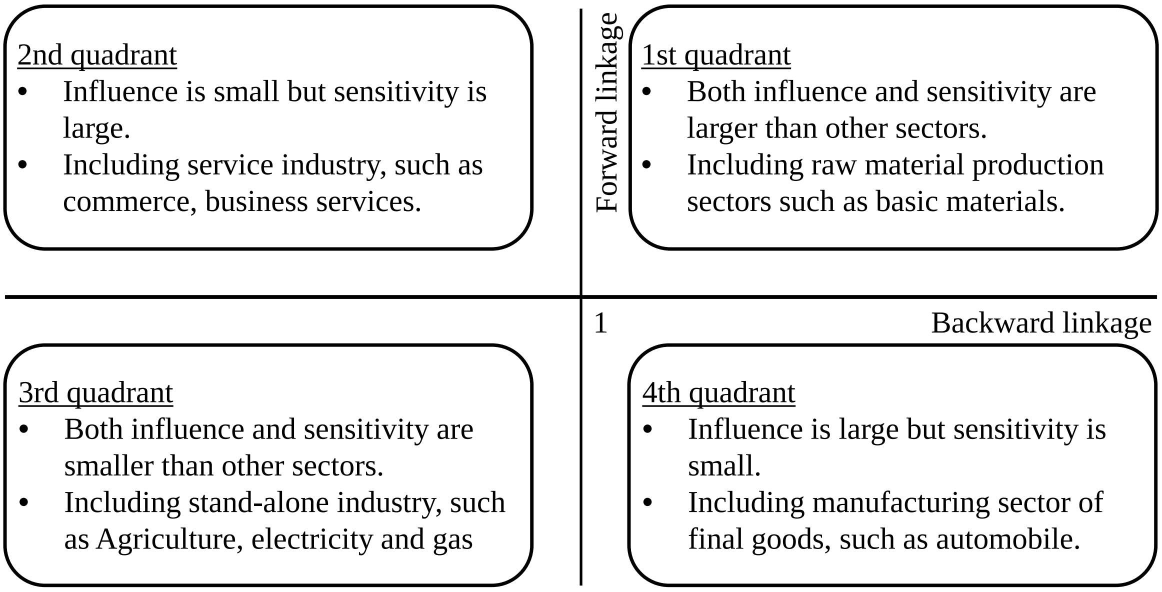


Fig. 1 Classification of industries by backward and forward linkages

The amount of domestic production induced by final demand can be divided into intermediate demand and added value. Equation (4) represents the added value **R** associated with each sector's domestic production.

$$\mathbf{R} = \mathbf{PX} \tag{4}$$

In this equation, **P** is a matrix of added value coefficients.

The amount of industry-wide energy consumption and environmental impact generated from an arbitrary level of final demand for the industry output is calculated via equation (5).

$$\mathbf{R}_{energy} = \mathbf{P}_{energy}\mathbf{X} \quad , \quad \mathbf{R}_{CO_2} = \mathbf{P}_{CO_2}\mathbf{X} \tag{5}$$

In this equation, $\mathbf{R}_{energy}$ is a vector of energy consumption, $\mathbf{P}_{energy}$ is a matrix of energy consumption coefficients, $\mathbf{R}_{CO2}$ is a vector of CO_2 emissions, and $\mathbf{P}_{CO2}$ is a matrix of CO_2 emissions coefficients.

The energy consumption coefficients and CO_2 emissions coefficients for each sector are taken from a database [35] and represent energy consumption and environmental impact per unit of output in each industry. It is noted that equations (1)-(5) are exiting methods from previous studies.

2.2 Hybrid I-O analysis

The I-O table integrates a wide variety of Japanese industries comprising approximately 400 sectors. However, no sector clearly captures renewable energy generation in the existing I-O table, making it difficult to analyze such a system by directly considering its technological characteristics. In addition, I-O analysis is generally less reliable than process analysis. To resolve these problems with I-O analysis, some have proposed hybrid approaches [23, 24, 36-41]. As an typical example, Suh and Huppes present a hybrid model that integrates the structure of process analysis with I-O analysis within a mathematical framework encompassing a product's entire lifecycle [41]. Using these mathematical models, this study proposes equation (6).

$$\mathbf{A}^{hybrid} = \begin{pmatrix} \mathbf{A}^{*} & \mathbf{C}^{d} \\ \mathbf{C}^{u} & \mathbf{A} \end{pmatrix} \tag{6}$$

Matrix **A*** is the commodity-by-commodity I-O technology coefficient matrix and can be used to express all lifecycle stages. It is expressed in various physical units per unit of operational time for each process and commodity.

Matrix $\mathbf{C}^{u}$ represents upstream cut-off flows to the process data, linked to the relevant industrial sector in the I-O table; $\mathbf{C}^{d}$ similarly captures downstream cut-off flows to the I-O table from the process data. Each element of $\mathbf{C}^u$ has a unit of monetary value per unit of operation time, while each element of $\mathbf{C}^d$ has one physical unit per unit of monetary value. Matrix **A** is almost the same as in the existing I-O table, but in some cases, conventional sectors in the existing I-O table must be updated to account for **A***, $\mathbf{C}^u$, and $\mathbf{C}^d$. Fig. 2 represents the correspondence relationship between equation (6) and an I-O table containing the new sectors. For example, if the new sectors are related to power generation, these new sectors affect the conventional power generation sector.

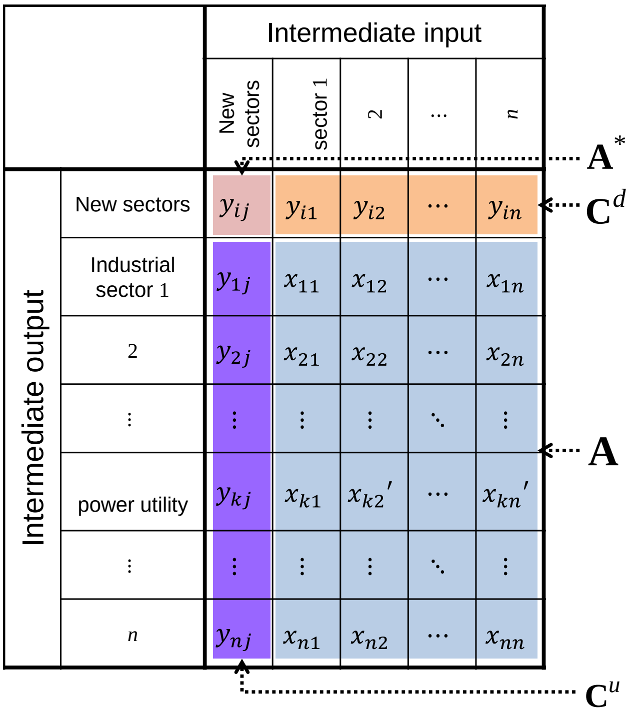


Fig. 2 I-O table for hybrid I-O analysis

3. Data

The data on wind power generation systems (i.e., installations) are the product and process LCA data from a V82-1.65 MW Vestas Wind System A/S [42, 43]. The wind turbines used to generate power in Japan include units produced domestically and imported from overseas (e.g., from Denmark, Germany, and China). Among these providers, Vestas, a Danish company, has reported data on both the product and construction materials of wind power generation systems based on the ISO14044 standard that contains detailed and transparent analysis. This study references this report to determine the specifications of the wind power generation system, as shown in Tables 1 and 2.

3.1 Development of new sectors

To conduct the analysis, we extend the I-O table with new services and components related to a wind power generation systems, such as "Tower," "Nacelle," "Rotor," "Cables," "Transformer," "Foundation," and "Wind power utility" based on the system process data.

The sectors related to wind turbine manufacturing and construction (i.e., "Tower," "Nacelle," "Rotor," "Cables," "Transformer," and "Foundation") are defined as expressing the I-O configuration for manufacturing and construction of the system components. In contrast, the "Wind power utility" sector captures the system's operation, electricity generation, and power transmission to each industrial sector. Domestic production of the sector was estimated based on electricity prices and the total amount of power generated annually by the system (2.89 GWh, which is assumed to correspond to a capacity factor of 20%). The unit price of wind power is fixed and was defined by the feed-in tariff (FIT) for renewable energy, as regulated under government energy policy in 2012 (23.76 JPY/kWh). As a result, the value of domestic production was calculated as 68.68 million JPY.

3.2. The input coefficient matrix in the hybrid model

Matrix $\mathbf{A}^{hybrid}$ has 411 rows and 411 columns synthesized from four submatrices: **A***, $\mathbf{C}^u$, $\mathbf{C}^d$, and **A**. Matrix **A*** has 7 rows and 7 columns and we assume it is a zero matrix, based on the assumption that sectors related to wind turbine manufacturing and construction do not trade materials or commodities with each other.

$\mathbf{C}^u$ has 404 rows and 7 columns and includes calculations for sectors related to manufacturing and construction (i.e., "Tower," "Nacelle," "Rotor," "Cables," "Transformer" and "Foundation"). These numbers are

Table 1 Specifications of the wind power generation system

Parameter	Amount	Unit
Diameter	82	m
Area swept	5.281	m^2
Nominal revolutions	14.4	rpm
Number of blades	3	-
Cut- in wind speed	78 (approx.)	m
Nominal wind speed	3.5	m/s
Cut-out wind speed (10 minutes)	13	m/s
Hub height (50Hz, 230V)	20	m/s
Nominal output	1.650	kW

Table 2 Construction materials for the wind power generation system

Components	Weight (t)	Value (million JPY)
Tower	**135.20**	**19.47**
Steel	126.10	12.59
Aluminum	2.60	1.13
Electronics	2.20	1.81
Plastic	2.00	3.63
Copper	1.30	0.22
Oil	1.00	0.10
Nacelle	**50.60**	**14.43**
Cast iron	18.00	8.37
Engineering steel	13.00	1.30
Stainless steel	7.80	0.78
Steel	6.30	0.27
Fiberglass	1.80	0.63
Copper	1.60	0.27
Plastic	1.00	1.81
Aluminum	0.50	0.21
Electronics	0.30	0.25
Oil	0.30	0.03
Rotor	**42.20**	**14.91**
Cast iron	11.30	5.26
Steel	4.20	0.42
Engineering steel	1.50	0.15
Epoxy, fiberglass, birch wood, and balsawood	25.20	9.09
Foundation	**832.00**	**6.66**
Concrete	805.00	3.97
Steel	27.00	2.69
Cables	**15.71**	**15.71**
Aluminum	5.58	5.58
Plastic	8.65	8.64
Copper	1.48	1.48
Transformer	**0.96**	**0.64**
Steel	0.50	0.05
Copper	0.13	0.02
Transformer oil	0.21	0.02
Insulation, paint, wood, porcelain	0.11	0.55

based on conversions of data taken from the process data reported by Vestas [43] into monetary amounts and fitting the results to the sector classification in the existing I-O table. The service sectors and added value by manufacturing and construction are approximated using the input configuration ratio of a sector similar to each new sector. In the calculations for the "Wind power utility" sector, the calculated domestic production (68.68 million JPY) is distributed in line with the operating cost shares shown in Table 3[44].

Table 3 Operating cost shares for the wind power generation system

Aspect	Corresponding sector in I-O table	Share of Cost (%)
Depreciation and amortization	Capital consumption allowance	40
Property and corporate taxes	Indirect taxes (excluding customs)	15
Maintenance costs	Construction repair	10
Insurance and interest expenses	Finance and insurance	10
Land rental costs	Real estate brokerage and leasing	1
General and administrative expenses	Compensation for employment	5
Profits	Operating surplus	19

$\mathbf{C}^{d}$ has 7 rows and 404 columns; within which we account for sectors related to manufacturing and construction considering only "domestic fixed capital formation," included in the final demand since it uses commodities not listed as endogenous. The calculations related to the "Wind power utility" sector estimate the amount of electricity supplied and the rate of supply to each sector in the I-O table. The amount of electricity generated by wind power is distributed in proportion to these rates. Electricity is regarded as a uniform product, whether generated by the conventional power sector or the wind power sector. Therefore, domestic electricity produced by the conventional power sector is substituted with that from the new wind power sector. In terms of the wind power sector, electricity generated is purchased at the FIT price; this becomes a negative effect induced by the difference in electricity price between the wind power sector and the conventional power sector.

A has 404 rows and 404 columns and is the same as the existing I-O table for Japan in 2005 [25]. It should be noted that the wind turbine manufacturing and construction sectors are based on single-year analyses, whereas the wind power sector overall refers to a 20-year analysis that considers the system's lifetime. Therefore, the output of the wind power sector is converted to its current value with an assumed discount rate of 3%. These conditions are then reflected in the results of this study.

4. Results and Discussion

4.1 Economic effects

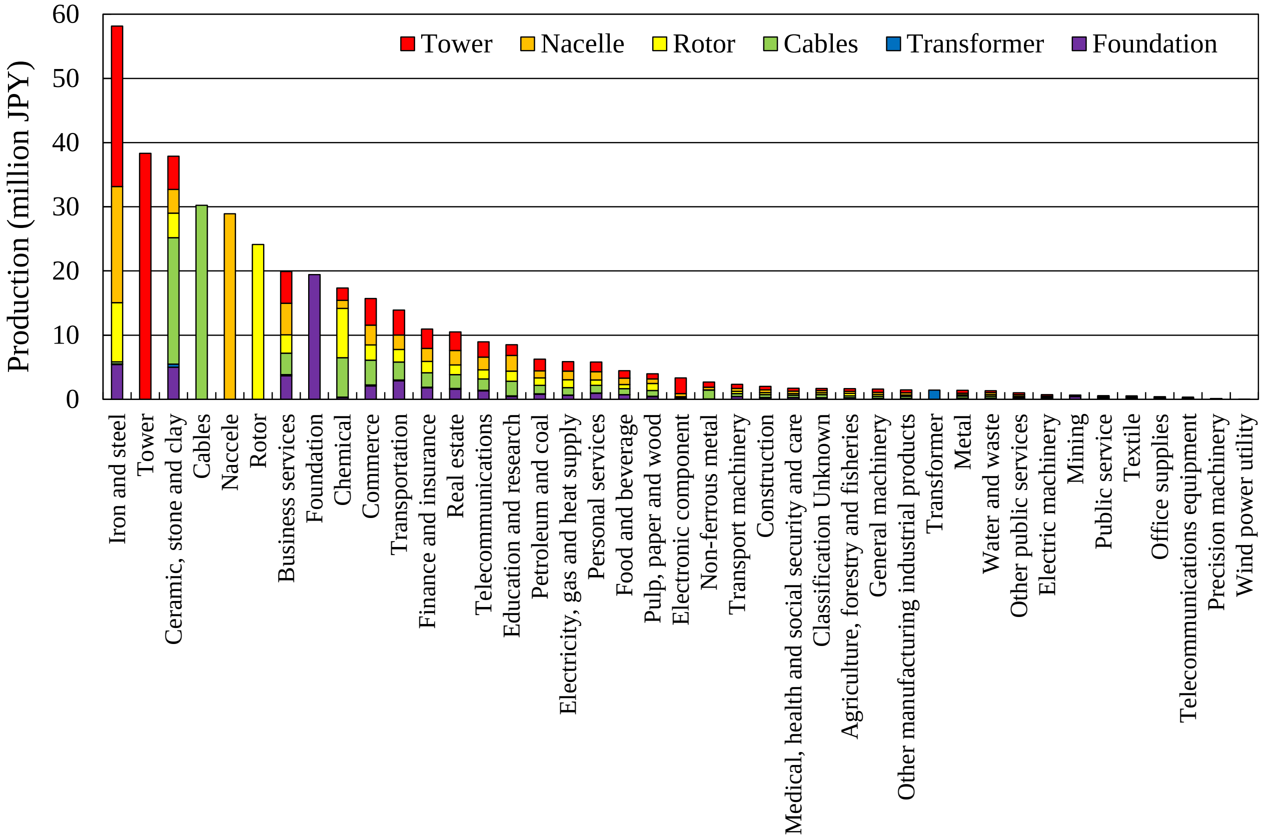
The analysis using the newly developed I-O table, including the new sectors related to wind power generation, estimated the value of induced domestic production to be 1,551 million JPY (396 million JPY from manufacturing and construction and 1,155 million JPY from operations). The amount of induced added value was estimated to be 965 million JPY (154 million JPY from manufacturing and construction and 810 million JPY from operations).

Fig. 3 depicts the direct and indirect effects on each industrial sector by manufacturing and constructing the wind power generation system; Fig. 3(a) illustrates domestic production, and Fig. 3(b) presents added value. Although there are both large and small induced effects, a range of industries experience economic ripple effects in terms of both production and added value. Despite this indirect effect, the largest induced effect was on the Iron and steel sector, which represented 15% of total production and 11% of total added value. This is because steel materials are used to make many of the components of the wind power generation system.

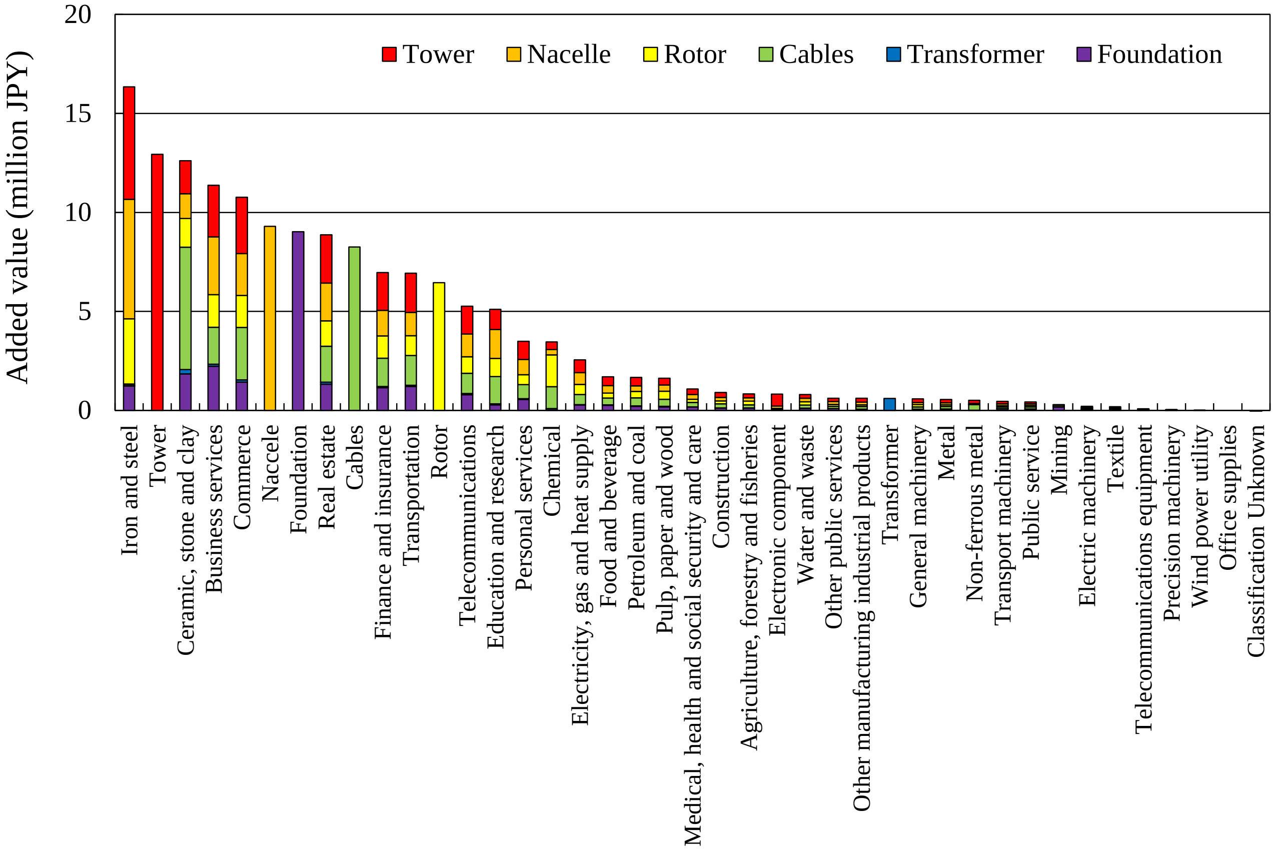
Comparing Fig. 3(a) and Fig. 3(b), the relative levels of added value in service industries such as sectors related to Business services, Commerce, and Real estate, are higher than that of domestic value, while part of the manufacturing and construction sectors, such as those related to Nacelle, Rotor, Cables, and Chemicals, have lower added value. The new coefficients of added value created by each industry's production activities or tied to gross national product (GNP), are high in the service industry. Since there are some sectors likely to receive added value, it is important to account for both direct and indirect ripple effects in order to evaluate the actual socioeconomic impact. On the other hand, the Iron and Steel; Tower; and Ceramic, Stone and Clay sectors are high in both domestic production and added value, so these sectors experience exceptional added values in line with the production targeting the wind power generation system installation.

Fig. 4 depicts the direct and indirect effects on in each industrial sector by wind power generation operations; Fig. 4(a) shows domestic production, and Fig. 4(b) shows added value. Since wind power uses only natural energy to generate electricity and there is little need to use the goods and services of other industries, the ripple effect on society as a whole is small. Production effects appeared only in the construction sector (i.e., maintenance) and finance and insurance sector (i.e., clerical financial processing). The decreased demand for conventional power and the negative effects of changes in electricity prices are represented as negative values in Fig. 4, but the indirect ripple effect of operating the wind power generation system is small.

Fig. 5 shows the relationship between sectors related to wind power generation and other sectors in the I-O table. By calculating and plotting the linkage effects, the manufacturing and construction sectors developed in this study are plotted in the fourth quadrant along with other manufacturing and construction sectors. The "Wind power utility" sector is plotted in the third quadrant, indicating that the linkage effects are smaller than those of the conventional power sector. This reflects the fact that the "Wind power utility" sector is one of the stand-alone industries in the I-O table because wind power generation,

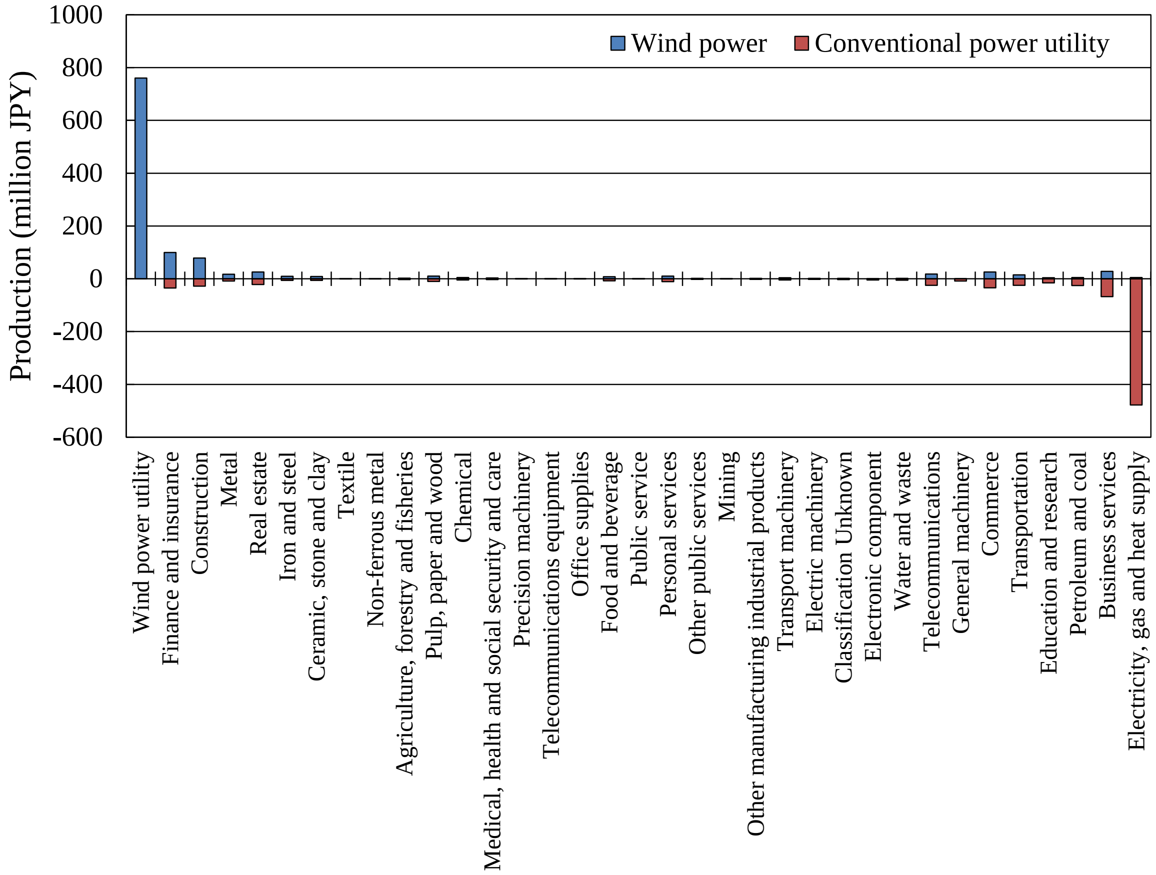


(a) Domestic production

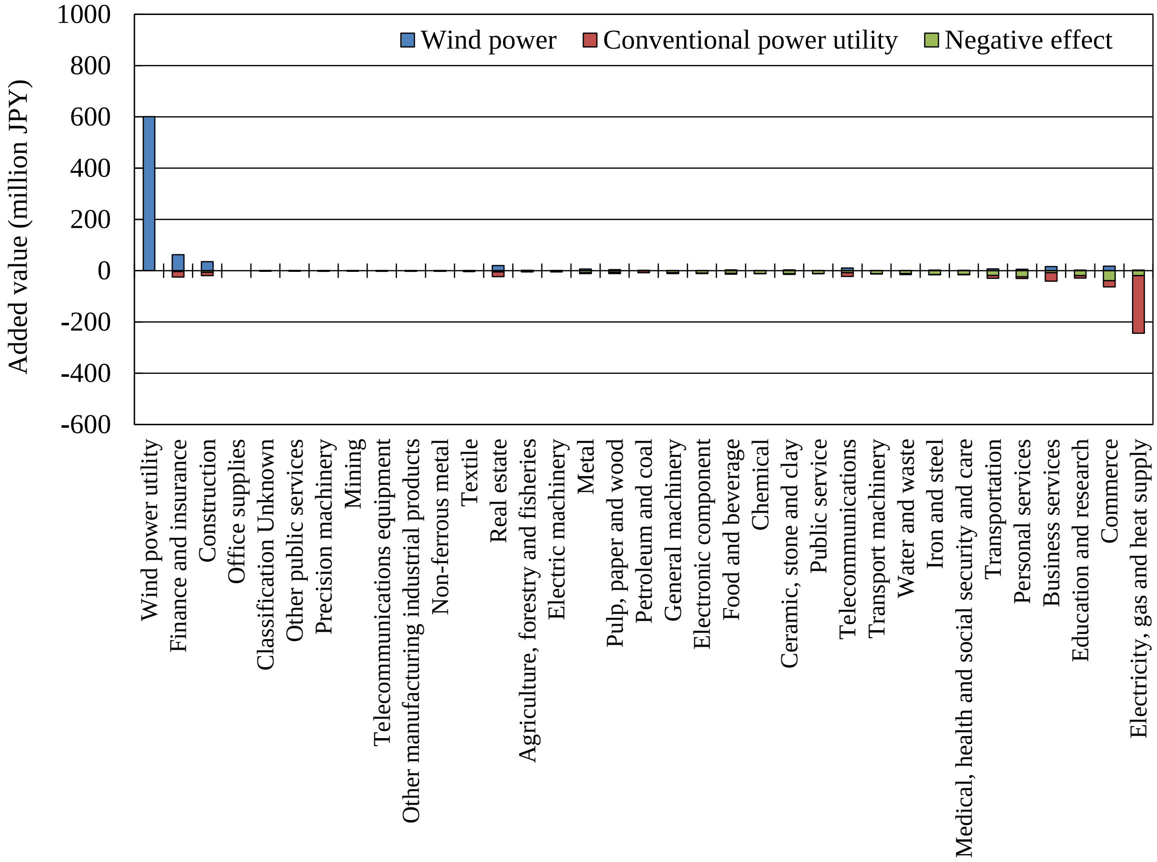


(b) Added value

Fig. 3 Effects of the wind power generation system’s manufacturing and construction, by sector



(a) Domestic production



(b) Added value

Fig. 4 Effects of the wind power generation system’s operation, by sector

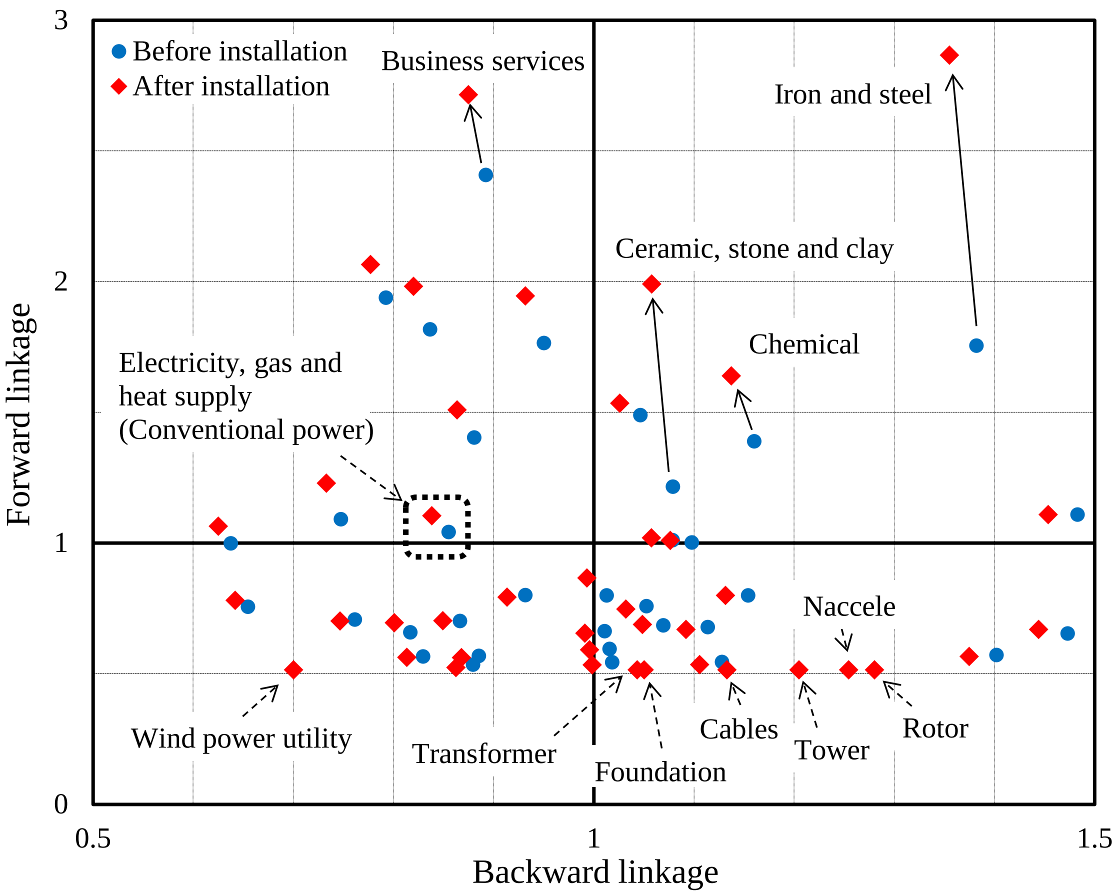


Fig. 5 Linkage effects for each industry before and after installation of the wind power generation system

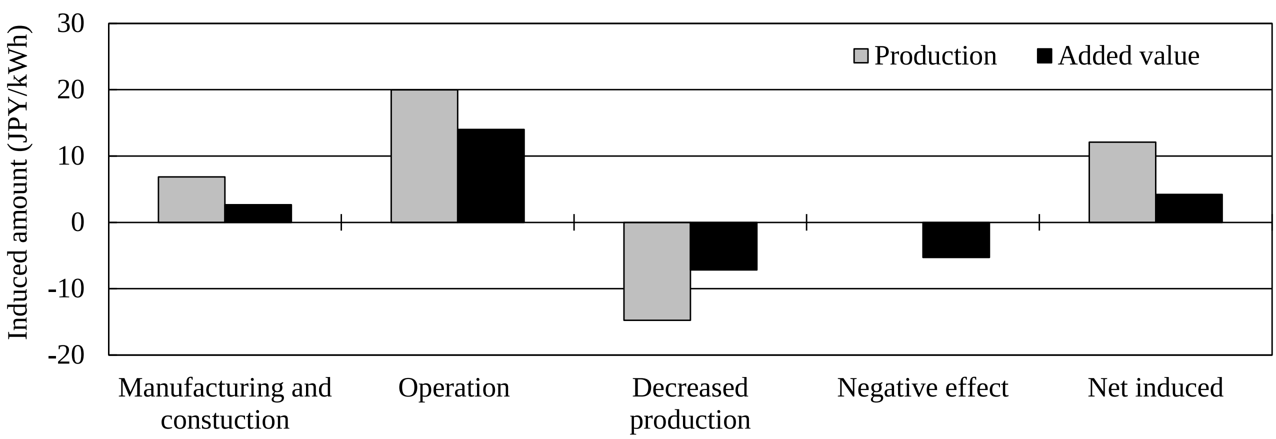
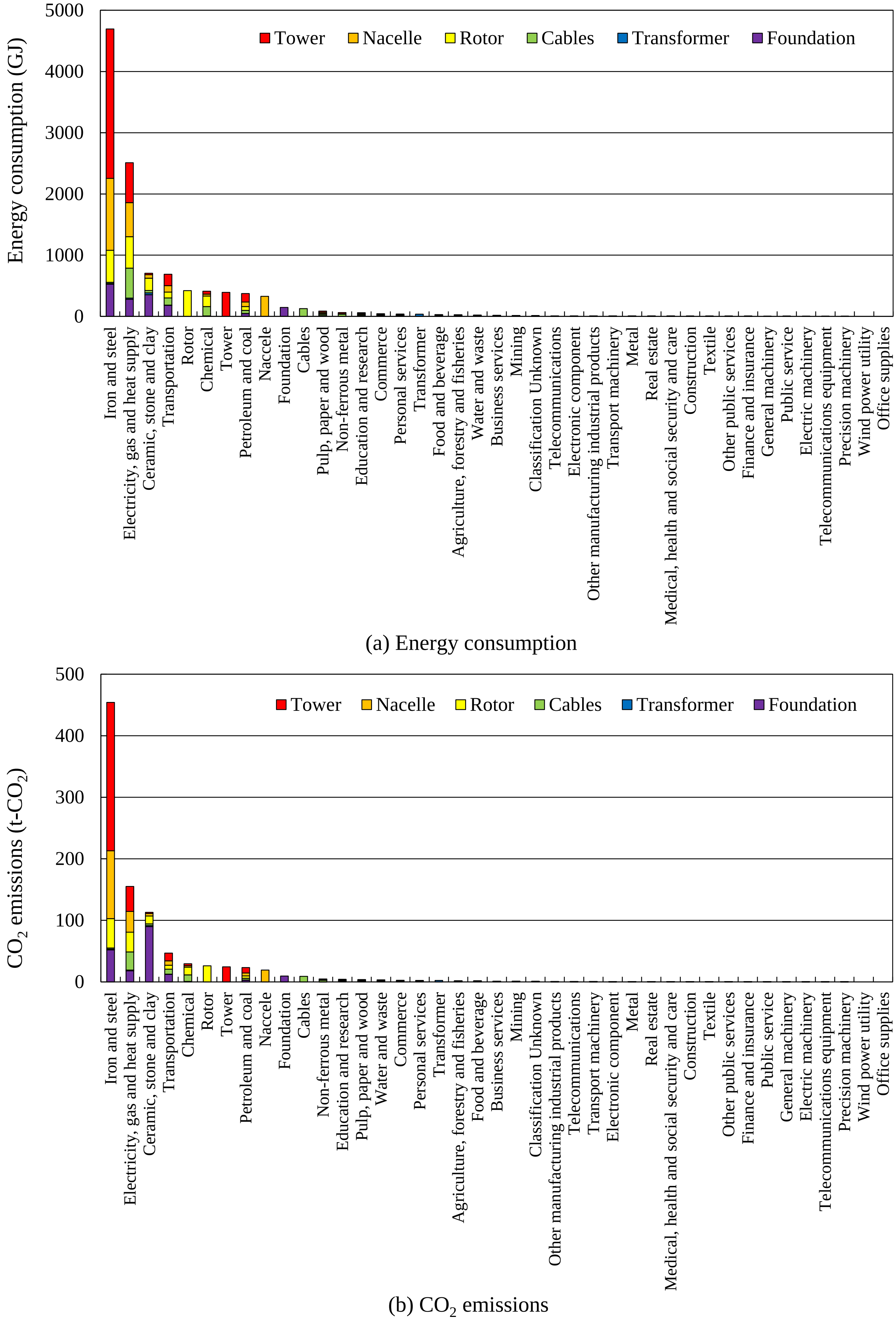


Fig. 6 Net production and added value per kWh.

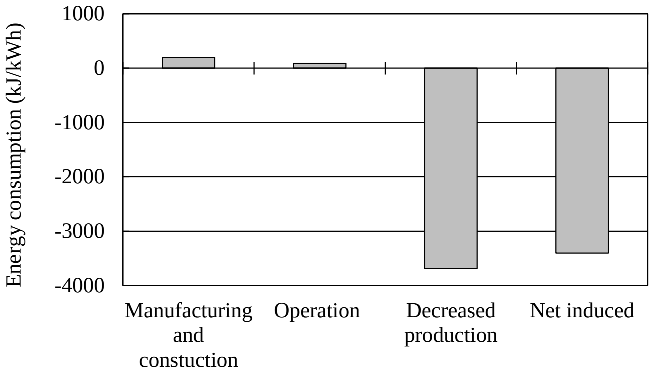
unlike conventional power technologies, does not require fossil fuels. The backward linkages decrease for most industries because the developed sectors' forward linkages are small, making them difficult to affect. In addition, the forward linkages become larger than before for the industrial sectors, such as "Iron and steel," which is 1.6 times its former size. These sectors deal in goods and services that are needed for manufacturing and construction of the wind power generation system, so their forward linkages increase from the wind power generation system installation. Fig. 5 also compares the structure of the exiting I-O table and the new I-O table with the added sectors. While industrial sectors closely related to manufacturing and constructing the wind power generation



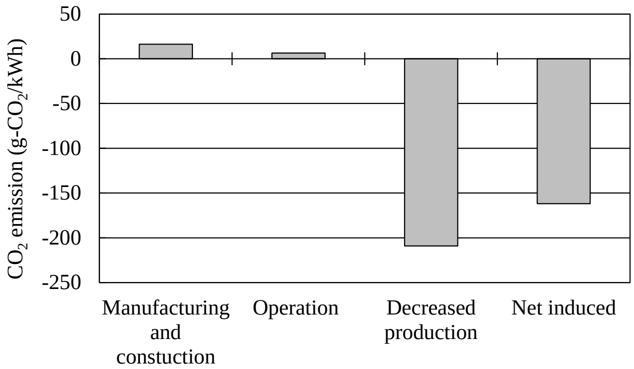
(a) Energy consumption

(b) CO_2 emissions

Fig. 7 Environmental burdens in each industry by manufacturing and constructing the wind power generation system



(a) Energy consumption



(b) CO_2 emissions

Fig. 8 Net environmental burden from the wind power generation system, per kWh

system, such as iron, steel, ceramic, stone and clay, have major changes, the positional relationship between the other sectors are not changed significantly in Fig. 5. In other words, the structure of the new I-O table is reasonable to for analyzing the economic ripple effect, such as in Figs. 3 and 4.

Considering the negative effects (i.e., decreased output of conventional power and additional cost), the net value is positive. This indicates that the overall economic effect of installing the wind power generation system is positive, despite some degree of economic burden in each sector. Fig. 6 shows the burden for each sector and the net value. It is noted that The Tower, Nacelle, Rotor, Cables, Transformer, and Foundation sectors influence manufacturing and construction. Further, operations affect the Wind power utility sector, while the conventional power sector experiences reduced production due to declining demand, and there is a negative effect from differences in prices between wind and conventional power. These values are converted to per-kWh estimates for comparison with other power generation technologies.

4.2 Energy and environmental effects

The amount of energy consumption and CO_2 emissions induced from manufacturing, construction, and operations were estimated to be 16 TJ and 1,316 t CO_2, respectively, mostly from manufacturing and construction. Fig. 7 depicts the direct and indirect environmental burdens arising in each industrial sector due to manufacturing and construction of the wind power generation system; Fig. 7(a) refers to energy consumption and Fig. 7(b) to CO_2 emissions. These burdens are concentrated in specific sectors (such as Iron and steel; Electricity, gas and heat supply; Ceramic, stone, and clay; and Transportation), which account for 75% of total energy consumption and 69% of total CO_2 emissions. Therefore, these energy and environmental burdens are important factors that should not be ignored because they are indirect effects from manufacturing and construction. It is necessary to move forward with reducing energy consumption and CO_2 emissions from such industries.

Considering the negative effects of decreased output from the conventional power sector, the associated net values of energy consumption and CO_2 emissions are negative. That is, less energy is consumed and less CO_2 emitted through the installation of the wind power generation system than is saved or reduced through the decreased output of the conventional power sector. Fig. 8 shows the amount of induced energy consumption and CO_2 emissions for each sector as well as the net value. These values are converted to per-kWh figures for comparison with other power generation technologies.

5. Conclusion

In this study, new sectors related to wind power generation systems were added to an I-O table that was then used to analyze the economic, energy consumption, and CO_2 emissions impacts associated with system installation. The results clearly showed that a wide range of industries experience economic ripple effects. The negative economic effects (i.e., reduced production in the conventional power sector and additional costs) are smaller than the positive effects of installing the wind power system. When considering the net value of energy consumption and CO_2 emissions, the installation saves energy and reduces CO_2 emissions. In each industrial sector, the material and energy impacts of system manufacturing, construction, and operation are large. This is particularly true for the iron and steel and power, gas, and heat supply sectors, which often supply the materials and energy used by wind and conventional power generation systems. Additionally, the environmental load factors of these sectors are higher than those of other sectors to start with. The results from this study are of particular interest to policymakers responsible for making related decisions.

This study's analysis focused on Japan and thus reflects Japanese social structures, as shown in the results of the I-O analysis. As the technological characteristics of wind power generation systems do not change significantly, the results suggest that installing wind power generation systems with technological characteristics similar to that examined here will have a favorable impact on Japan. The I-O analysis is available for several countries with a domestic I-O table. Furthermore, many areas use wind power generation systems made by Vestas. Therefore, this paper may be of use for those in other countries, and the results of analysis may reflect the social structure in each country.

Acknowledgements

This work was supported by Grant-in-Aid for Scientific Research (KAKENHI, Grant Number 24360403) of Japan Society For The Promotion of Science.

References

[1] Intergovernmental Panel on Climate Change. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press (2014) 511-597(Chapter 7).

[2] International Energy Agency. World Energy Outlook 2013; (2013) 197-229(Chapter 6).

[3] H. Dai, X. Xie, Y. Xie, J. Liu, T. Masui. Green growth: The economic impacts of large-scale renewable energy development in China; Applied Energy, 162 (2016) 435-449.

[4] N. Apergis, J. E. Payne. The renewable energy consumption–growth nexus in Central America; Applied Energy, 88 (2011) 343-347.

[5] W. Liu, H. Lund, B. V. Mathiesen, X. Zhang. Potential of renewable energy systems in China; Applied Energy, 88 (2011) 518-525.

[6] International Energy Agency. Technology Roadmap Wind energy 2013 edition; (2013).

[7] B. Tremeac, F. Meunier. Life cycle analysis of 4.5MW and 250W wind turbines; Renewable and Sustainable Energy Reviews, 13 (2009) 2104-2110.

[8] B. Reimers, B. Ozdirik, M. Kaltschmitt. Greenhouse gas emissions from electricity generated by offshore wind farms; Renewable Energy, 72 (2014) 428-438.

[9] C. Marimuthu, V. Kirubakaran. Carbon pay back period for solar and wind energy project installed in India: A critical review; Renewable and Sustainable Energy Reviews, 23 (2013) 80-90.

[10] E. Martínez, E. Jiménez, J. Blanco, F. Sanz. LCA sensitivity analysis of a multi-megawatt wind turbine; Applied Energy, 87 (2010) 2293-2303.

[11] E. Martínez, F. Sanz, S. Pellegrini, E. Jiménez, J. Blanco. Life cycle assessment of a multi-megawatt wind turbine; Renewable Energy, 34 (2009) 667-673.

[12] R. H. Crawford. Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of

size on energy yield; Renewable and Sustainable Energy Reviews, 13 (2009) 2653-2660.

[13] S. Alvarez, M. Sosa, A. Rubio. Product and corporate carbon footprint using the compound method based on financial accounts. The case of Osorio wind farms; Applied Energy, 139 (2015) 196-204.

[14] Y. Wang, T. Sun. Life cycle assessment of CO_2 emissions from wind power plants: Methodology and case studies; Renewable Energy, 43 (2012) 30-36.

[15] A. Verma, A. Kumar. Life cycle assessment of hydrogen production from underground coal gasification; Applied Energy, 147 (2015) 556-568.

[16] A. Thakur, C. E. Canter, A. Kumar. Life-cycle energy and emission analysis of power generation from forest biomass; Applied Energy, 128 (2014) 246-253.

[17] C. Strazza, A. D. Borghi, P. Costamagna, A. Traverso, M. Santin. Comparative LCA of methanol-fuelled SOFCs as auxiliary power systems on-board ships; Applied Energy, 87 (2010) 1670-1678.

[18] J. Mª López, Á. Gómez, F. Aparicio, F. J. Sánchez. Comparison of GHG emissions from diesel, biodiesel and natural gas refuse trucks of the City of Madrid; Applied Energy, 86 (2009) 610-615.

[19] U. Desideri, S. Proietti, F. Zepparelli, P. Sdringola, S. Bini. Life Cycle Assessment of a ground-mounted 1778 kW_p photovoltaic plant and comparison with traditional energy production systems; Applied Energy 97, (2012) 930-943.

[20] F. Ardente, M. Beccali, M. Cellura, V. L. Brano. Energy performances and life cycle assessment of an Italian wind farm; Renewable and Sustainable Energy Reviews, 12 (2008) 200-217.

[21] Y. Mizumoto, Y. Uchiyama, K. Okajima. Environment, energy, economic analysis of solar PV system installation with hybrid input-output analysis; Master's thesis for Graduate School of Systems and Information Engineering, University of Tsukuba; (2012).

[22] M. Lenzen, U. Wachsmann. Wind turbines in Brazil and Germany: an example of geographical variability in life-cycle assessment; Applied Energy, 77 (2004) 119-130.

[23] R. Heijungs, S. Suh. The Computational Structure of Life Cycle Assessment; Kluwer Academic Publishers (2011).

[24] S. Suh. Material and energy flows in industry and ecosystem networks; Leiden University Press (2004).

[25] Ministry of Internal Affairs and Communications of Japan. 2005 Input-output table; (2009)(Japanese).

[26] T. T. Raa. The Economics of Input-Output Analysis; Cambridge University Press (2006).

[27] W. Leontief. Input-Output Economics: Second Edition; Oxford University Press (1986).

[28] A. O. Hirschman. The Strategy of Economic Development; Yale University Press (1958).

[29] D. Chun, C. Woo, H. Seo, Y. Chung, S. Hong, J. Kim. The role of hydrogen energy development in the Korean economy: An input-output analysis; International Journal of Hydrogen Energy, 39 (2014) 7627-7633.

[30] J.R. San Cristóbal, M. V. Biezma. The mining industry in the European Union: analysis of inter-industry linkages using input-output analysis; Resources Policy, 31 (2006) 1-6.

[31] M. Sonis, G. J. D. Hewings. Economic landscapes: Multiplier project matrix analysis for multiregional input-output systems; Hitotsubashi Journal of Economics, 40 (1999) 59-74.

[32] R. Duarte, J. Sánchez-Chóliz, J. Bielsa. Water use in the Spanish economy: an input-output approach; Ecological Economics, 43 (2002) 71-85.

[33] S. Y. Han, S.H. Yoo, S. J. Kwak. The role of the four electric power sectors in the Korean national economy: an input-output analysis; Energy Policy, 32 (2004) 1531-1543.

[34] Y. Zhao, Z. Zhang, S. Wang, Y. Zhang, Y. Liu. Linkage analysis of sectoral CO_2 emissions based on the hypothetical extraction method in South Africa; Journal of Cleaner Production, 103 (2015) 916-924.

[35] K. Nansai, Y. Moriguchi, S. Tohno. Embodied Energy

and Emission Intensity Data for Japan Using Input-Output Table (3EID); Center for Global Environmental Research National Institute for Environmental Studies Independent Administrative Institution, (2010).

[36] A. M. Rodríguez-Alloza, A. Malik, M. Lenzen, J. Gallego. Hybrid inputeoutput life cycle assessment of warm mix asphalt mixtures; Journal of Cleaner Production, 90 (2015) 171-182.

[37] A. Malik, M. Lenzen, P. J. Ralph, B. Tamburic. Hybrid life-cycle assessment of algal biofuel production; Bioresource Technology, 184 (2015) 436-443.

[38] E. Igos, B. Rugani, S. Rege, E. Benetto, L. Drouet, D. S. Zachary. Combination of equilibrium models and hybrid life cycle-input–output analysis to predict the environmental impacts of energy policy scenarios; Applied Energy, 145 (2015) 234-245.

[39] Q. Jiang, T. Li, Z. Liu, H. Zhang, K. Ren. Life Cycle Assessment of an Engine with Input-Output Based Hybrid Analysis Method; Journal of Cleaner Production, 78 (2014) 131-138

[40] Q. Jiang, Z. Liu, T. Li, H. Zhang, A. Iqbal. Life Cycle Assessment of a Diesel Engine Based on an Integrated Hybrid Inventory Analysis Model; Procedia CIRP, 15 (2014) 496 -501.

[41] S. Suh, G. Huppes. Methods for Life Cycle Inventory of a product; Journal of Cleaner Production 13, (2005) 687-697.

[42] Vestas Wind Systems A/S. V82-1.65 MW.

[43] Vestas Wind Systems A/S. Life cycle assessment of electricity produced from onshore sited wind power plants based on Vestas V82-1.65 MW turbines; (2006).

[44] Y. Ishikawa, R. Nakamura, A. Matsumoto. Economic effects of renewable energy in the Tohoku region: analysis of solar power and wind power generation introduced by inter-regional input-output table; Research Institute of Economy, Trade and Industry, (2012) 12 (Japanese)