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Hybrid input–output table method for socioeconomic and environmental assessment of a wind power generation system

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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 CO_2 emissions.

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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.

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

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Nomenclature

$\mathbf{X}$	vector of domestic production
$\mathbf{I}$	unit matrix
$\mathbf{A}$	matrix of input coefficients
$\mathbf{F}^d$	vector of domestic final demand
$\mathbf{E}$	vector of exports
$\mathbf{M}'$	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
$\mathbf{R}$	vector of added value
$\mathbf{P}$	matrix of added value coefficients
$\mathbf{R}_{energy}$	vector of energy consumption
$\mathbf{P}_{energy}$	matrix of energy consumption coefficients
$\mathbf{R}_{CO_2}$	vector of CO_2 emissions
$\mathbf{P}_{CO_2}$	matrix of CO_2 emissions coefficients
$\mathbf{A}^{hybrid}$	matrix of input coefficients in hybrid model
$\mathbf{A}^*$	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

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 $\mathbf{X}$ required to meet an arbitrary final demand for output is calculated by Eq. (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.

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

In this equation, $\mathbf{I}$ is an unit matrix, $\mathbf{M}'$ is a diagonal matrix with diagonal elements as import coefficients, $\mathbf{A}$ is a matrix of input coefficients, $\mathbf{F}^d$ is a vector of final domestic demand, and $\mathbf{E}$ is a vector of exports. A polynomial of $\mathbf{I}$–$\mathbf{M}'$ 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 Eq. (2).

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

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 Eq. (3).

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

In Eqs. (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.

The amount of domestic production induced by final demand can be divided into intermediate demand and added value. Eq. (4) represents the added value $\mathbf{R}$ associated with each sector's domestic production.

$$\mathbf{R} = \mathbf{P}\mathbf{X} \tag{4}$$

In this equation, $\mathbf{P}$ 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 Eq. (5).

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

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

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