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Comprehensive Evaluation of Power Generation Methods by Inclusive Impact Index

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Renewable energy is considered worldwide as a sufficient solution to mitigate climate change. Since the application of a new technology is affected by various factors, it is crucial to consider both the advantages and disadvantages of new technology related to, for example, the environment, economy, and society. Most of the current studies do not focus on the quantifiable measurement of the potential of renewable energy as an alternative to fossil fuel energy, especially in power generation sector. This paper aimed to quantitatively recognise the sustainability of different renewable power sources compared to conventional power sources by using Triple I. The Inclusive Impact Index, Triple I, is a metric developed to assess environmental sustainability and economic feasibility of utilisation technologies to predict their public acceptance. Triple I can be obtained by subtracting biocapacity (BC) and generated benefits (B) from total ecological footprint (EF), ecological risk (ER), human risk (HR), and costs (C) caused by the system. Findings from this paper found that fossil fuel-based power generation was not sustainable due to the significant environmental burden. Apart from tidal energy and large-scale Ocean Thermal Energy Conversion (OTEC) systems, the high cost of power plant installation and operation led to the unsustainability of ocean energy systems. Nuclear, wind, geothermal, hydro, and tidal and OTEC (100 MW) were found sustainable.

1. Introduction

Since the First Industrial Revolution took place in 1750, the raising demand for electricity due to economic growth has been secured mostly using fossil fuels, such as coal and oil and nuclear power. This adds enormous amounts of greenhouse gases (GHG) such as carbon dioxide (CO_2) to the atmosphere, which is the most significant driver of climate change. The Fukushima Daiichi Nuclear Power Plant incident in Japan in 2011 manifested noticeable potential risks of nuclear power. These situations have made the need for sustainable energy sources that can reduce environmental burdens and ensure human safety become a matter of global concern for decades. Renewable energy is considered as an ideal solution for the future energy provision. This paper aims to quantitatively recognise the sustainability of different renewable power sources compared to conventional power sources.

Since the sophisticated sustainability assessment requires the integration of both environmental and economic issues, a simplified Inclusive Impact Index, Triple I light, was applied in this study. Triple I light was developed by the Inclusive Marine Pressure Assessment and Classification Technology (IMPACT) in 2006. This indicator employs life cycle-based ecological footprint and life cycle costing technique to assess impacts of the studied system on the environment and economy. In this study, the sustainability of 13 different sources of power generation, including oil, gas, nuclear, wind, geothermal, biomass, hydro, solar, tidal, ocean current, wave, OTEC were examined. The environmental indicators include life cycle assessment using CO_2 emissions. Economic indicators include economic evaluation by costs and benefits. The environmental aspects and the economic aspects are evaluated separately. The purpose of this survey is to integrate environmental and economic aspects and quantitatively assess various power generation methods, especially whether renewable energy is sustainable.

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2. Materials and methods

2.1 Introduction to renewable energy

Renewable energy is energy that is derived from natural processes that are continuously replenished at a higher rate than they are consumed. Renewable energy systems also release less CO_2 than conventional power generation systems. This study evaluated various renewable energy sources, including wind, geothermal, biomass, hydro, solar, tidal, ocean current, wave and OTEC. In which, wind, geothermal, biomass, hydro, and solar are land-based renewable energy while tidal, ocean current, wave, and OTEC are marine renewable energy. Tidal energy system attempts to extract energy from the flow of ocean currents using a horizontal axis turbine to generate electricity. Ocean current energy system converts horizontal kinetic energy of water by tide into rotational energy of a turbine to generate electricity. Wave energy system generates electricity using kinetic energy of waves. For example, Oyster wave power generator: turbine is turned by pendulum structure. OTEC is a method to generate electricity using the temperature difference between the warm surface seawater and the cold deep one. The basic structure is the same as thermal power generation.
The different capacities of power generation plants considered in this paper were as follows:

- Hydro power plant: small scale (hydro small) - without dam and large scale (hydro) - using dam;
- Solar Photovoltaic system: small scale (PV small) for home use and large scale (PV) for commercial use;
- OTEC: 10 MW and 100 MW systems.

2.2 Inclusive Impact Assessment

2.2.1 Inclusive Impact Index (Triple I)

To evaluate the sustainability of various power generation technologies, an integrated method using life-cycle assessment approach to estimate the Inclusive Impact Index (Triple I) was chosen. Triple I can be obtained by subtracting biocapacity (BC) and generated benefits (B) from total ecological footprint (EF), ecological risk (ER), human risk (HR), and costs (C) caused by the system (Eq (1)) (Nguyen et al., 2015). Functional unit for the assessment was one kWh.

$$\text{Ⅲ} = [(EF - BC) + \alpha EF] + \gamma[\beta HR + (C - B)] \quad (1)$$

Where α, β, and γ is the conversion factor from ER to EF, HR to C and from economic value to environmental value, respectively.

2.2.2 Triple I light

In many energy development schemes, climate change mitigation and high installation and operation costs are two main issues related to renewable energy which are commonly put on the table. To solve the controversy over the two issues, Triple I light was applied. Triple I light focuses on evaluating life cycle-based ecological footprint and life cycle cost of a studied system and excludes the calculation of risk, including ER and HR (Eq (2)).

$$\text{Ⅲ}_{light} = EF - BC + \gamma(C - B) \quad (2)$$

Several scholars have applied the ratio of EF to GDP of the country where the studied system is implemented, as the conversion factory γ (Nguyen et al., 2015). In this study, γ was calculated as Eq(3):

$$\gamma = \frac{EF_{Japan}}{GDP_{Japan}} = \frac{6.388 \times 10^{8}}{5.879 \times 10^{12}} = 1.087 \times 10^{-4} \quad \text{(Gha.y/USD)} \quad (3)$$

where 6.388×10^8 Gha is the EF of Japan in 2012, and 5.879×10^{12} USD/y is GDP of Japan in 2012 (Global Footprint Network, 2016).
With regards to ecological footprint, costs, and benefits off the system were estimated based on the collected data on the construction, operation and disassembly of power plants, and the process of transporting, burning and discarding power generation fuels. Ecological footprint of CO_2 emissions is calculated as Eq(4):

$$EF = f_{forest} \times A_{forest} \times LC\text{-}CO_2 \quad (4)$$

where f_{forest} =1.26 Gha/ha is equivalence factor of forests. A_{forest} = 0.19 ha/t CO_2 is CO_2 absorption in the forest per hectare (Otsuka, 2011), and LC-CO_2: life cycle CO_2 is the amount of carbon dioxide that emerges from plant development to disposal.

2.2.3 Environmental indicator

This study aimed to estimate the total environmental impacts of various power generation methods. Several previous studies on environmental impacts of power generation methods have been carried out. Carbon dioxide (CO_2) as a major share in GHG emissions has a great influence on global warming. The amount of CO_2 emissions was thus chosen to be an environmental impact indicator. Life cycle assessment (LCA) based on CO_2 emissions was conducted. Total CO_2 emissions associated with the construction, operation and disassembly of power plants, and the process of transporting, burning and discarding power generation fuels was analysed.

2.2.4 Economic indicator

Economic indicators are mainly composed of cost (C) and benefit (B). Cost of construction, operation, disposal and fuel used were estimated. The value of B was the unit price of electricity in Japan, which is USD/kWh. This price originally includes a power generation promotion charge of 0.007 USD/kWh, which is a renewable energy subsidy. As the amount of the subsidy is declining year by year, it was excluded from the calculation. This made the price of electricity in Japan became 0.202 USD/kWh (TEPCO, 2014).

3. Results and discussion

3.1 Environment assessment

There was a considerable difference between fossil fuels, including coal, oil and gas, and other sources of power generation as summarised in Table 1. Direct CO_2 emissions are CO_2 emissions from fossil fuel combustion in power plant, and indirect CO_2 emissions are CO_2 emissions from other processes in power plant. An abundant amount of direct CO_2 emissions was observed in fossil fuel-based power generation plants. Fossil fuel energy currently shares appropriately 85 % of Japan electricity generation. Regarding OTEC, we found that the value of EF decreased as the capacity of power plant increased. Substituting OTEC (10 MW) for fossil fuel power generation resulted in reduction of more than 90 % of CO_2.

Table 1: Summary of power plant capacity, direct and indirect CO_2 emissions and EF

Power generation source	Capacity (MW)	CO_2 emission (direct) (g CO_2/kWh)	CO_2 emission (indirect) (g CO_2/kWh)	EF (gha/kWh)	Reference
Coal	1,000	864	79	2.3×10^{-4}	Imamura et al., 2016
Oil	1,000	695	43	1.8×10^{-4}	Imamura et al., 2016
Gas	1,000	376	98	1.1×10^{-4}	Imamura et al., 2016
Nuclear	1,000	-	20	4.8×10^{-6}	Imamura et al., 2016
Wind	20	-	25	6.0×10^{-6}	Imamura et al., 2016
Geothermal	55	-	13	3.1×10^{-6}	Imamura et al., 2016
Biomass	457	-	43	1.0×10^{-5}	Spath and Mann, 2004
Hydro (small)	3.2	-	3.7	8.9×10^{-7}	Dones et al., 1996
Hydro	10	-	11	2.6×10^{-6}	Imamura et al., 2016
PV (small)	0.0038	-	38	9.1×10^{-6}	Imamura et al., 2016
PV	2.0	-	59	1.4×10^{-5}	Imamura et al., 2016
Tidal	8,640	-	5.7	1.4×10^{-6}	Adams, 2008
Ocean current	1.2	-	15	3.6×10^{-6}	Walker and Howell, 2011
Wave	0.32	-	25	6.0×10^{-6}	Walker and Howell, 2011
OTEC (10 MW)	10	-	42	1.0×10^{-5}	Aalbers, 2015
OTEC (100 MW)	100	-	12	3.0×10^{-6}	Aalbers, 2015

3.2 Economy assessment

Based on Table 2, among the renewable energy sources, costs of wind, geothermal, hydro, tidal, OTEC (100 MW) were the lowest, which are less than 0.15 USD per kWh. Costs of biomass, hydro (small), PV (small) and PV were about twice and costs of ocean current, wave and OTEC (10 MW) were several times those costs of wind, geothermal, hydro, tidal and OTEC (100 MW).

Table 2: Summary of cost and C - B

Power generation method	Cost (USD/kWh)	C - B (USD/kWh)	Reference
Coal	0.09	- 0.120	METI, 2015
Oil	0.27	0.060	METI, 2015
Gas	0.12	- 0.090	METI, 2015
Nuclear	0.08	- 0.120	METI, 2015
Wind	0.15	- 0.060	METI, 2015
Geothermal	0.10	- 0.100	METI, 2015
Biomass	0.27	0.060	METI, 2015
Hydro (small)	0.22	0.020	METI, 2015
Hydro	0.10	- 0.100	METI, 2015
PV (small)	0.26	0.060	METI, 2015
PV	0.20	0.004	METI, 2015
Tidal	0.09	- 0.110	Crumpton, 2004
Ocean current	0.47	0.270	Ocean Energy Systems, 2015
Wave	0.67	0.470	Ocean Energy Systems, 2015
OTEC (10 MW)	0.65	0.450	Ocean Energy Systems, 2015
OTEC (100 MW)	0.15	- 0.050	Ocean Energy Systems, 2015

Revenue of each power generation option was calculated based on the cost and selling price. The results indicated that not all cases were economically sustainable. This was because operation costs of the studied system exceed the revenue from the plant. It is crucial to develop a low-cost renewable energy technology. Financial support from the government also plays an important role in the application of the renewable energy system.

3.3 Triple I light calculation

Nuclear, wind, geothermal, hydro, tidal and OTEC (100 MW) were the power generation methods evaluated as sustainable as shown in Table 3 and Figure 1. Since nuclear did not include nuclear fuel waste disposal and OTEC (100 MW) has not been realised at this stage, the two sources were excluded from the sustainable energy source list. Regarding unsustainable power generation sources, coal, gas and PV had high environmental impacts, and biomass, hydro (small), PV (small), ocean current, wave and OTEC (10 MW) had high costs. Oil appeared to have disadvantages in both environmental and economic impacts due to vast amount of CO_2 emissions and high costs. These showed a strong influence of the balance between environmental factor and economic factor in the sustainable potential of a system.

Table 3: Summary of EF, γ(C - B) and Triple I light [j]

Power generation method	EF (gha/kWh)	γ(C - B) (gha/kWh)	III_{light}
Coal	2.3×10^{-4}	$- 1.3 \times 10^{-5}$	2.1×10^{-4}
Oil	1.8×10^{-4}	6.8×10^{-6}	1.8×10^{-4}
Gas	1.1×10^{-4}	-9.3×10^{-6}	1.0×10^{-4}
Nuclear	4.8×10^{-6}	$- 1.3 \times 10^{-5}$	$- 8.2 \times 10^{-6}$
Wind	6.0×10^{-6}	$- 6.0 \times 10^{-6}$	$- 6.3 \times 10^{-10}$
Geothermal	3.1×10^{-6}	$- 1.1 \times 10^{-5}$	$- 7.7 \times 10^{-6}$
Biomass	1.0×10^{-5}	6.8×10^{-6}	1.7×10^{-5}
Hydro (small)	8.9×10^{-7}	2.2×10^{-6}	3.1×10^{-6}
Hydro	2.6×10^{-6}	$- 1.1 \times 10^{-5}$	$- 8.3 \times 10^{-6}$
PV (small)	9.1×10^{-6}	6.0×10^{-6}	1.5×10^{-5}
PV	1.4×10^{-5}	$- 4.5 \times 10^{-7}$	1.4×10^{-5}
Ocean current	1.4×10^{-6}	$- 1.2 \times 10^{-5}$	$- 1.1 \times 10^{-5}$
Tidal	3.6×10^{-6}	2.9×10^{-5}	3.3×10^{-5}
Wave	6.0×10^{-6}	5.1×10^{-5}	5.7×10^{-5}
OTEC (10 MW)	1.0×10^{-5}	4.9×10^{-5}	5.9×10^{-5}
OTEC (100 MW)	3.0×10^{-6}	$- 5.7 \times 10^{-6}$	$- 2.7 \times 10^{-6}$

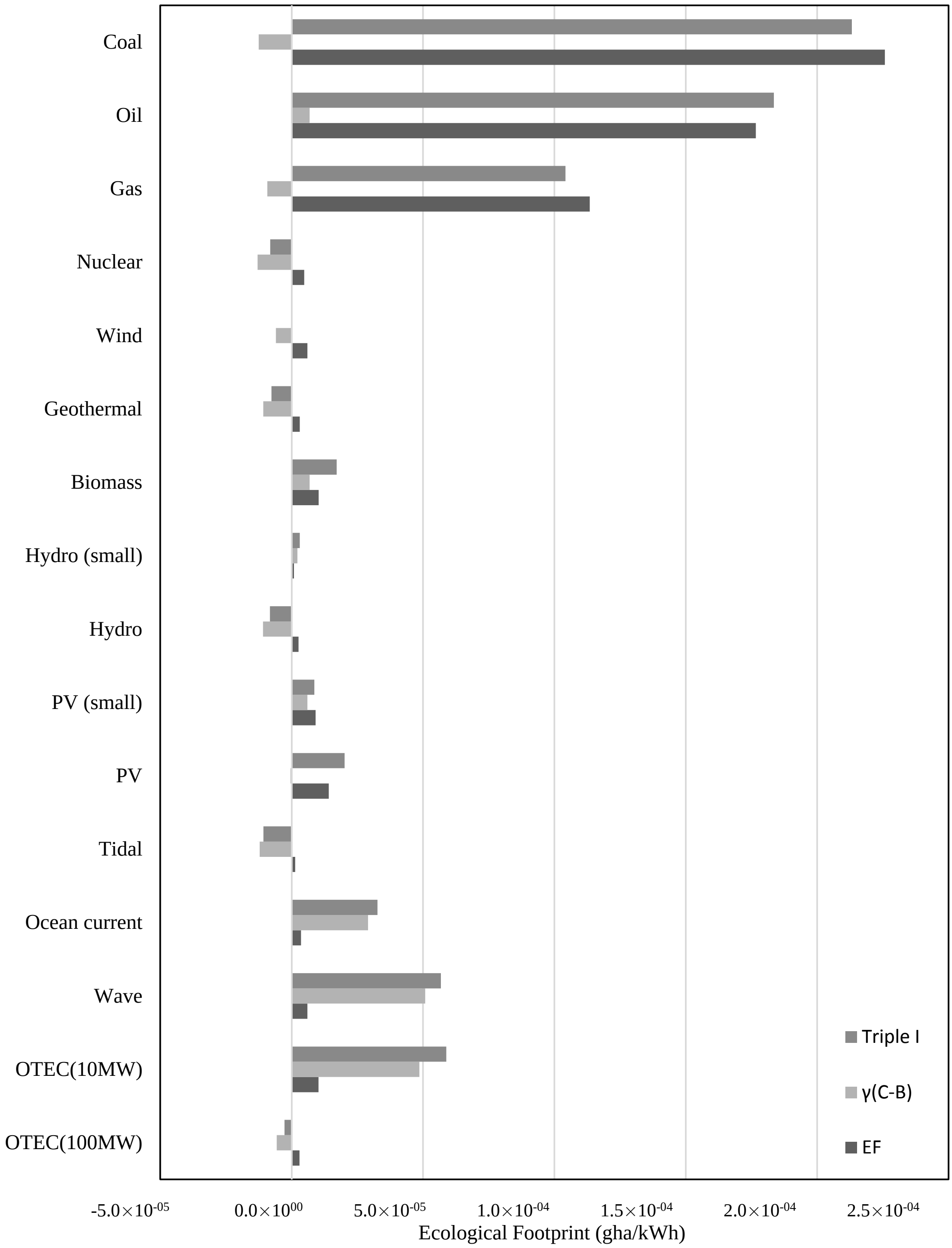

Figure 1: Summary of EF, γ(C - B) and Triple I light[j]

4. Conclusion

In this study, we applied Triple I light to evaluate impacts and benefits of power generation methods. Findings from this study showed that wind, geothermal, hydro and tidal were found to be sustainable in modern power generation technology. The results also indicated that those sources were promising technique from both environmental and economic perspective. By integrating environmental and economic indicators, the sustainable potential of a system was considered diversely and evaluated comprehensively.

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