Emergy-based sustainability evaluation of wind power generation systems

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HIGHLIGHTS

- Emergy is used to quantify the sustainability level of wind farms.
- A GHG-based indicator is incorporated into emergetic accounting.
- Possible pathways to achieve sustainable wind farm management are analyzed.

ABSTRACT

With large-scale commercialization of wind technology, one must investigate economical and sustainable wind resource utilization. In this paper, emergy analysis is used to quantify the environmental pressure, renewability, economic efficiency, and sustainability of a typical wind power system, considering the lifetime stages from extraction and processing of raw materials and resources to the final product (electricity) via material transportation, construction and operation. Possible pathways to achieve sustainable management of wind energy supply chain were also analyzed based on scenario analysis. Results show that wind power is a promising means of substituting traditional fossil fuel-based power generation systems, with the lowest transformity of $4.49 \times 10^4$ sej/J, smaller environmental loading ratio of 5.84, and lower greenhouse gas emission intensity of 0.56 kg/kWh. To shed light on potential pathways to achieve sustainable and low-carbon wind energy supply chain management and make informed choices, a sensitivity analysis was done by establishing scenarios from the perspectives of material recycling and technical development. Results suggest that using new materials of lower energy intensity or recycled materials in upstream wind turbine manufacturing and construction materials are the most effective measures.

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1. Introduction

Driven by concerns about greenhouse gas (GHG) emissions, rising energy prices, and energy shortages, development of the wind power industry with great GHG emission mitigation potential has been accelerating in recent years, with 51.473 GW of new wind capacity installed globally in 2014 alone [1]. According to the 2013 IEA Technology Roadmap, the share of wind power in electricity supply should continue to increase, from its current 2.6% to 18% by 2050 [2]. Because wind power relies on the wind resource for a portion of its input, it is often presented as a very “clean and sustainable” energy, with little or no consideration of the ecological costs and related environmental impacts. However, wind farms may require higher initial investments in infrastructure than fossil-based power systems [3]. Therefore, one must study the entire supply chain of wind resource utilization to account for its efficiencies, environmental impacts, GHG emissions, and sustainability, thereby facilitating long-term wind resource utilization management and planning.

To determine the environmental impacts caused by wind power penetration, life cycle assessment (LCA), which is advantageous in explicit and rigorous calculation of direct and indirect environmental effects, has been widely used in evaluating the hidden environmental emissions of wind energy technologies [4–14]. However, LCA of wind power systems does not quantify social cost and the
environment’s role in absorbing and processing pollution [15].
Thus, it is not adequate for the evaluation of a technology’s net
contributions to the economy and sustainability of the energy
conversion process.

Emergy ontology, proposed by Odum [16], asserts that “all
wealth stems from the environment and its myriad systems and
processes, and that the value of services and commodities should
be based on the energy and resources required to produce them
rather than on what someone is willing to pay for them”. Since
energy traces to the beginning and origin of the being (products
or services), it is described as “energy memory”, which represents
a constant presence in a unified way [17]. Emergy analysis consid-
ers all systems to be networks of energy flows, and determines
the energy value of the streams and systems involved by multiplying
their transformities. The latter are defined as the ratios of emergy
required to make products to the energy of those products [18].
Because emergy analysis provides a more feasible approach to
assess the status and position of different energy carriers in the
universal energy hierarchy, and considers both the natural proper-
ties and economic characteristics of a system, it is widely
employed to evaluate public policy options and environmental
impacts of energy systems. This lends quantitative insight into
questions of resource management [19–22].

For emergy analysis of renewable energy systems, there has
been widespread research into the sustainability of biofuels and
bioenergy, such as wheat plantation/ethanol distillery systems
[23], residual material-based bioethanol production [24], corn
ethanol production [25], palm-based biofuel refinery systems
[26], soybean-based biodiesel production [27], and biogas [28,29].
In terms of renewable power generation systems, since the pioneer-
ing work of Brown and Ulgiati [30,31] that evaluated six electricity
production systems using energy and emergy accounting tech-
niques to rank their relative thermodynamic and environmental
efficiencies, there have been only limited applications. For example,
Buonocore et al. [32] performed a LCA and emergy assessment of a
20-MW dry stream geothermal power plant in the Tuscany region
(Italy), aiming at understanding the extent to which the power
plant was environmentally sound and if there were steps and/or
components requiring further attention. Focusing on solar PV
power generation systems, Zhang et al. [33] presented an ecological
accounting framework based on embodied energy and emergy
analyses to examine the performance of the 1.5-MW Dahan solar
tower power plant in Beijing. Using a revised operational definition
of the emergy yield ratio, Brown et al. [34] investigated perfor-
ance in two cases, cadmium telluride PV and oil-fired thermal
electricity production. Takahashi and Sato [35] proposed two novel
indices based on emergy analysis to evaluate public acceptance
altogether with economic and environmental aspects of eight power
generation systems. For wind power generation systems, Yang et al.
[36] presented a basic emergy diagram and emergy indicators to
evaluate the performance of a wind power generation system
aggregating various associated renewable/nonrenewable resources
and purchased emergy inputs. Iribarren et al. [37] combined
emergy analysis with data envelopment analysis for ecocentric
benchmarking of wind power generation systems.

All the above studies proved emergy analysis a powerful tool in
the assessment of renewable power generation system dynamics. The
two existing emergy studies of wind power generation sys-
tems provide information on environmental pressure and resource
use efficiency. However, environmental emissions (especially
GHG), which are undesirable outputs of wind power generation
systems, have not yet been incorporated into emergy analysis.
Improvements to wind power generation systems using emergy
as a benchmark should be further discussed.

In the present work, the renewability, economic efficiency and
environmental pressure of wind power generation systems during
the whole lifetime stages were evaluated and depicted based on
emergy analysis and emergent ternary diagrams. The indicator
Em,CO₂ was proposed as a useful goal function for potential system
optimization in the context of low-carbon and sustainable devel-
opment. Moreover, scenario analysis was conducted to find ways
to improve sustainability of wind energy supply chain. The pro-
posed accounting framework may shed light on balancing resource
conversion efficiency, environmental pressure, and economic per-
formance of wind power generation, as well as provide managerial
implications for the design of sustainable wind power supply chain
management strategies.

2. Materials and methods

2.1. Emergy analysis

With increasing recognition of the importance of environmental
integrity, which provides free and necessary inputs (sometimes on
a renewable basis) to electric production systems and is a sink for
emissions, environmental inputs to energy production processes
should be recognized as services performed by the environment
[30]. To integrate the environmental loading exerted by wind farm
construction and operation into the sustainability accounting
framework, emergy analysis, which is a measure of past and pre-
sent environmental support to a process and explores the interplay
of natural ecosystem and human activities, is used in this paper. All
resources and energy used to produce electricity are expressed in
the form of emergy, with their solar transformities as conversion
factors.

The emergy diagram of the studied wind farm is shown in Fig. 1.
This diagram reveals the main steps of a wind farm project and all
main input flows to each step, along with feedback, degraded
resource, and money flows. Thereby, a clear overview of the entire
process is obtained for a comprehensive evaluation [23]. In the dia-
agram, only one type of environmental resource is used by the wind
farm, namely, the wind resource on the plant site (R). This is the
direct driving force of electricity production. Nonrenewable envi-
ronmental resources (N) mainly include land losses. Flows of mater-
ial, equipment, human services from the economy that are used to
construct, operate, and maintain the wind farm are categorized as
purchased emergy (F). The electricity output (Y) is the yield of the
process, to which the total emergy input is assigned. The co-
product output of pollutants (C), i.e., GHG emission, is also shown
in the emergy diagram.

Based on a reevaluation and subsequent recalculation of energy
contributions by Odum [38], the emergy baseline is set as
15.83 × 10²⁴ sej/yr.

2.2. GHG emission accounting

Two approaches are available in quantifying the GHG emission
of wind power generation systems, i.e., the process-based and
environmental input–output-based LCA. The conventional
process-based accounting is a bottom-up approach, which captu-
res all environmental impacts following the supply chain from
cradle to grave. However, there is a cutoff criteria in the process-
based method, which neglects parts that are considered unimpor-
tant or contribute little to the results. Environmental input–
output-based LCA, which is based on the national account, can
eliminate the cutoff from process-based accounting. However,
accuracy of the results may be reduced because of uncertainty gen-
erated by sectoral aggregation [39]. Because process-based LCA is
typically used in micro systems [40–42] and environmental
input–output-based LCA is more appropriate for national or
regional levels [43–50], we choose process-based accounting for
the evaluation of GHG emissions of wind power generation systems in this paper.

GHG emissions embedded in a wind farm were calculated by first doing an inventory of all input energy and material flows to construction and operation processes. Afterwards, total GHG emissions from the invested energy and materials into the full chain of processes, from extraction and processing of raw materials and resources to the final product (electricity) via material transportation, construction and operation, is summed [51]. This is given by Eq. (1).

\[
C = \sum m_i \times c_i, \quad i = 1, 2, \ldots n
\]

\[
CI = C/E_{out}
\]

Here, C is GHG emissions; we considered CO₂, CH₄ and N₂O emissions. \(m_i\), is the i-th input flow of material or energy, and \(c_i\) is the GHG emission coefficient of the i-th flow. CI is the GHG emission per unit of wind power output. \(E_{out}\) is power generated and delivered from the wind farm.

2.3. Emergy-based evaluation indicators

We used some basic emergy-based indices with respect to economic efficiency, environmental load, and sustainability level. Implications and expressions of these indices (emergy yield ratio (EYR), environmental loading ratio (ELR), emergy sustainable index (ESI), and percentage renewable (R%)) are listed in Table 1.

In addition to these conventional emergy indices [30,52,53], the system-level diversity index (SDR), derived from the modified Shannon information formula, was used as an indicator of system performance and provided a quantitative assessment of diversity. It is defined as the ratio of actual diversity to maximum potential diversity of a specific system [54].

\[
SD = - \sum \left( \frac{U_i}{U} \right) \ln \left( \frac{U_i}{U} \right), \quad SDR = SD/SD_{max}
\]

where \(U_i\) = energy input of the i-th flow = (amount of the i-th flow; J or g) \times (emergy intensity of the i-th flow; sej/J or sej/g). SD is system diversity, \(SD_{max}\) is maximum potential diversity when the total emergy is uniformly assigned to each input. Thus, a SD nearer \(SD_{max}\) (and therefore a ratio \(SD/SD_{max}\) closer to 1) suggests greater system resilience. The classification roles of input flows included in the calculation procedure affects the values of SD and \(SD_{max}\). Depending on how input flows are aggregated, \(SD_{max}\) may be different for the same system [55]. Consequently, SDR is not always compatible between studies.

To link GHG emission and emergy analysis and evaluate the holistic sustainability of a wind farm, \(E_{em}CO₂\) is also proposed to present a useful goal function for possible low-carbon and sustainable system optimization [17]. \(E_{em}CO₂\) is defined as the ratio of GHG...
emission per joule of electricity generation and ESI, which can be used as a GHG numéraire to account for the tradeoff between the low-carbon optimization level of the production system and long-term sustainability of that system in the context of the surrounding environment and biosphere. The lower the $E_a$, the greater the low-carbon optimization embedded in the sustainability framework.

$$E_a = C/E_{aux}/ESI$$

(4)

2.4. Description of a typical wind farm

The study wind farm is in Inner Mongolia, China, and covers an area of 33 km². The vegetation is constituted by spontaneous grass and small shrubs. There is a northern continental climate in which annual average temperatures of the south, central and north parts are 4.2, 2.1 and −3.2 °C, respectively. Annual precipitation is 441 mm and annual solar duration 2800 h. The study site is rich in wind resources, with 23–47 average annual windy days and average wind speed 6.98 m/s at 75-m height.

There are 33 wind turbines installed on the wind farm, each of which has a generating capacity of 1.5 MW, hub height 75 m, and blade diameter 87 m. A substation with a 220 kV step-up transformer was constructed to decrease line loss. The control system was also installed at the substation to make it “unattended”. The annual optimal gross electricity output of the wind farm is 138.5 GWh. Because of auxiliary power and power losses, power output actually delivered to the electrical grid is 111.7 GW. The equivalent full-load operating hours are 2257 h per year. The lifetime of the farm is 21 years, of which the construction phase takes 12 months and the design operational period 20 years.

Data for the material and energy inputs of the wind farm were kindly provided by the developer, China Xiehe Wind Power Investment Co., Ltd., and the designer, Beijing Juhe Electrical Engineering Design Limited. The data include construction materials, energy sources, labor in construction and operation and maintenance phases, environmental inputs, and power output.

3. Results and discussion

3.1. Energy analysis

Table 2 summarizes emergy flows of the wind farm. All input materials, energy, services and labor are listed and were converted to emergy by means of appropriate conversion factors. Because a large amount of nonrenewable and purchased emergy was invested, the construction phase makes up the largest proportion of total input. This is followed by the operational phase, constituting 49.03% of total input. Emergy used for the transportation of raw materials and energy sources contributes only a very small fraction.

The emergy inputs of various materials are depicted in Fig. 2. Labor and services are the dominant emergy sources, constituting 47.84% of total emergy. The wind resource is the typical renewable input, with a proportion of 14.48%. Even though the wind farm is primarily a renewable resource-based electricity generation system, a large amount of emergy inputs from nonrenewable energy sources and purchased emergy from the economy are invested. In purchased emergy input, building works make up the largest proportion at 26.10%, followed by the wind turbine, at 14.48% of total emergy input. Fossil fuels such as diesel, gasoline and electricity only make up a small fraction, owing to substitution of the wind resource in this power generation system. Water is also used directly by the wind farm in the construction and operational phases (0.56%). The transformer makes up the smallest proportion of all emergy inputs.

3.2. GHG emission of the wind farm

Fig. 3 shows GHG emissions in different phases during the wind farm lifetime. The total GHG emission of transportation, construction, and operational stages is 2.55E+04 t CO₂-equivalent. Materials and fuels used in the construction phase are the largest GHG emitters, with a proportion of 92.16%. In this phase, 46.86% of GHG emission stems from wind turbines. Building materials, especially concrete and steel, are another GHG emission source in the construction phase. The operational phase is the second largest contributor, in which GHG emissions from wind turbine substitution, nonrenewable energy consumption, and water supply are respectively 62.17%, 19.31%, and 18.52% of total emissions. Transportation occupies the smallest proportion at 0.56%, which is mainly caused by the consumption of diesel fuel.

3.3. Emergy-based Indicators

The emergy-based indicators that reflect the sustainable level of the wind farm and comparisons of various power generation systems are presented in Table 3.

The 13% of the wind farm is 14.60%, higher than traditional thermal power plants, but slightly lower than solar and hydro power plants. This is because although the wind resource as a renewable energy can replace conventional commercial energy such as oil and coal, a substantial amount of purchased emergy (such as that of wind turbines) flows into the wind power generation system during the lifetime of the farm, making it less renewable than expected.

The transformity of the wind farm was found to be 4.49 × 10³ sej/J, the lowest among all power plants listed in Table 3. This means that it has a high overall efficiency at the global scale of the biosphere. EYR is used to evaluate the potential contribution of the wind farm to the economy. As shown in Table 3, the EYR of the farm was only 1.17, much smaller than the 5.06 of the solar tower power plant, 7.65 of the hydro power plant, 5.48 of the coal-based thermal power plant, and 4.21 of the oil-based power plant. This reveals that the production of wind power does not create sufficient growth for the system, with a high emergy content of resources invested from the economy. ELR is directly related to the fraction of renewable resources and can be considered a measure of ecosystem stress from production [62]. The ELR of the wind power generation system (5.84) is small compared with that of thermal power plants, owing to the substitution of wind by fossil fuels. However, the ELR of the system is larger than those of the solar tower and hydro power plants, indicating that the system leads to stronger adverse effects on the environment than other types of renewable power generation technologies. The larger ELR of the wind power generation system demonstrates a greater dependence on non-renewable and purchased resources (N + F).

The ESI is determined by both EYR and ELR. To interpret the results in a more direct manner, the emergent ternary diagram proposed by Giannetti et al. [63] was used to graphically represent the environmental indicators EYR, ELR and ESI, (Fig. 4). The blue line is a collection of dots with $ESI = 1$. The ESI of the wind power generation system is below that line and is the smallest among all the power generation systems. This is because of the smallest EYR. Thus, we might expect better performance of the wind power generation system by improving the economic conversion efficiency and alleviating environmental pressure. SDR is specified to represent the diversity of a specific system. A larger SDR (close to 1) means greater resilience in the face of fluctuations. Because the emergy inputs of the system concentrate on categories such as labor and steel, the SDR of the wind farm is only 0.52. A complex production structure of the farm with more diversified inputs (e.g., the use of alternative materials) would better resist external fluctuations such as steel price increases.
Table 2
Emergy table for the wind farm.

<table>
<thead>
<tr>
<th>Components</th>
<th>Materials</th>
<th>Quantity</th>
<th>Unit</th>
<th>Transformity</th>
<th>Unit</th>
<th>References</th>
<th>Emergy input (sej)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transportation phase</strong></td>
<td>Diesel</td>
<td>4.60E+01</td>
<td>t</td>
<td>1.11E+05</td>
<td>sej/J</td>
<td>[52]</td>
<td>2.18E+17</td>
</tr>
<tr>
<td>Labor and services (10% renewable, 90% nonrenewable)</td>
<td>4.21E+05</td>
<td>$</td>
<td>5.87E+12</td>
<td>sej/$</td>
<td>[57]</td>
<td>2.47E+18</td>
<td></td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.69E+18</td>
</tr>
<tr>
<td><strong>Construction phase</strong></td>
<td>Equipment foundation</td>
<td>Concrete</td>
<td>1.43E+04</td>
<td>m³</td>
<td>2.27E+09</td>
<td>sej/g</td>
<td>[58]</td>
</tr>
<tr>
<td></td>
<td>Steel</td>
<td>1.26E+03</td>
<td>t</td>
<td>7.80E+09</td>
<td>sej/g</td>
<td>[59]</td>
<td>9.83E+18</td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>1.00E+04</td>
<td>t</td>
<td>8.06E+04</td>
<td>sej/J</td>
<td>[52]</td>
<td>1.07E+18</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
<td>4.45E+02</td>
<td>t</td>
<td>1.11E+05</td>
<td>sej/g</td>
<td>[52]</td>
<td>2.11E+18</td>
</tr>
<tr>
<td></td>
<td>Gasoline</td>
<td>1.21E+02</td>
<td>t</td>
<td>2.92E+09</td>
<td>sej/g</td>
<td>[60]</td>
<td>3.53E+17</td>
</tr>
<tr>
<td></td>
<td>Electricity</td>
<td>1.65E+03</td>
<td>MW h</td>
<td>1.85E+05</td>
<td>sej/J</td>
<td>[31]</td>
<td>1.10E+18</td>
</tr>
<tr>
<td></td>
<td>Wind turbines</td>
<td>Steel</td>
<td>6.05E+03</td>
<td>t</td>
<td>7.80E+09</td>
<td>sej/g</td>
<td>[59]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fiber glass</td>
<td>1.40E+02</td>
<td>t</td>
<td>5.04E+09</td>
<td>sej/g</td>
<td>[61]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Epoxy</td>
<td>8.58E+01</td>
<td>t</td>
<td>6.22E+09</td>
<td>sej/g</td>
<td>[34]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Copper</td>
<td>2.85E+02</td>
<td>t</td>
<td>3.36E+09</td>
<td>sej/g</td>
<td>[19]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aluminum</td>
<td>1.65E+01</td>
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<td>5.73E+09</td>
<td>sej/g</td>
<td>[34]</td>
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<tr>
<td></td>
<td></td>
<td>Polyester</td>
<td>9.90E+00</td>
<td>t</td>
<td>6.22E+09</td>
<td>sej/g</td>
<td>[34]</td>
</tr>
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<td></td>
<td>Transformer substation</td>
<td>Silicon</td>
<td>6.00E-01</td>
<td>t</td>
<td>1.68E+09</td>
<td>sej/g</td>
<td>[52]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Steel</td>
<td>1.10E+01</td>
<td>t</td>
<td>7.80E+09</td>
<td>sej/g</td>
<td>[59]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Copper</td>
<td>4.80E+00</td>
<td>t</td>
<td>3.36E+09</td>
<td>sej/g</td>
<td>[19]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Labor and services (10% renewable, 90% nonrenewable)</td>
<td>5.54E+06</td>
<td>$</td>
<td>5.87E+12</td>
<td>sej/$</td>
<td>[57]</td>
</tr>
<tr>
<td></td>
<td>Land loss</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.80E+05</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.81E+20</td>
</tr>
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<td><strong>Operation and maintenance phase</strong></td>
<td>Wind</td>
<td>1.41E+16</td>
<td>J</td>
<td>2.520</td>
<td>sej/J</td>
<td>[52]</td>
<td>3.55E+19</td>
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<tr>
<td></td>
<td>Gasoline</td>
<td>1.16E+02</td>
<td>t</td>
<td>2.92E+09</td>
<td>sej/g</td>
<td>[60]</td>
<td>3.39E+17</td>
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<tr>
<td></td>
<td>Water</td>
<td>8.76E+03</td>
<td>t</td>
<td>8.06E+04</td>
<td>sej/g</td>
<td>[52]</td>
<td>9.40E+17</td>
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<tr>
<td></td>
<td>Wind turbine substitutions</td>
<td>Steel</td>
<td>1.71E+02</td>
<td>t</td>
<td>7.80E+09</td>
<td>sej/g</td>
<td>[59]</td>
</tr>
<tr>
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<td></td>
<td>Copper</td>
<td>4.28E+01</td>
<td>t</td>
<td>3.36E+09</td>
<td>sej/g</td>
<td>[19]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fiber glass</td>
<td>1.29E+02</td>
<td>t</td>
<td>5.04E+09</td>
<td>sej/g</td>
<td>[61]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Epoxy</td>
<td>8.58E+01</td>
<td>t</td>
<td>6.22E+09</td>
<td>sej/g</td>
<td>[34]</td>
</tr>
<tr>
<td></td>
<td>Labor and services (10% renewable, 90% nonrenewable)</td>
<td>6.63E+06</td>
<td>$</td>
<td>5.87E+12</td>
<td>sej/$</td>
<td>[57]</td>
<td>3.89E+19</td>
</tr>
<tr>
<td></td>
<td>Additional human services for plant operation (10% renewable, 90% nonrenewable)</td>
<td>1.68E+07</td>
<td>$</td>
<td>5.87E+12</td>
<td>sej/$</td>
<td>[57]</td>
<td>9.87E+19</td>
</tr>
<tr>
<td></td>
<td>Land loss</td>
<td>1.21E+05</td>
<td>m²</td>
<td>8.00E+10</td>
<td>sej/m²/year</td>
<td>[57]</td>
<td>1.94E+17</td>
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<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.77E+20</td>
</tr>
<tr>
<td><strong>Total emergy, without L and S</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.88E+20</td>
</tr>
<tr>
<td><strong>Total emergy, with L and S</strong></td>
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<td>3.61E+20</td>
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<tr>
<td><strong>Yield</strong></td>
<td></td>
<td></td>
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<td>8.04E+15</td>
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<tr>
<td><strong>Transformity, without L and S</strong></td>
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<td>4.49E+04</td>
</tr>
</tbody>
</table>

![Fig. 2. Emergy input of different components of the wind farm.](image-url)
The $E_{\text{gCO}_2}$ value of the wind farm is larger than those of the hydro and solar power plants, but smaller than fossil fuel-driven power generation systems, indicating that the wind power generation system is sustainable when GHG emission is included in the evaluation framework. This can be attributed to that system’s lower GHG emission intensity ($g/J$). It is therefore concluded that the wind power generation system is more sustainable than the fossil fuel-driven systems.

![Fig. 3. GHG emissions of different phases of the wind farm.](image)

### Table 3
Comparison of five power systems with emergy-based indicators.

<table>
<thead>
<tr>
<th>Items</th>
<th>Wind farm (1.5 MW)$^a$</th>
<th>Solar tower power plant (1.5 MW)$^b$</th>
<th>Hydro (85 MW)$^c$</th>
<th>Coal (1280 MW)$^c$</th>
<th>Oil (1280 MW)$^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$ (%)</td>
<td>14.60</td>
<td>71.94</td>
<td>68.84</td>
<td>8.79</td>
<td>6.56</td>
</tr>
<tr>
<td>$T_r$ ($sej/J$)</td>
<td>$4.49 \times 10^4$</td>
<td>$6.39 \times 10^4$</td>
<td>$6.23 \times 10^4$</td>
<td>$1.71 \times 10^5$</td>
<td>$2.00 \times 10^5$</td>
</tr>
<tr>
<td>EYR</td>
<td>1.17</td>
<td>5.06</td>
<td>7.65</td>
<td>5.48</td>
<td>4.21</td>
</tr>
<tr>
<td>ELR</td>
<td>0.84</td>
<td>0.39</td>
<td>0.45</td>
<td>10.4</td>
<td>14.2</td>
</tr>
<tr>
<td>$ESI$</td>
<td>0.20</td>
<td>13.1</td>
<td>16.9</td>
<td>0.53</td>
<td>0.30</td>
</tr>
<tr>
<td>$SDR$</td>
<td>0.52</td>
<td>0.44</td>
<td>–</td>
<td>–</td>
<td>0.29</td>
</tr>
<tr>
<td>$E_{\text{gCO}_2}$ ($g/J$)</td>
<td>$3.90 \times 10^{-5}$</td>
<td>$7.70 \times 10^{-7}$</td>
<td>$1.91 \times 10^{-7}$</td>
<td>$5.83 \times 10^{-5}$</td>
<td>$8.69 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

$^a$ This paper.

$^b$ Zhang et al. [33].

$^c$ Brown and Ulgiati [30].

![Fig. 4. Representation of esource flow line (a) and sustainability line (b) of power generation systems. Note: (a) The relative proportions of the elements being given by the lengths of the perpendiculars from the given point to the side of the triangle opposite the appropriate element. These lines are parallel to the triangle sides and are very useful for comparing the use of resources by-products or processes. (b) The graphic tool permits one to draw lines indicating constant values of the sustainability index. The sustainability lines depart from the N apex in the direction of the RF side allowing the division of the triangle into sustainability areas, which are very useful to identify and compare the sustainability of products and processes [64].](image)
that wind power is a sustainable alternative compared with traditional thermal power plants when carbon emissions are incorporated in the sustainability assessment [65].

4. Scenario analysis

Based on the above results, efforts toward feasible and practical improvements should be made to promote wind farm sustainability. To explore future optimization directions of the wind farm, three hypothetical scenarios were designed. These scenarios focused on aspects such as material recycling and technical renovation, which could potentially contribute to changes in GHG emissions, intensity and sustainability of the wind power generation system. Parameters and settings of the scenarios and responsive changes of system inputs are listed below.

Scenario I: One important aspect is dismantling of the wind turbine, especially subsequent material recycling, which implies a significant reduction of the nonrenewable energy input of the wind power generation system. However, the dismantling at lifetime end remains in planning at a theoretical level. Because no detailed data on wind farm disposal are available, we applied a principle used by Kabir et al. [12] for material disposal and recycling of wind turbines.

Scenario II: Annual electricity output of the wind power generation system is 183.5 GWh, but only 111.7 GWh of wind power is connected to the grid. Obviously, a large proportion of electricity is abandoned or depleting in the operational and power delivery phases. If on-grid (useful) wind power is increased, energy- and energy-related indicators will respond to the change. Therefore, in Scenario II, a 10% increase of on-grid power is established to observe changes in sustainability of the wind power generation system.

Scenario III: To monitor the influence of technological improvements, energy intensity of major material input (steel) of the wind power generation system is assumed to be reduced by 10% in this scenario. GHG emission intensity and energy of steel respond to this change, which leads to fluctuation of energy-based indicators.

According to the three policy scenarios above, we evaluated the performance of these future alternatives for the wind power generation system (Table 4). CI, ESI and \( E_{\text{Em}} \text{CO}_2 \) of the scenarios are accounted for in relation to the current status.

With the energy intensity of steel decreased by 10%, GHG emission and purchased emergy input of the wind farm were reduced by 9.05% and 0.53%, respectively. These results show that reducing the energy intensity of steel input (Scenario III) is undoubtedly another approach to improve the CI and ESI, leading to a \( E_{\text{Em}} \text{CO}_2 \) decrease of 9.49%. However, because the wind power generation system is diversified and complex with a SDR of 0.52, technological change of one component cannot have a substantial effect on system behavior.

5. Conclusions

After a decade of rapid growth of wind power capacity worldwide, sustainable wind energy utilization has become an important issue of energy supply chain management. In the present study, emergy analysis was used to evaluate the structure, function, efficiency and sustainability of a typical wind power generation system considering its whole lifetime stages. GHG emission accounting was also incorporated into the energy analysis framework to provide a more comprehensive goal function concerning global warming issue. Moreover, emergy-based scenario analysis was done to find potential pathways for sustainable wind energy supply chain management. The proposed methodology and indicators may also be used to quantify the environmental impacts and ecosystem supports and identify the conversion efficiencies of similar renewable power generation systems.

Based on the evaluation results, we conclude that the wind power generation system is competitive compared with traditional fossil fuel-driven power generation systems in terms of alleviating environmental loading and GHG emissions. However, the EYR of the wind system is the smallest of all the power generation systems (even smaller than that of thermal power), implying that it has a low conversion rate of purchased energy, i.e., low economic efficiency. Thus, improving the utilization efficiency of purchased energy, materials and services, e.g., reducing unnecessary maintenance costs and services, is crucial for sustainable development of the wind power generation system.

Scenario analysis showed that material recycling can make great contributions to GHG emission reduction and sustainable power generation. Therefore, it should be taken into account early in the design and manufactory process of wind turbines. It is also important to innovate efficient means of material recycling of turbines to increase the recycling rate and make full use of energy and material. Steel constitutes the largest emergy input in the wind power generation system. Using steel with lower energy intensity for turbine construction and wind farm building can not only improve the sustainability of a wind power system but also bring significant environmental benefits at larger scale. In addition, diverse clean and new materials should be introduced to the manufacture of wind turbines, e.g., using thermoplastic composites in blade construction, and exploring bamboo fiber-reinforced composite and bioadhesives to substitute for epoxy resin.

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