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Emergy and Sustainability Ternary Diagrams of Energy Systems: Application to Solar Updraft Tower

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Abstract: To facilitate sustainable energy development, one has to understand the limited availability of nonrenewable energy resources, and the ability of the earth to renew or recover. Emergy is an instrument that measures environmental loading, ecological economics, and regional sustainable development. In this study, emergy indicators are calculated to investigate the sustainability of solar updraft tower (SUT). SUT produces energy from the hot air, utilizing a combination of a solar collector, central tower, and air turbines. The results demonstrate that the sustainability of SUT grew as the size of the plant increased. Further, emergy ternary diagrams are drawn to facilitate the comparison between SUT and various technologies. The resources-use efficiency of wind energy and SUT, 200 MW is found to be the lowest among all energy technologies presented in this research. Scenario analysis is performed to explore the future optimization directions. The results demonstrate that the development direction of SUT systems should mainly focus on reducing the materials demanded by the manufacturing and construction of its solar collectors. This study aims to demonstrate the value of emergy as a powerful instrument for drawing long-term sustainable strategies in energy markets for a greener tomorrow.

Keywords: emergy; emergy ternary diagrams; sustainability; environmental loading; energy systems assessment; solar updraft tower

1. Introduction

The World Commission on Environment and Development in 1987 developed the official definition of the sustainable development concept for the first time, describing it as “the development which meets the needs of current generations without compromising the ability of future generations to meet their own needs” [1,2]. The realization of such development necessitates awareness of the limited availability of nonrenewable resources, and the ability of the earth to renew or recover [3]. The greening of energy emerged as a key element in any region to facilitate sustainable socioeconomic development. Total global carbon emissions from the power sector were about 13.4 billion tons in 2016, about 42% of total carbon emissions from fuel combustion. Coal-fired power plants are one of the largest sources of air pollution. High CO₂ levels accelerated the negative impact on the environment, including, but not limited to, global warming and the rising sea level. An inefficient relationship with the environment will lead to a dramatically negative impact on societies and economies [4]. Therefore, clean energy infrastructure is essential economically, politically, environmentally, and socially for a greener tomorrow.

While the public emphasizes the imperative of green energy infrastructures, engineers and researchers doubt the investment in greener generation technologies like wind and solar unless new evaluation mechanisms are introduced to support renewables and decarbonization strategies [5]. On the one hand, the de-risking of investments and the idea of reliable sources of energy limit

investment strategies in renewables worldwide. On the other hand, some countries around the globe (Denmark, 2019) had nearly half of their total energy consumption powered by renewable resources (wind energy) [4]. Thus, there is a body of academic knowledge that claims that the efficient management of renewable resources and the diversified use of green energy technologies can offer a reliable energy infrastructure. To accelerate and strengthen the greening of the energy industry, one has to understand the complexity of the energy markets and their abundant considerations.

This paper addresses “emergy”, proposed by Howard T. Odum [6,7], as a powerful instrument for measuring sustainable development. Emergy is able to facilitate regional sustainable development, ecological management, and environmental conservation for policymakers [8]. Emergy analysis considers that the formation of any system on earth derives from solar energy. The emergy value of any resource is its “solar energy memory” or, in other words, the amount of solar energy directly and/or indirectly used in its formation process. Different types of resources (material, energy, labor, etc.) possess different properties and are expressed in different units. The concept of solar transformity in emergy analysis quantifies the emergy value of any resource in one unified unit. Consequently, the framework of emergy analysis in the environmental accounting of any economic system requires ecological and economic emergy transformation chains to determine the total emergy input that drives the system (system empower). As a result, all systems are evaluated on an ecocentrism basis [3,7,9].

M. T. Brown and S. Ulgiati [3] presented emergy in the evaluation of electricity production systems and compared six power plants based on their emergy indicators. Consequently, many researchers reported the evaluation of various power generation technologies based on an emergy analysis. These studies include, but are not limited to, hydropower stations [10,11], geothermal and biomass [12,13], wind energy [14–16], solar photovoltaics and solar thermal collectors [17], and solar tower power plant systems [18]. Furthermore, emergetic ternary diagrams were presented by B. F. Giannetti et al. [19] as graphic tools that offer not only prompt visualization of emergy analysis but also readily recognize system improvements. C. M. V. B. Almeida et al. [20] discussed emergetic ternary diagrams in the application of electricity production systems.

Solar updraft tower (SUT) is one of the green technologies for acquiring renewable energy [21–24]. In nature, the updraft effect causes wind and hurricanes. The geometry of SUT mimics the wind cycle in nature to produce the thermal wind that drives turbines to generate electricity. It generates power using the sun as the only source of energy and using only air as working fluid without phase change; there is no water demand or working mediums, and no cooling mechanisms are needed [25]. While many areas worldwide suffer from severe water shortages, SUT saves gallons of cooling water associated with conventional and solar thermal generation plants [25]. Together with its low-cost thermal energy storage potential, SUT energy can be generated around the clock, eliminating environmental threats associated with the use of batteries in photovoltaic and wind power generation plants. Numerous studies reported cost–benefit models to assess the economic feasibility of SUT power plants [26–28]. Further, other researchers reported the ecological analysis in the lifecycle of SUT power plants [22,29]. I. Elsayed and Y. Nishi examined the sustainability of SUT power generation technology using the Inclusive Impact Index concerning both ecological and economic costs [30]. Despite that, emergy analysis of an SUT power plant has not been reported.

The main contribution of the present study is the evaluation of large-scale SUT power plants using emergy as a benchmark (Figure 1). Emergy accounting and emergy-based indicators are estimated to investigate the relative performance and sustainability of SUT systems. Comparisons of emergy indicators with various conventional and renewable power-generation technologies are then performed. To facilitate the latter comparison, emergetic ternary diagrams are drawn to provide a better interpretation of emergy accounting results and to visualize the interactions between power plants and the environment. Additionally, based on emergetic ternary diagrams, scenario analysis is performed to explore future optimization directions of large-scale SUT power plants. This paper offers a way forward to draw the sustainability pathways of large-scale SUT power systems for optimal socioeconomic decision-making.

Table 1. The design parameters of J. Schlaich et al. [22] for SUT commercial models used in the calculations of the present study.

Item	SUT Power Generation Capacity			
	5 MW	30 MW	100 MW	200 MW
Tower Height (m)	550	750	1000	1000
Tower Diameter (m)	45	90	110	120
Collector Diameter (m)	1250	3750	4300	7000
Collector Height (m)	3	3	3	3
Electricity Output ¹ (GWh/y)	14	99	320	680

¹ The SUT power plant site is assumed to have an annual global solar radiation of 2300 kWh/m²/y. Besides, there is no additional thermal storage.

2.2. Materials and Resources in the Lifecycle of SUT Power Plants

Since SUT power plants demand massive structures and materials, questions of technical constraints and energies expended to construct the plant are recurrent [21]. Estimating from the Manzanares pilot, W. Haaf et al. reported the building materials and energies to construct a 100 MW SUT (concrete tower and glass collector) [21]. Subsequently, J. Schlaich and other researchers reported the lifecycle analysis of SUT power plants [22,30]. The turbines are at the periphery of the transitional area between the collector and tower. J. Schlaich et al. reported an approximate number of 24 to 36 turbines for large-scale SUT power plants [22]. Thus, this study considers the use of horizontal-axis turbines with rated capacities of 4.1 and 5 MW. The design theory of the SUT turbines is usually adapted from horizontal-axis wind turbines [22,26,28]. Henceforth, the materials of 4.1 and 5 MW wind turbines are quoted from [33,34].

The construction period of a large-scale SUT power plant is approximately two to three years [22,29,31]. This study assumes that the materials require transportation from a region 1000 km away from the plant's location. The present study adapted the materials, weights, and energy for the construction of the tower and collector from W. Haaf et al. [21]. Table 2 illustrates the materials, component weights, and machinery for construction of the study's SUT power plants.

Table 2. Materials and energy consumption for the construction of commercial SUT power plants of different capacities.

Item		Material	SUT Power Generation Capacity			
			5 MW	30 MW	100 MW	200 MW
Components' manufacturing materials						
Tower		Concrete (ton)	4.54×10^5	4.54×10^5	8.26×10^5	8.26×10^5
Collector		Glass (ton)	1.27×10^4	6.82×10^4	1.60×10^5	3.97×10^5
		Resin and fiberglass (ton)	2.42×10^2	1.21×10^3	5.54×10^3	9.68×10^3
Turbines		Iron (ton)	1.19×10^2	5.94×10^2	2.01×10^3	4.75×10^3
		Steel (ton)	5.93×10^1	2.97×10^2	8.18×10^2	2.37×10^3
		Copper (ton)	9.60×10^0	4.80×10^1	1.33×10^2	3.84×10^2
		Silica (ton)	1.00×10^0	5.00×10^0	1.28×10^1	4.00×10^1
Installation						
Transportation of materials		Diesel fuel (J)	9.43×10^{14}	1.07×10^{15}	1.94×10^{15}	2.49×10^{15}
Construction works	Reinforcement of tower	Steel (ton)	1.65×10^4	2.25×10^4	3.00×10^4	3.00×10^4
	Collector's load-bearing structure	Steel (ton)	6.47×10^4	6.47×10^4	9.60×10^4	1.56×10^5
	Collector's foundations	Concrete (ton)	7.27×10^3	1.69×10^4	2.50×10^4	4.07×10^4
	Machinery	Electricity (MWh)	6.00×10^4	1.10×10^5	1.50×10^5	2.00×10^5

In the present analysis, there is no additional thermal storage, thus no salt or water usage. Additionally, no replacement tower or collector is in place [29]. Therefore, work for the operation and maintenance during the lifetime of the plant is necessary mainly for the turbines. A great deal of data from wind power stations can be used to estimate turbine substitutions' materials in the lifecycle.

The intended service life of commercial SUT power plant ranges from 80 to 120 years [27]; this study considers a lifetime of 30 years.

2.3. Emergy Analysis

The sun is the primary source of energy that fuels the earth's biological and economic growth. Emergy theory, proposed by H. T. Odum, traces the origin of the products and services formation. Considering that solar energy is the main energy input to the Earth, emergy measures how much energy would be needed to form a resource if solar radiation were the only input. Thus, emergy describes the amount of one form of energy invested in the system or, in other words, the "energy memory" of any system. Emergy converts different forms of energy, materials, goods, and human labor and services to equivalents of solar energy in a unified unit, solar embodied joules, abbreviated sej. The emergy required to make one unit of product is called the "solar transformity (sej/unit)" [6,7,9,35].

Emergy assumes all living systems sustain one another by participating in a network of energy flows; even the economy can be incorporated into this energy flow network. Hence, emergy analysis for any technology measures all input and output quantities, considers it as a network of emergy flows, and then determines the total emergy value. This approach helps to analyze the effect of each material and process, and the contribution of the ecosystem (environmental services); thus, it guides the future development of the technology. In emergy community, price does not reflect the real value of the environmental resources. The money is paid only to humans for their services, not to the environmental contributions and resources [35]. The emergy evaluation of any system can be divided into three consecutive steps. The first determines the analysis scale and boundary (analyzing the input and output data of the system). The second computes an emergy diagram and evaluation table. Finally, the third calculates emergy-based indices.

2.3.1. Analysis Scale and System Boundary

Emergy analysis is used in this study to evaluate the sustainability of power generation systems. The research scale is a power generation plant, the solar updraft tower. In the case of power plants, the types of inputs include energy resources (oil, coal, wind, solar radiation, etc.), materials (concrete, steel, glass, etc.), and labor and services necessary to construct, operate, and maintain the plant. The boundary of the analysis covers all phases of the SUT including manufacturing, installation (construction and transportation), and operation and maintenance during its lifetime. The main output of the system is the electricity generated.

2.3.2. Emergy Diagram and Evaluation Table

A typical emergy flow network is shown in Figure 2. The engineering systems comprise renewable and nonrenewable resources powered by both the ecosystem and human work. Therefore, the framework inputs of any engineering system are divided into three types: renewable resources (R), such as solar radiation, wind, rain, etc.; nonrenewable resources (N), such as land area, groundwater, etc. (limited availability); and purchased resources (F), which refers to economic transactions such as electricity, machinery, and human labor, etc. Renewable and nonrenewable resources are considered local resources. The emergy value of an input resource (i) is expressed as follows:

$$\text{Emergy}_i = \text{Quantity}_i \times \text{Solar transformity}_i \quad (1)$$

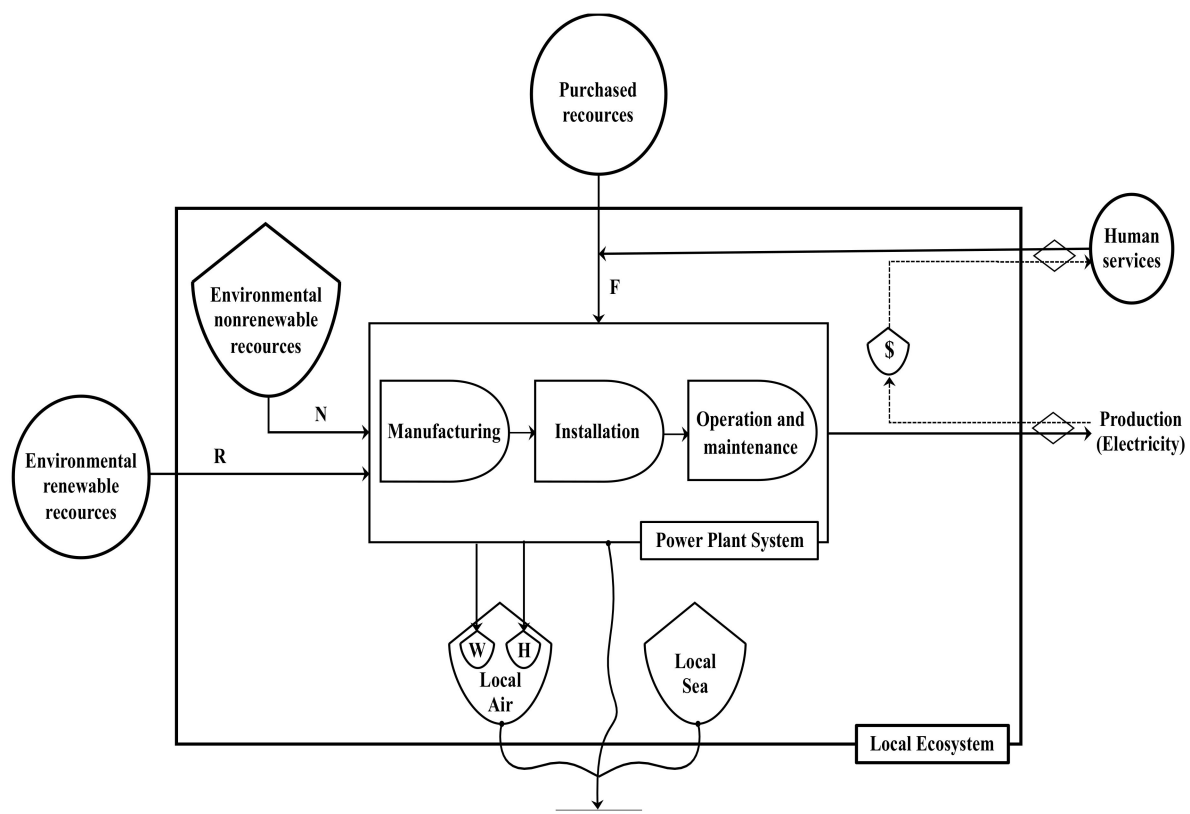


Figure 2. Typical emergy flow diagram of SUT power plant. The diagram shows the environmental renewable (R) and nonrenewable (N) inputs supplied by the local ecosystem, together with purchased inputs (F) from the economic systems. The electricity produced by the plant is the output from the SUT system. Local air storage represents the atmosphere, which receives pollutants (W) and heat released by the power plant (H). Local sea storage represents the marine environment [3,19].

The emergy baseline is a basic parameter for the equation, as it is the base of solar transformities calculations. The emergy transformity data adopted from references should all have the same baseline. The emergy baseline of the solar transformities used in this study is “ 15.83×10^{24} sej/y”. The total emergy input into the system is described as the emergy yield driving the system which equals the sum of emergy inflows ($R + N + F$). The annual electricity production (AEP) of the power plant is converted to joules using the standard conversion of 3.6×10^6 J/kWh.

2.3.3. Emergy indicators

Based on the above characteristics of emergy flows, emergy-based indices were established to investigate the efficiency and sustainability of various systems. In the present work, the most common emergy-based indicators were used to evaluate power generation from SUT power plants [3].

The transformity (Tr) of the system is the emergy invested to generate one unit of electricity. It measures the environmental and economic resources' use efficiency (emergy conversion efficiency) of the system as a whole (Equation (2)) (E_{out} is the total electricity production).

$$Tr = \frac{R + N + F}{E_{out}} \quad (2)$$

Emergy yield ratio (EYR) is the total emergy yield driving the system divided by the outside emergy sources (goods and services) from the economy. It measures the ability of the system to rely on

local resources. The higher the value of this index, the larger the contribution to the economy per unit of energy invested (Equation (3)).

$$EYR = \frac{R + N + F}{F} \quad (3)$$

Environmental loading ratio (*ELR*) is the local nonrenewable resources and total purchased resources from the economy divided by local renewable resources. It measures the stress on the environment and the potential impact of the system on the ecosystem (Equation (4)).

$$ELR = \frac{N + F}{R} \quad (4)$$

Emergy index of sustainability (*EIS*) is the emergy yield ratio per unit of environmental loading. It measures the overall sustainability of the system (Equation (5)). A high resources utilization efficiency (*EYR*) and low stress on the ecosystem means more sustainable technology. A power plant with *EIS* higher than “1” is considered sustainable [3].

$$EIS = \frac{EYR}{ELR} \quad (5)$$

2.4. Emergetic Ternary Diagrams

A ternary diagram is a three-dimensional graph but is illustrated in two dimensions in a triangular coordinate system. This graph type is proposed for the analysis of mixed components. It is commonly used to visualize phase diagrams in the physical sciences [19,20]. Emergetic ternary diagrams were presented by B. F. Giannetti et al. [19] to represent graphically emergy indicators. The authors presented emerggetic ternary diagrams as graphic tools that offer not only prompt visualization of emergy data but also readily illustrate system improvements [19].

The emergy driving the system (100%) equals the sum of the percentages of the three types of Emergy resources' inflows (*R%*, *N%*, and *F%*) which are the elements of the emerggetic ternary diagram. The diagram is an equilateral triangle where each corner represents an element (resources type). The triangular coordinates are chosen with renewable resources (*R*) on the top apex, nonrenewable resources (*N*) on the left apex, and purchased resources (*F*) on the right apex. The total emergy input into the system is represented by points within the triangle, the percentage of each element being given by the length of the perpendicular line from the given point to the side of the triangle opposite to the appropriate element. Moreover, the emerggetic ternary diagram has auxiliary lines to facilitate emergy analysis: resource flow lines, sustainability lines, and sensitivity lines. Resource flow lines define emergy indicators *EYR* and *ELR*. Sustainability lines define the emergy index of sustainability, *EIS*. The sensitivity lines point out the system's behavior with changes in elements (resource fluxes) associated with the apex of each sensitivity line. The latter lines are very useful for identifying areas of improvement to enhance the sustainability of the systems.

In the present work, the emerggetic ternary diagrams were depicted to provide a better understanding of emergy flows for SUT systems and to visualize the interactions between the power plant and the environment. Moreover, the graphical analysis facilitates the comparison between SUT systems and various energy technologies presented in this research.

2.5. Data Sources

The studied SUT power plants consist of concrete towers and glass solar collectors. The data in this study are mainly from the feasibility and lifecycle assessment reports of large-scale SUT. The total area of the canopy is considered the plant area, at a site with an annual global solar radiation of 2300 kWh/m²/year [22]. The total masses and the electricity consumption for the construction of the tower and collector are adapted from the sample estimates of W. Haaf et al. [21]. Turbines' materials are calculated by analogy with similar wind turbines [34]. During the operation and maintenance phase,

it is assumed no replacement of the tower or collector is taking place [29]. Meanwhile, one-third of the turbine's materials should be substituted during the average useful life [33,34]. Labor and services costs for installation (engineering, tests, etc.) and operation and maintenance are derived from [22]. In the calculation, considering the energy and materials loss in the production process, and due to the difficulty of getting data, some calculations are still not included [16]. The solar transformity coefficients of each resource are quoted from relevant references.

3. Results: Emergy Accounting

All the input flows during manufacturing, installation, and operation and maintenance of the SUT, 200 MW power generation plant are analyzed and described in Table 3. Energy sources, materials, land loss, and human labor and services expressed in their common units (J, kg, m³, \$, etc.) were converted to emergy flows (sej) by means of appropriate emergy transformation coefficients (called solar transformity, sej/unit). The total emergy of the SUT system accounts for all environmental contributions, energies, and human services used directly and indirectly to produce and maintain the power plant. The fractions of emergy inputs for the SUT, 200 MW plant are depicted in Figure 3. The manufacturing materials of the components are the dominant inputs, constituting 34.9% of total emergy. This is followed by construction works (materials and energy consumption), constituting 29.0% of total emergy. The latter results are the output of the massive structure and materials demanded by a large-scale SUT power plant. Meanwhile, the glass of the canopy makes up the largest proportions of components' manufacturing materials, constituting 20.8% of the total emergy inputs. The emergy invested by local environmental resources like solar radiation and land area contribute small fractions of the total emergy driving the system; this is because of the small solar transformity value of the latter resources. The other generation capacities of the SUT systems are evaluated using emergy tables like Table 3, and the results of emergy flows are listed in Table 4.

Table 3. Emergy evaluation table of SUT, 200 MW power generation plant during lifetime.

Item		Quantity	Unit	Transformity (sej/Unit)	Emergy (sej)
Energy source					
Solar energy (R)		9.56×10^{18}	J	1.00×10^0 [7]	9.56×10^{18}
Power plant area					
Land use (N)		3.85×10^7	m ² /y	8.00×10^{10} [15]	9.24×10^{19}
Components' manufacturing materials					
Tower	Concrete (F)	8.26×10^5	ton	5.08×10^{14} [3]	4.19×10^{20}
Canopy	Glass (F)	3.97×10^5	ton	1.90×10^{15} [17]	7.55×10^{20}
	Resin and fiberglass (F)	9.68×10^3	ton	8.07×10^{15} [14]	7.81×10^{19}
Turbines	Iron (F)	4.75×10^3	ton	8.60×10^{14} [16]	4.09×10^{18}
	Steel (F)	2.37×10^3	ton	2.77×10^{15} [3]	6.57×10^{18}
	Copper (F)	3.84×10^2	ton	2.00×10^{15} [3]	7.68×10^{17}
	Silica (F)	4.00×10^1	ton	1.68×10^{15} [16]	6.72×10^{16}
SUBTOTAL					1.26×10^{21}
Installation					
Transportation	Diesel fuel (F)	2.49×10^{15}	J	6.60×10^4 [7]	1.64×10^{20}
	Steel reinforcement of tower (F)	3.00×10^4	ton	4.82×10^{15} [16]	7.53×10^{20}
Construction works	Steel load-bearing structure (F)	1.56×10^5	ton	4.82×10^{15} [16]	1.45×10^{20}
	Concrete foundations (F)	4.07×10^4	ton	5.08×10^{14} [3]	2.07×10^{19}
	Electricity for machinery (F)	7.20×10^{14}	J	1.85×10^5 [3]	1.33×10^{20}
SUBTOTAL					1.22×10^{21}
Maintenance resources					
Turbine substitution (33% replacement rate) (F)		5.69×10^3	ton		2.96×10^{19}
Human labor and services					
Other costs for installation (26%R and 74%F)		5.04×10^7	US\$	5.87×10^{12} [36]	2.96×10^{20}
Labor and services for operation (26%R and 74%F)		1.22×10^8	US\$	5.87×10^{12} [36]	7.18×10^{20}
TOTAL					
Total emergy without human labor and services					2.61×10^{21}
Total emergy with human labor and services					3.63×10^{21}
Production					
Electricity output		2.45×10^{15}	J/y		

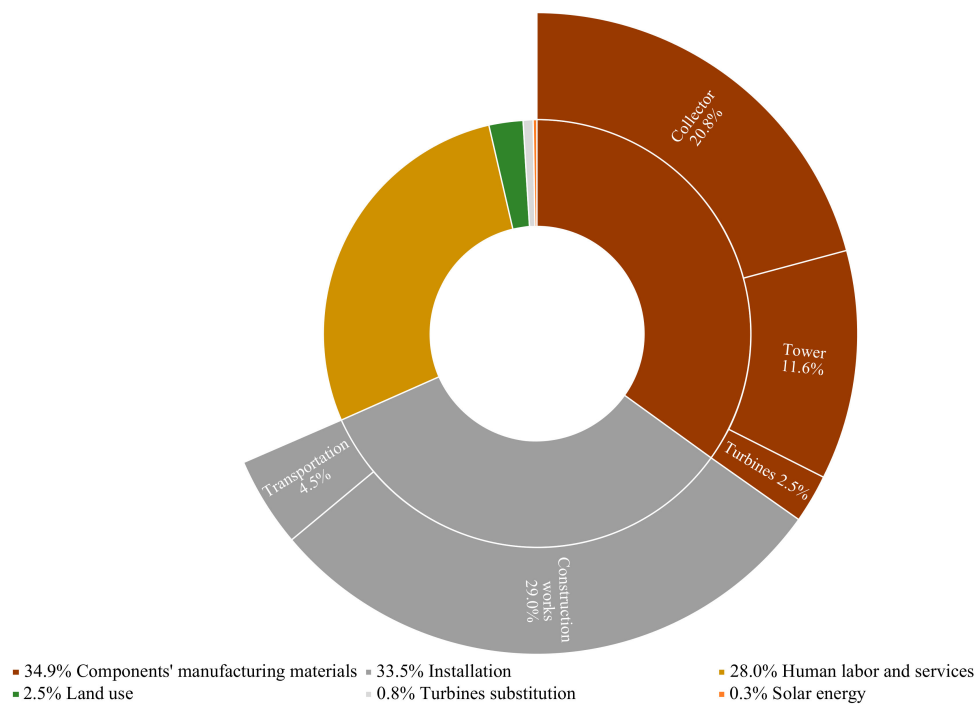


Figure 3. Fractions of energy input flows for SUT, 200 MW.

Table 4. Emergy input flows and annual energy production of commercial SUT power plants of different capacities.

Energy Flow		SUT Power Generation Capacity			
		5 MW	30 MW	100 MW	200 MW
R	Environmental renewable resources (sej)	2.05×10^{19}	7.49×10^{19}	1.81×10^{20}	2.73×10^{20}
N	Environmental nonrenewable resources (sej)	2.95×10^{18}	1.59×10^{19}	3.49×10^{19}	9.24×10^{19}
F	Purchased resources (sej)	8.13×10^{20}	1.16×10^{21}	2.14×10^{21}	3.26×10^{21}
Total 1	Total emergy flows, without human labor and services (sej)	7.58×10^{20}	9.65×10^{20}	1.68×10^{21}	2.61×10^{21}
Total 2	Total emergy flows, with human labor and services (sej)	8.36×10^{20}	1.25×10^{21}	2.36×10^{21}	3.63×10^{21}
AEP	Annual energy production (J/y)	5.04×10^{13}	3.56×10^{14}	1.15×10^{15}	2.45×10^{15}

4. Evaluation and Discussion

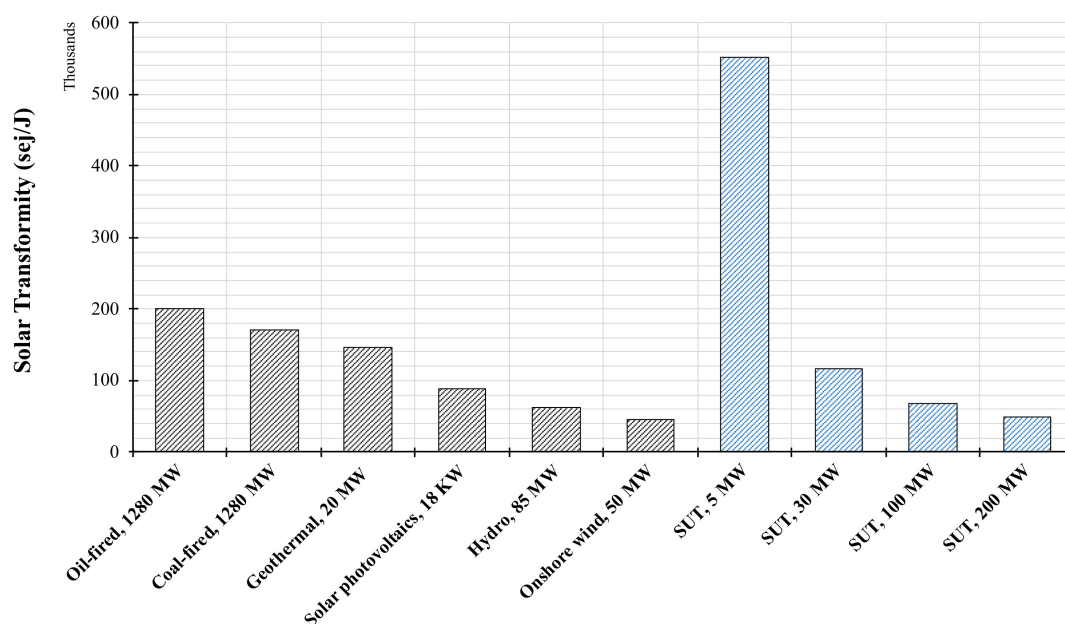
4.1. Emergy-Based Indicators

In order to investigate the relative performance and sustainability of SUT generation systems, their emergy indicators are presented in Table 5, together with comparisons of various conventional and renewable power generation technologies. Although the emergy input flows increased as the capacity of SUT enlarged, the SUT, 100 and 200 MW performed the best with regard to emergy-based indicators. This confirms that the sustainability of SUT grew as the size of the plant increased. Similar conclusions were achieved using a different method to assess SUT power plants [30].

Table 5. Comparison of energy resources' inflows and energy indicators for various power generation technologies.

	Power Generation Technology	R (sej/y)	N (sej/y)	F (sej/y)	Tr (sej/J)	EYR	ELR	EIS
Solar Updraft Tower Systems								
#1	5 MW	6.82×10^{17}	9.82×10^{16}	2.71×10^{19}	5.53×10^5	1.03	39.88	0.03
#2	50 MW	2.50×10^{18}	5.28×10^{17}	3.85×10^{19}	1.17×10^5	1.08	15.65	0.07
#3	100 MW	6.04×10^{18}	1.16×10^{18}	7.14×10^{19}	6.82×10^4	1.10	12.01	0.09
#4	200 MW	9.11×10^{18}	3.08×10^{18}	1.09×10^{20}	4.94×10^4	1.11	12.27	0.09
Renewable Power Generation								
#5	Solar photovoltaics, 18 kW [17]	1.00×10^{14}	3.05×10^{13}	4.88×10^{15}	8.92×10^4	1.03	48.93	0.02
#6	Onshore wind, 50 MW [15]	2.64×10^{18}	1.08×10^{16}	1.54×10^{19}	4.49×10^4	1.17	5.84	0.20
#7	Geothermal, 20 MW [3]	3.36×10^{19}	4.61×10^{18}	1.00×10^{19}	1.47×10^5	4.81	0.44	11.05
#8	Hydro, 85 MW [3]	1.69×10^{19}	4.45×10^{18}	3.21×10^{18}	6.23×10^4	7.65	0.45	16.90
Conventional Power Generation								
#9	Oil-fired, 1280 MW [3]	3.12×10^{20}	3.32×10^{21}	1.13×10^{21}	2.00×10^5	4.21	14.24	0.30
#10	Coal-fired, 1280 MW [3]	3.68×10^{20}	3.05×10^{21}	7.63×10^{20}	1.71×10^5	5.48	10.37	0.53

Transformity (Tr) is an important indicator to measure the overall efficiency of the production system at the biosphere scale. Power plants with greater transformities demand more environmental and economic resources to meet the same electricity demand. Large-scale SUT power plants are excellent in terms of energy conversion, except for very small generation capacities. The transformity of onshore wind energy and SUT, 200 MW is found to be the lowest among all conventional and renewable generation technologies presented in this research (Figure 4). Further, it is the closest in value to the thermodynamic minimum transformity for electricity production cycles [3]. This is an outcome of the simplicity of this technology as its materials are very conveniently based on environmentally sound production from renewable or recyclable materials.

**Figure 4.** Energy transformity of various power generation technologies.

The energy yield ratio (EYR) of SUT, 200 MW (1.1) is higher than solar photovoltaics. However, the value is much smaller than those of the other power generation plants. In general, EYR evaluates the protentional contribution of the power plant to the economy, and the smaller EYR of SUTs indicates a relatively high amount of energy resources invested by the economy.

The environmental loading ratio (ELR) measures the environmental stress of the power plant. The ELR of SUT, 200 MW (12.27) is small compared to solar photovoltaics and oil-fired power generation plants. However, the latter value is larger than those of the other renewable power plants. The larger

environmental stress is the negative effect of the enormous land area (nonrenewable resources) demanded by the SUT power plant compared to other renewable technologies.

The sustainability of power generation plants is interpreted by the emergy Index of Sustainability (*EIS*), which is the ratio of *EYR* to *ELR*. It should be considered that an *EIS* less than one indicates an unsustainable process from the viewpoint of emergy-based indices [3]. The *EIS* of large-scale SUT (0.09) is higher than the solar photovoltaics. However, the latter value is lower than other power plants and lower than one. This is because of the high value of *ELR*.

4.2. Emergetic Ternary Diagram

The graphical analysis assists the interpretation of emergy accounting results and the discussion. Therefore, emergetic ternary diagrams were drawn to facilitate the comparison between SUT and various energy technologies. In Figure 5, points #1 to #10 represent SUT and various power generation technologies which are presented in this paper (Table 5). The position of any point is plotted based on the percentages of the three emergy resources inflows *R*, *N*, and *F*. To clarify, in Figure 5a, point #10 (coal-fired, 1280 MW) is composed of 9% of *R*, 73% of *N*, and 18% of *F*. The resource flow lines are parallel to the triangle side and indicate a constant value for each resource flow (Figure 5b). They also identify emergy indicators *EYR* (yellow lines) and *ELR* (green lines). The resource flow lines are very useful for comparing the use of resources by each power plant [19,20]. By way of illustration, it can be observed that geothermal (#7) and coal-fired (#10) had almost the same quantity of purchased resources (*F*), but the quantities of renewable and nonrenewable resources (*R* and *N*) are extremely different. Moreover, it can be observed that SUT, solar photovoltaics, and wind-powered plants demanded higher quantities of purchased resources (*F*) than other power generation plants presented in this research.

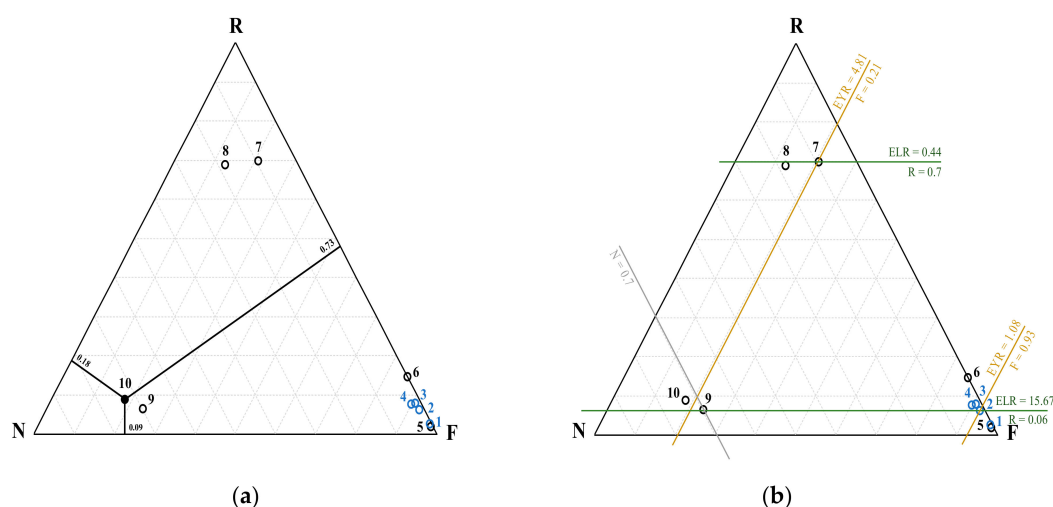


Figure 5. Emergetic ternary diagrams representing SUT and various power generation systems shown in Table 5. (a) represents the composition of point #10 (coal-fired, 1280 MW) and (b) the use of resource flow lines (*EYR*: emergy yield ratio; *ELR*: environmental loading ratio).

The emergy index of sustainability *EIS* is presented in emergetic ternary diagrams through the sustainability lines (orange lines) which indicate constant values of *EIS* (Figure 6a). The sustainability lines depart from the *N* apex in the direction of the *RF* side. According to M. T. Brown and S. Ulgiati [3], power plants with an *EIS* higher than one denote sustainable power generation in a long term. Consequently, the sustainability line where *EIS* = 1 divides the triangle into sustainability areas. The presentation of the sensitivity lines (Figure 6b) is very significant for identifying critical elements that may be changed to improve the sustainability of power plant systems. The sensitivity lines are straight lines that depart from an apex towards the opposite side. They can be drawn for any point (system) inside the triangle and trace the impact of changes in a given resource flux (*R*, *N*,

or F), while the other two fluxes remain constant. By way of illustration, it can be observed that the sustainability of SUT, 200 MW (#4) can be improved by changing the quantities of purchased resources. In the same way, an increase in the renewable services of a coal-fired (#10) plant may enhance its sustainability. As such, the sensitivity lines are a powerful tool to draw the sustainability pathways for decision-makers [19,20].

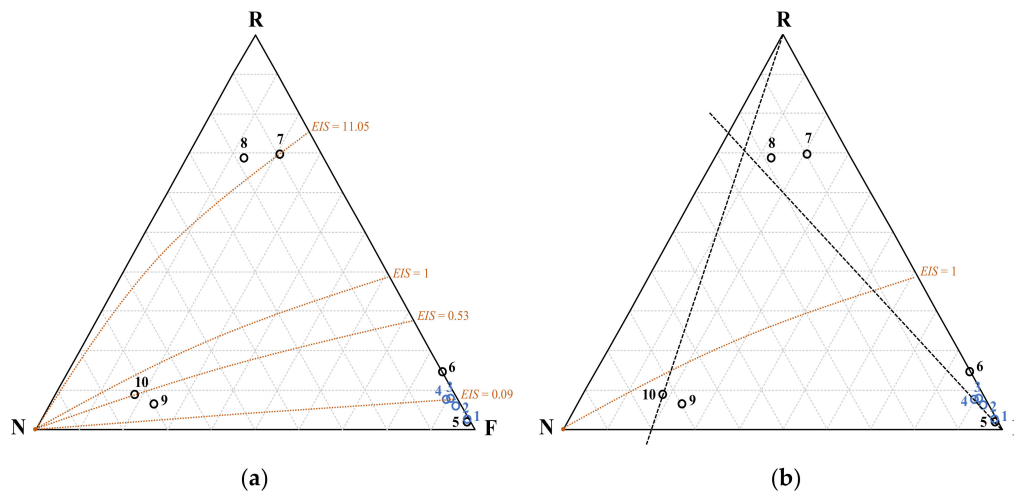


Figure 6. Representation of the auxiliary lines of emergetic ternary diagrams: (a) the use of sustainability lines, and (b) the use of sensitivity lines for SUT and various power generation systems shown in Table 5 (EIS : energy index of sustainability).

4.3. Scenario Analysis

To further investigate the above results and explore future optimization directions of the SUT power plant, scenario analysis was performed. Based on the energy index of sustainability, the sustainability of the SUT power generation system is less than coal-fired and oil-fired power generation systems. Further, its value is less than one which means unsustainable generation in the long term. Among the other capacities of SUT, large-scale SUT, 200 MW performs the best with regard to emergy-based indicators. It is worth studying SUT, 200 MW in terms of EIS change.

Derived from the sensitivity lines of emergetic ternary diagrams, the sustainability of SUT is strongly relative to purchased resources. The scenario analysis focus on dominant purchased resources includes the materials of the tower, collector, and turbines (manufacturing and construction materials). Additionally, the transportation distance of materials to the plant's location (1000 km in this study) was accounted for. The latter resources are taken as variables and the relationship between EIS is shown in Figure 7. The EIS of the SUT, 200 MW is mostly affected by the emergy of collector materials, followed by tower materials. On the other side, the turbines' materials and transportation distance have weak impacts. Therefore, the development direction of large-scale SUT power generation systems should mainly focus on reducing materials demanded by the manufacturing and construction of solar collectors.

The service life of a commercial SUT power plant ranges from 80 to 120 years [27]. Figure 8a shows the ESI of SUT, 200 MW changes with the length of lifetime (30 years in this study). It can be seen that the length of the SUT lifecycle has a slight impact on its sustainability.

As a final point, the emergy indicators are relative measures and depend on the characteristics of the fractions of emergy inputs. To compare different systems by the emergy index of sustainability, one has to follow the perspective of the evaluation [3]. To clarify further, the renewable fraction of human labor and services changes with the economic level of different regions and time periods, which directly affects EIS [3,14]. In fact, numerical variations of emergy indicators can be found in the literature for the same power generation technology. In the present analysis, the renewable fraction of human labor and services is considered as 26% [36]. In Figure 8b, the change of the EIS with the

percentage of the renewable fraction of human labor and services is observed. Notably, the change in renewable fraction has a relatively high impact on *EIS*. Therefore, in the emergy evaluation, the region and economic level should be unified to facilitate a successful comparison of different power generation systems.

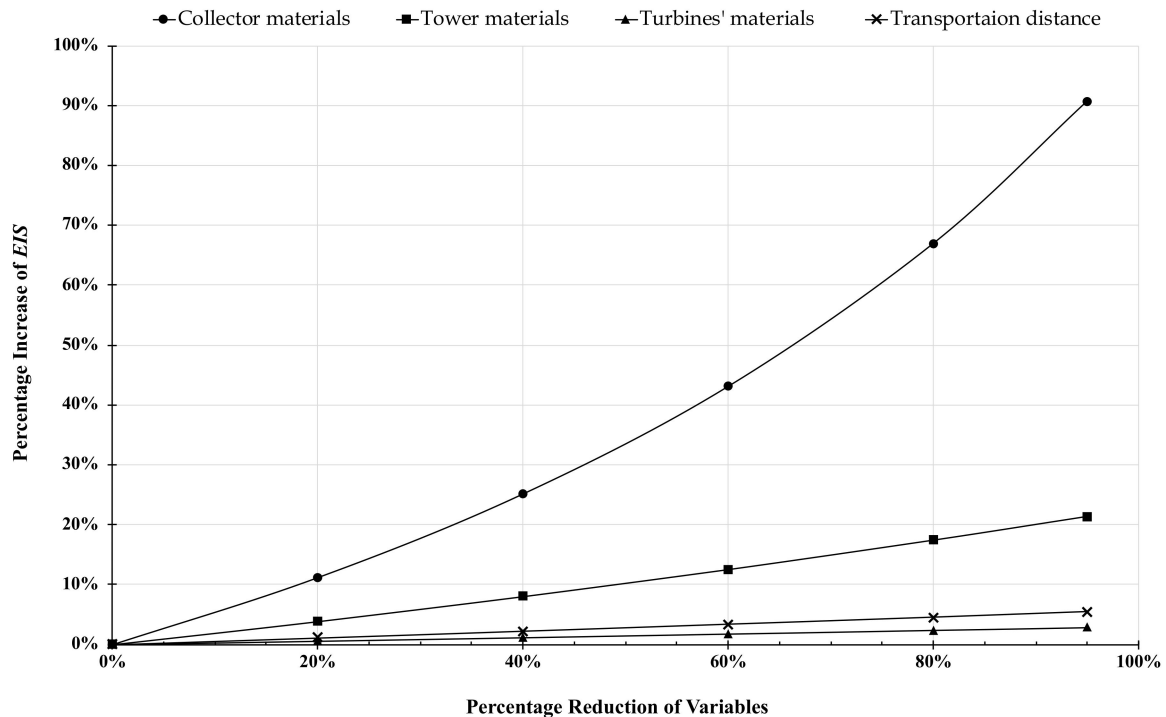


Figure 7. Percentage increase in *EIS* of SUT, 200 MW with the reduction of the tower, collector, and turbines' materials, as well as transportation distance of these materials to the plant's location.

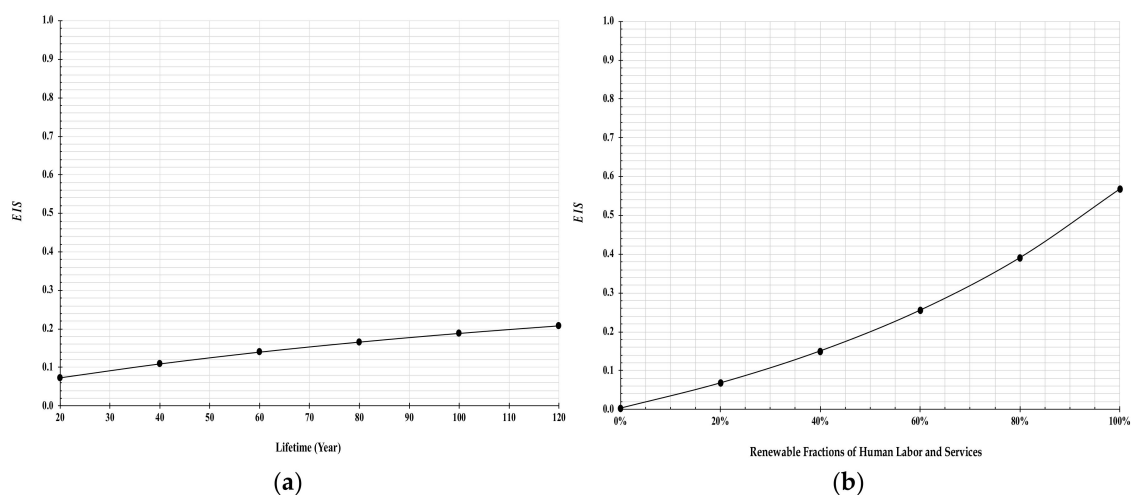


Figure 8. Changes in *EIS* of SUT, 200 MW with: (a) lifetime length of the power plant and (b) renewable fractions of human labor and services.

5. Conclusions

Clean energy infrastructure is essential economically, politically, environmentally, and socially for a greener tomorrow. To accelerate and strengthen the greening of the energy industry, the sustainable evaluation mechanisms of energy systems should be empowered. This paper addresses “emergy” as a powerful instrument to facilitate efficient energy management for policymakers as they choose

alternatives concerning the environment. The framework of emergy analysis for the power plant system involves ecological and economic emergy transformation chains to determine the total emergy input that drives the system. Thereupon, all energy systems are evaluated on an ecocentrism basis. Solar updraft tower (SUT) is one of the green technologies for acquiring renewable energy. SUT produces energy from the hot air, utilizing a combination of a flat plate solar collector, a central tower, and air turbines. Emergy accounting and emergy-based indicators are estimated to investigate the relative performance and sustainability of four power-generation capacities of SUT power plants.

Energy sources, materials, land loss, and human labor and services were converted to emergy flows. The total emergy of the SUT system accounts for all environmental contributions, energies, and human services used directly and indirectly to produce and maintain the power plant. The SUT, 100 and 200 MW performed the best with regard to emergy-based indicators. The results demonstrate that the sustainability of SUT grew as the size of the plant increased. For SUT, 200 MW, the manufacturing materials of the components are the dominant inputs, constituting 34.9% of total emergy. This was followed by the construction works (materials and energy consumption), constituting 29.0% of total emergy. The latter results are the output of the massive structure and materials demanded by a large-scale SUT power plant. Large-scale SUT power plants (100 and 200 MW) are excellent in terms of resources-use efficiency (emergy conversion). The emergy transformity of onshore wind energy and SUT, 200 MW was found to be the lowest among all conventional and renewable generation technologies presented in this research. This is the outcome of the simplicity of this technology as its materials are very conveniently based on environmentally sound production from renewable or recyclable materials.

Emergetic ternary diagrams were drawn to facilitate the comparison between SUT and various energy technologies. The sensitivity lines of emergetic ternary diagrams are very significant in identifying critical elements that may be changed to improve the sustainability of power plant systems. Derived from sensitivity lines, the sustainability of SUT is strongly relative to purchased resources. Scenario analysis was performed to explore future optimization directions of the SUT power plant. The scenario analysis focus on dominant purchased resources included the materials of the tower, collector, and turbines (manufacturing and construction materials). The transportation distance of materials to the plant's location was also taken into account. The *EIS* of the SUT, 200 MW was mostly affected by the emergy of collector materials, followed by that of tower materials. On the other side, the turbines' materials and transportation distance had weak impacts. Therefore, the development direction of large-scale SUT power generation systems should mainly focus on reducing materials demanded by the manufacturing and construction of solar collectors. Moreover, it can be seen from the analysis that the length of the SUT lifecycle had a slight impact on its sustainability. Notably, the change in the percentages of the renewable fraction of human labor and services had a relatively high impact on *EIS*. The renewable fraction changes with the economic level of different regions and time periods. Therefore, in the emergy evaluation, the region and economic level should be unified to facilitate a successful comparison of different power generation systems.

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