

Chapter 2

Main Methods

Abstract In order to have a better understanding of the different aspects (economic performance, environmental impacts, sustainability) of the biogas projects, ecological–economic methods are used to formulate the integrated assessment framework. First, economic method (cost–benefit analysis) was used to assess the economic feasibility of the biogas project. Moreover, DEA method was used to make an economic efficiency assessment, based on which the optimization suggestions could be provided. In terms of the environmental impact evaluation, life-cycle assessment model was established to evaluate the energy cost and environmental impact of biogas system, based on which the key sections for energy saving and emission reduction of biogas systems could be identified. As for the sustainability analysis, considering ecological and social inputs, emergy analysis and exergy analysis were employed to quantify the environmental pressure, renewability, economic efficiency, and sustainability of biogas systems. Possible pathways to achieve sustainable and low-carbon biogas project management were also analyzed based on the scenario analysis. Finally, analytic hierarchy process (AHP) method was adopted to incorporate categories of indicators to have a comprehensive performance analysis of the biogas system.

Keywords Cost–benefit analysis · DEA · LCA · Emergy · Exergy · Analytic hierarchy process

2.1 Life-Cycle Assessment (LCA)

2.1.1 Background of LCA

Life-cycle assessment (LCA) dates from the late 1960s and early 1970s, and has experienced three development stages, i.e., the conception (1970–1990), standardization (1990–2000), and elaboration stages (2000–present) (Guinée et al. 2011).

Various studies were conducted in the first stage to evaluate the cumulative energy requirements for the production of products and industrial processing such as steel, pulp and paper, and petroleum refining. In the early 1970s, when oil crisis took place, extensive energy studies had been conducted for a lot of industrial systems (Fava and Page 1992). By the end of the 1980s, LCA had been widely used by private companies in European countries such as Sweden, Switzerland, and the USA (Huppes 1996; Udo de Haes 1993). However, there is a lack of a common theoretical framework for LCA studies. As a consequence, the conceptions and results of LCA were widely diverging.

With the increasing severe environmental issues threatening the economic development and human living, people's environmental consciousness was running high gradually during 1990–2000. LCA is a powerful tool in tackling these issues, by analyzing the environmental impacts from the cradle to grave or from cradle to gate. Discussion on the importance of the life cycle of products was heated during 1980s to 1990s (Guinée et al. 2011). Now, LCA is experiencing a boom in the directions of breadth, depth, and applications and has becoming a policy analysis tool worldwide. LCA experienced unprecedentedly evolution in this period (e.g., Guinée et al. 1993a, b; Ayres 1995; Finnveden 2000). Some organizations also dedicated in the standardization of LCA framework. The Society of Environmental Toxicology and Chemistry (SETAC) started becoming a leader and coordinator in improving and harmonizing LCA framework, terminology, and methodology (SETAC-Europe 1993; Fava et al. 1993). Similar efforts were also undertaken by International Organization for Standardization (ISO). International standards on LCA have been made, including ISO 14040 (LCA within environmental management), ISO 14041 (inventory analysis), ISO 14042 (impact assessment), ISO 14043 (interpretation). These standards were then rephrased to ISO 14040 and ISO 14044 in 2006. Therefore, primary LCA procedure and standardization had been accomplished in this period.

In the third stage, LCA experienced a bloom in both methodology improvement and applications. Under the basic ISO framework, diverging approaches had been proposed, which contributed to the development of LCA. For example, calculation technologies were extended from process LCA to environmental input–output-based LCA (EIO-LCA) (Hendrickson et al. 1998; Peters 2007) and hybrid LCA (Lenzen 2002; Crawford 2008). Assessment method had been extended from midpoint evaluation (CML 2002, EDIP 2003, TRACI) and endpoint methods (EPS, Ecoindicator 99) toward methods that try to combine these two approaches and model impacts at both mid- and endpoint levels (LIME, ReCiPe, IMPACT2002+). Risk assessment was also incorporated into LCA (Nishioka et al. 2006; Saouter and Feijtel 1999; Sonnemann et al. 2004). In terms of applications, LCA continued to grow in importance in national decision making in both EU (European Commission 2013) and the USA (EPA 2013).

2.1.2 Methodology of LCA

LCA is a tool to assess the potential environmental impacts and resources used throughout a product's life cycle, i.e., from raw material acquisition, via production and use phases, to waste management (ISO 2006). It is a lifetime assessment that incorporates all material and energy inputs of a specific process and assesses their impact on natural environment, human health, and resource depletion. Using LCA, the following merits can be achieved:

- (1) LCA is a powerful tool in examining the environmental impacts of a product or service throughout its life cycle;
- (2) LCA provides a comprehensive overview of a product or service and avoids simply shifting from one stage of the lifetime to another, from one place to another, or from one environmental issue to other ones;
- (3) LCA can guide decision-making process for enterprises, sectors, and governments;
- (4) LCA helps to make clear the actual life-cycle environmental impacts of a product, which is always underestimated by people.

There are three steps for a standard LCA. (i) First of all, the goal and scope of the concerned system should be determined. Within the defined research scope, all the mass and energy inputs and outputs during lifetime stages of the chosen product, covering production, utilization, and final disposal and recycling, should be compiled in the inventory; (ii) based on the inventory of inputs and outputs, environmental impacts associated with the mass and energy flows should be quantified; and (iii) interpretation of the results and finding out appropriate ways to release the environmental, economic, and other pressures (Dincer and Rosen 2007). The LCA framework proposed by ISO is demonstrated in Fig. 2.1.

Two approaches are available in quantifying the environmental impacts of a product, i.e., the process-based and environmental input–output-based LCA (EIO-LCA). The conventional process-based LCA is a bottom-up approach, which traces all environmental impacts along with the supply chain. However, there are some cutoff criteria in process-based LCA, which neglect the parts that are considered unimportant or make few contributions to the results. This may lead to an underestimation of the LCA results. According to Suh et al. (2004), the impacts of the cutoff are 20% for many impact categories. Environmental input–output-based LCA can eliminate the cutoff derived from process-based LCA, as it is based on the national account and contains national economy and imports. However, the accuracy of EIO-LCA results may be decreased due to the uncertainty generated in sectoral aggregation (Mattila et al. 2010). In addition, data used in EIO-LCA are always outdated, as national input–output tables are not published on an annual basis.

To overcome the deficiencies of these two methods, hybrid LCA, proposed by Carnegie Mellon University (CMU), was proposed as a state-of-the-art LCA (Hendrickson et al. 1998; Lave et al. 1995). The hybrid LCA represents methods

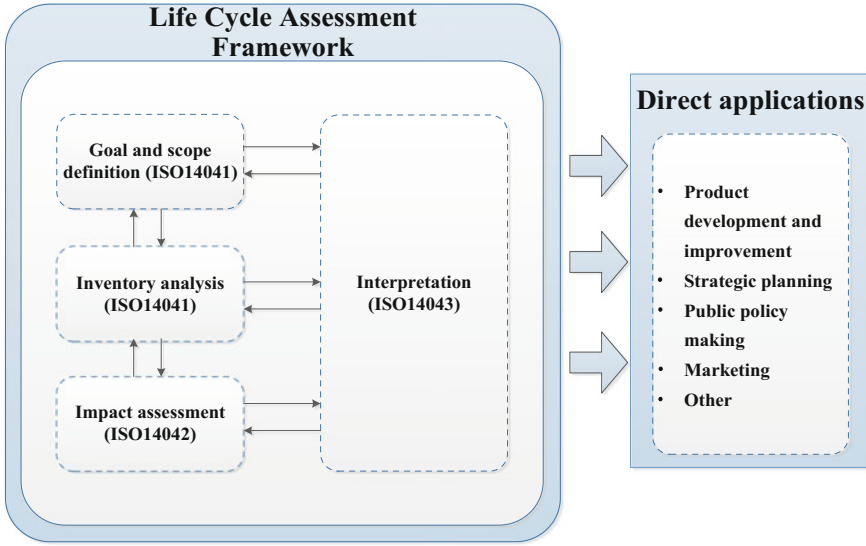


Fig. 2.1 LCA assessment framework

that combine process-based and EIO analysis to reduce uncertainty (Zhai and Williams 2010). Now, three prevailing hybrid LCA methods exist, namely additive hybrid (Bullard and Herendeen 1975), economic-balance hybrid (Williams 2004), and mixed-unit hybrid (Hawkins et al. 2007). Several real-world applications have been presented recently (e.g., Li et al. 2012; Whitaker et al. 2013), which demonstrate that hybrid LCA can avoid truncation and erroneous rankings of LCA results.

2.1.3 LCA-Based Integrated Evaluation Indices

Based on the LCA results, a multiobjective evaluation system is necessary to monitor biogas project performance from a systematic perspective. In the present work, an indicator system that is beneficial to a synthesized consideration of embodied energy, GHG emission, and economic factors in system optimization and policymaking was proposed.

Energy efficiency, GHG emission per energy output, and internal rate of return (IRR) are normally used for overall performance analysis. Distinct from these, new indicators of energy intensity and GHG emission intensity, defined as energy and GHG emission cost per unit profit, are proposed as goal functions for potential low-carbon and high-efficiency optimization of biogas systems. The calculation and implication of each indicator are shown in Eqs. (2.1)–(2.6).

Material recycling rate (MRR) is defined as the ratio of recycled materials in the dismantling phase to total material input based on the embodied energy metric, as shown in Eq. (2.1). MRR per se cannot be a proper energy indicator for sustainability issues, because it does not include the difference between thermal and mechanical energy based on the second law of thermodynamics. However, MRR may describe the material recyclability of a biogas system. The higher the MRR, the more materials recycled in the dismantling phase. Since recycled materials can be reused to substitute material input for biogas system construction, energy use and GHG emissions embodied in the construction phase would be reduced:

$$\text{MRR} = E_{\text{recycled}}/E_{\text{in}} \quad (2.1)$$

where E_{recycled} is the embodiment of materials recycled in the dismantling stage and E_{in} is the total embodied energy input.

Energy efficiency (EE) has been frequently used as an indicator to calculate the energy budget in earlier studies. In the case of electricity generation, energy intensity entails comparison of the primary energy used in the manufacture, transportation, construction, operation, decommissioning, and other stages of a facility life cycle with the amount of electricity generated. The less energy required to produce one unit of electricity, the more efficient the biogas system. EE is calculated as:

$$\text{EE} = E_{\text{in}}/E_{\text{out}} \quad (2.2)$$

Similarly, the GHG emission per energy output (ECD) associated with nonrenewable energy cost can be determined as:

$$\text{ECD} = C_{\text{in}}/E_{\text{out}} \quad (2.3)$$

where C_{in} is the direct and indirect GHG emission of the production process, and E_{out} is the total energy of electricity generated by a biogas system.

New indicators of energy intensity (EI) and GHG emission intensity (CI) are defined as embodied energy and GHG emission cost per unit profit, respectively:

$$\text{EI} = E_{\text{in}}/(B - C) \quad (2.4)$$

$$\text{CI} = C_{\text{in}}/(B - C) \quad (2.5)$$

where C and B are economic costs and benefits of the biogas project, respectively.

IRR is the value of the discount rate when net present value equals zero, which can be calculated by:

$$\sum [C/(1 + \text{IRR})^n] = \sum [B/(1 + \text{IRR})^n] \quad (2.6)$$

Table 2.1 LCA-based integrated evaluation indices

Index	Equations	Implications
MRR	$E_{\text{recycled}}/E_{\text{in}}$	Material recyclability of systems
EE	$E_{\text{in}}/E_{\text{out}}$	Energy conversion efficiency
ECD	$C_{\text{in}}/E_{\text{out}}$	GHG emission per energy output
EI	$E_{\text{in}}/(B - C)$	Energy intensity
CI	$C_{\text{in}}/(B - C)$	GHG emission intensity
IRR	$\sum [C/(1 + \text{IRR})^n] = \sum [B/(1 + \text{IRR})^n]$	A return rate used in capital budgeting for the measurement and comparison of the profitability of economic investments

Indices proposed to evaluate the system performance of biogas system are shown in Table 2.1.

2.2 Economic Assessment

2.2.1 Cost–Benefit Analysis

Economic benefit (EB) stands for the increasing economic value for the biogas project operation. It is the incremental value comparing before-construction and after-construction of biogas project and can be expressed by:

$$\text{EB} = \sum_{i=1}^n \text{EB}_i \quad (2.7)$$

where EB_i represents the i th benefit ($i = 1, 2, \dots, n$), including (1) economic benefits for substitute coal, firewood, electricity, chemical fertilizer, feed, and increased fruits; (2) environment and social benefits, such as health improvement and job creativity.

Economic cost (EC) refers to the additional economic costs during the life span of biogas system:

$$\text{EC} = \sum_{i=1}^n \text{EC}_i \quad (2.8)$$

where EC_i is the economic cost for the i th additional cost ($i = 1, 2, \dots, n$), with both construction costs and management costs (fermentation, maintenance, and utilization costs) being considered.

Based on the EC and EB, four financial valuation criteria (NPV, CBR, PB, EEC) are used for economic feasibility evaluation. All the four decision criteria are

included in the analysis from different aspects and can increase confidence in the viability of the investment opportunity.

Net present value (NPV) is a measurement of profit calculated by subtracting the present values of cost cash flows from the present values of benefit over a period of time. It is the sum of the net present benefits annually in the whole life span of the project, which can be given as:

$$NPV = \sum_{t=0}^n \frac{(EB_t - EC_t)}{(1+r)^t} \quad (2.9)$$

where r is the discount rate and t represents the specific year within the life span of biogas project, and t_0 is the first year of biogas project (construction period). If the value of $NPV > 0$, the discounted benefit exceeds the discounted cost and the project would be feasible with positive benefits.

Benefit-to-cost ratio (BCR) is a description of the input–output efficiency. The formula can be explained as follows:

$$BCR = \frac{\sum_{t=0}^n \frac{EB_t}{(1+r)^t}}{\sum_{t=0}^n \frac{EC_t}{(1+r)^t}} \quad (2.10)$$

If $BCR > 1$, the project is feasible with a good operation efficiency, the benefit could not make up for the cost otherwise.

Payback period (PB) is time needed to return its primary investment, which could be a reflection of the operation risk. Annual net profit is not equal every year, so the accumulated net profit in different years is calculated to find the specific year where all the primary cost is returned. The formula can be calculated by:

$$PB = CI/NP \quad (2.11)$$

where CI represents the initial investment, and NP is the net profit every year.

Economic effectiveness coefficient (EEC) is a comprehensive indicator coordinating eco-benefit quota, eco-efficiency indicator, and operation risk index, revealing the integrated effect of the biogas project. It can be written as:

$$EEC = \frac{NPV * BCR}{PB} \quad (2.12)$$

2.2.2 Data Envelopment Analysis (DEA)

DEA's initial models called CCR (Charnes–Cooper–Rhodes) were developed by Charnes et al. (1978) to evaluate overall technical efficiency. Based on the primary models, Banker et al. (1984) introduced BCC (Banker–Charnes–Cooper) models to

assess pure technical efficiency (Chen et al. 2015; Shabanpour et al. 2017). The relationship between two types of efficiency is that the overall technical efficiency equals pure technical efficiency multiplied by scale efficiency. The relationship can be expressed by:

$$\text{Overall efficiency} = Pa/Pb \quad (2.13)$$

$$\text{Pure technical efficiency} = Pc/Pb \quad (2.14)$$

$$\text{Scale efficiency} = Pa/Pc \quad (2.15)$$

In this work, the input-oriented versions were chosen for both CCR and BCC models considering that it would be much easier to improve efficiency by controlling the inputs than outputs of the biogas projects. Assume that there are z decision-making units (DMUs) converting m inputs into n outputs. For the j th DMU, $x_{ij}(i = 1, 2, \dots, m, j = 1, 2, \dots, k)$ inputs produce $y_{jr}(r = 1, 2, \dots, n)$ outputs. The matrix could be expressed by Lin et al. (2015):

$$\begin{cases} x_j = (x_{1j}, x_{2j}, \dots, x_{mj})^T, j = 1, 2, \dots, k \\ y_j = (y_{1j}, y_{2j}, \dots, y_{nj})^T, j = 1, 2, \dots, k \\ v = (v_1, v_2, \dots, v_m)^T \\ u = (u_1, u_2, \dots, u_n)^T \end{cases} \quad (2.16)$$

where v represents input weights vectors and u stands for the vectors of output weights.

For the j th DMU, efficiency value can be gained through CCR-DEA model and expressed by Ma et al. (2010):

$$\begin{cases} \text{Max } \frac{u^T y_{jo}}{v^T x_{jo}} \\ s.t. \frac{u^T y_j}{v^T x_j} \leq 1 \\ v \geq 0, u \geq 0 \\ j = 1, 2, \dots, k \end{cases} \quad (2.17)$$

Model 1 can be converted into a linear programming problem through the Charnes–Cooper transformation as follows:

$$\begin{cases} \text{Max } u^T y_{jo} \\ w^T x_j - u^T y_j \geq 0 \\ w^T x_{jo} = 1 \\ w \geq 0, u \geq 0 \\ j = 1, 2, \dots, k \end{cases} \quad (2.18)$$

where $w = tv$ represents the new vectors of input weights, and $\mu = tu$ means output weights.

The model 2 can be converted into a linear programming model and non-Archimedean infinitesimal for convenient evaluation, and the equivalent CCR model could be written as model 3:

$$\begin{cases} \text{Min}(q - r(e^T s^- + e^T s^+)) \\ x_j h_j + S^- = q x_j \\ y_j h_j + S^+ = y_j \\ h_j \geq 0, j = 1, 2, \dots, k \\ S^- \geq 0, S^+ \geq 0 \end{cases} \quad (2.19)$$

where q and h_j are the dual variable; e^+ and e^- represent m and n dimension unit vectors, respectively; S^+ and S^- stand for the slack variables, respectively. So the judgments of the CCR dual model could be gained: If $r < 1$, the evaluated DMUs are relatively ineffective; if $r = 1$, the evaluated DMUs are relatively effective.

2.3 Emergy Analysis

2.3.1 Emergy Concept

As the biosphere is generally considered to be driven by direct solar energy and by other sources of available energy deriving from solar radiation, solar emergy, i.e., the available solar energy directly and indirectly used for a product or service, is suggested as a common measure (Campbell 1998; Odum 1996) of sustainability analysis. Emergy, developed by Odum in 1960s, is defined as the availability of energy of one kind that is used up in transformations directly and indirectly to make a product or service (Odum et al. 2000). The unit of emergy is emjoule, a unit referring to the available energy of one kind consumed in transformations. Taken sunlight, electricity, and human service as examples, all of them in different energy hierarchy can be unified on a common basis by converting them in the unit of emjoules of solar energy. The aim of emergy analysis for a specific natural or artificial system is to investigate the relationship between socioeconomic development and the natural environment, which is not limited to issues of efficient resource use and can be regarded as an attempt to fit the concerned production procedure into the multidimensional surrounding ecosystems (Yang and Chen 2014).

In emergy analysis, each form of available energy input required in the lifetime of the investigated system is converted into its solar emergy equivalent, by multiplying the available energy by an appropriate solar transformity (or unit emergy value, UEV), which is a conversion factor of available energy into emergy. Solar transformity is an indirect measure of the total support needed to generate a unit (J) of resource flow or storage. Transformity can therefore be assumed as an indicator of the position of a resource in the universal energy transformation

hierarchy. The larger the transformity, the more solar energy required for the production and maintenance of the resource, product, or service of interest, and the higher its position in the energy hierarchy of the universe (Odum 1988, 1996).

As emergy analysis offers a more practical methodology to assessing the status and position of different energy carriers in the universal energy hierarchy and gives consideration to both the natural properties and economic characteristics of a system, it is widely used to evaluate public policy options and environmental impacts of renewable energy, which gives quantification of sustainable resource management questions (Chen and Chen 2012; Lapp 1991; Pereira and Ortega 2010; Yang et al. 2011). The procedure of emergy analysis includes: (1) collecting relevant ecological and socioeconomic information such as material inputs concerned with the studied biogas system; (2) determining the system boundary and main energy sources and clarifying the interrelationships among different components, based on which the emergy diagram should be drawn using emergy symbols; the components should be listed in sequence based on their transformities, and inputs with larger transformity should be listed in the right horizontally and at the top vertically; (3) compiling emergy table. Emergy table should include input items, the quantity of energy or material inputs, solar emergy transformity, and solar emergy. (4) Some emergy-based indicators should be employed for sustainable evaluation based on the requirement of specific research.

2.3.2 *Emergy Diagram*

The emergy diagram reveals the main processes of a specific system and all material input flows to each process, feedback flows, resource degradation flows, and monetary flows. Thereby, an overview of the whole process encompassing main components and their relationships within the system could be demonstrated for a comprehensive evaluation (Dong et al. 2008). In this diagram, the inputs include renewable environmental resource (R) and nonrenewable environmental resources (N), which are the direct driving forces of a specific process from the environment; the flows of material, equipment, human labor from the economy (F) that are used for the construction, operation, and maintenance the biogas power generation system; and the system output (Y), which is the yield of the process, to which the total emergy input is assigned. The co-product output of pollutants (C) can also be embraced in the diagram. Figure 2.2 shows the commonly used symbols used in emergy diagram.

2.3.3 *Emergy Indices*

Emergy indices employed in this study derive from Brown and Ulgiati are listed below:

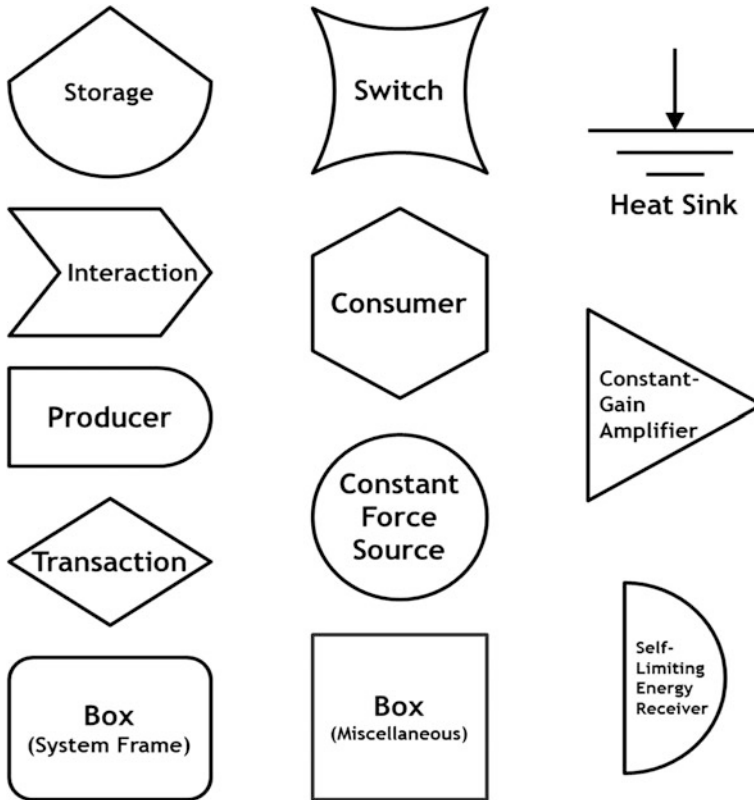


Fig. 2.2 Emergy systems language

The emergy yield ratio (EYR) is expressed as the emergy of total output Y divided by the emergy of purchased inputs outside the system of concern. The expression is $EYR = Y/F$. It is an indicator of the yield divided by purchased emergy input and gives a measure of the ability of the process to exploit local resources. The larger the emergy yield ratio, the more output are gained, given the purchased emergy unchanged.

The environmental loading ratio (ELR) is specified as $ELR = (F + N)/R$, which is the ratio of purchased F and nonrenewable indigenous emergy N to free environmental emergy R . This indicator represents the pressure of human activities on local environment and can be used as a measurement of the environmental burden caused by human activity. If there is a relative large value of ELR, it indicates that the local ecosystem is enduring severe pressure and may induce irreversible degradation of ecosystem function.

The emergy investment ratio (EIR) is the ratio of emergy purchased from outside to the indigenous emergy inputs. It can be expressed as $F/(R + N)$. Generally, the

higher the emergy investment ratio, the more money circulates and thus the higher economic development level of a system (Yang et al. 2010). It is not an independent index, but linked to the above EYR.

Emergy sustainable index (ESI) is the value of EYR divided by ELR. If a system has a high emergy yield ratio and a low environmental loading ratio, it is thereby sustainable, vice versa.

In addition to these conventional emergy indices, the system-level diversity ratio (SDR), derived from the modified Shannon information formula, is also used as an indicator to reflect the system performance and provide a quantitative assessment of the diversity.

Derived from the modified Shannon information formula, a system-level diversity ratio (SDR) was introduced by Ulgiati et al. (2011) to provide a quantitative assessment of the diversity of a system's supporting resources, defined as the ratio of actual diversity to the maximum potential diversity of a specific system. This indicator can reflect the ability to react to both biological and technological fluctuation of outputs. A lower SDR implies the output concentrates on specific kinds, which can be easily influenced by both biotic stress and market fluctuates. As a consequence, a SD closer to SD_{\max} (and therefore a ratio SD/SD_{\max} closer to 1) suggests higher system resilience (Table 2.2).

Table 2.2 Indicators for the energy and emergy analysis

Items	Expressions	References	Implications
Total energy inputs (T)	$F + N + R$	Odum (1996)	Total energy flux of the system
Percentage of renewable energy ($R\%$)	$R/(F + N + R)$	Odum (1996)	The dependence of the system on renewable emergy
Transformity	$(F + N + R)/E_{\text{out}}$	Odum (1996)	Emergy used to generate one unit of electricity
Emergy yield ratio (EYR)	Y/F	Brown and Ulgiati (1997)	Economic efficiency of a biogas system
Environmental loading ratio (ELR)	$(F + N)/R$	Brown and Ulgiati (1997)	Environmental loading exerted by the biogas system
Emergy sustainable index (ESI)	EYR/ELR	Brown and Ulgiati (1997)	Sustainability of the biogas system
System-level diversity index (SDR)	$SD = -\sum \left[\left(\frac{U_i}{U}\right)\right] \ln\left(\frac{U_i}{U}\right),$ $SDR = SD/SD_{\max}$	Brown et al. (2006)	The complexity and diversity of the biogas system
$E_m\text{CO}_2$	$C/E_{\text{out}}/ESI$	Ju and Chen (2011)	The ratio of the real CO_2 emission released and the emergy-based sustainability indicator (ESI) per joule biodiesel

$$SD = - \sum \left[\left(\frac{U_i}{U} \right) \right] \ln \left(\frac{U_i}{U} \right) \quad (2.20)$$

$$SDR = SD/SD_{\max} \quad (2.21)$$

where U_i = emergy input of the i th flow = (amount of i th flow; J or g) \times (emergy transformity of the i th flow; in units of sej/J or sej/g). SD is the system diversity, and SD_{\max} is the maximum potential diversity when the total emergy is evenly assigned to each input. As a consequence, a SD closer to SD_{\max} (and therefore a ratio SD/SD_{\max} closer to 1) suggests higher system resilience.

2.3.4 Emergetic Ternary Diagrams

Graphic representation can be used for the interpretation of results in a more direct manner. Several models have been proposed to represent graphically environmental indicators (Giannetti et al. 2006). For example, Lozano (2006) offered a condensed graphical overview of the myriad of sustainability indicators. Jalal and Rogers (2002) provided a graphical representation of the state of the environment. A graphical representation of the indices obtained by emergy accounting was also reported by Brown and Ulgiati and Ulgiati and Brown (1998). Since proposed by Gibbs and Roozeboom for the analysis of mixed components, ternary diagrams have been widely used in multidisciplinary (Giannetti et al. 2006). Hofstetter et al. (2000) firstly introduced ternary diagrams into ecological and environmental studies. Ternary diagram was then used to represent the interrelationships of ecosystem degradation, human health, and energy depletion. Giannetti et al. (2006) combined ternary diagram with emergy analysis and proposed an emergetic ternary diagram to shed light on sustainability management. The special data treatment and graphic representation provided by emergetic ternary diagram make it possible to compare various processes and systems, evaluate improvements, and follow the system performance over time (Chen and Chen 2012).

Emergetic ternary diagram consists of an equilateral triangle that has coordinates. The R , N , and F are assigned as three corners of this equilateral triangle. In the emergetic ternary diagram, the sum of proportions of R , N , and F is 1. Ternary combinations are represented by points within the triangle, while the relative proportions of the elements (R , N , F) are represented by the lengths of the perpendiculars from the given point to the side of the triangle opposite the appropriate element (Almeida et al. 2007). The resource lines and sustainability lines (Fig. 2.3) are employed to show the resource allocation in power generation systems. Detailed descriptions of emergetic ternary diagrams could be referred to Giannetti et al. (2006) and Almeida et al. (2007):

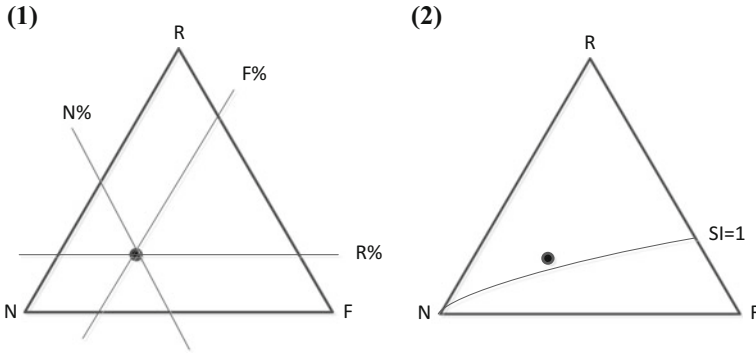


Fig. 2.3 Properties of emergetic ternary diagrams

- (1) 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.
- (2) 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 (Almeida et al. 2007).

2.4 Extended Exergy Analysis

2.4.1 Extended Exergy Analysis Framework

Extended exergy analysis is an extension of traditional exergy analysis, highlighting the primary production factors, including nonmaterial energy resource elements, labor production factors, and economic parameters. Thus, extended exergy bridges the “production value” gap between the majority of energists and economists (Chen and Chen 2009). Extended exergy (EE) intrinsically measures the amount of primary exergy homogeneously expressed in Joules that is cumulatively used over the production, operation, and disposal processes (Dai et al. 2012). The calculation of extended exergy is given by Eq. (2.20):

$$EE = CExC + E_C + E_W + E_e \quad (2.22)$$

where EE is the total extended exergy input of a specific system, CExC is the cumulative exergy cost, E_C represents the exergy equivalent of the monetary flow,

E_W represents the exergy equivalent of human labor, and E_e is specified as the greenhouse gas emission abatement costs.

Extended exergy costs include three parts: (1) the standard material and energy primary resource exergy used in the lifetime of the biogas project (quantified by their respective cumulative exergy content), (2) labor flows, (3) monetary flows (two social, economic factors), and (4) greenhouse gas emission abatement costs, which are measurement of the burden of greenhouse gas emission exerted by the artificial biogas project on the atmosphere. Moreover, for cost–benefit analysis, the energy and economic outputs and greenhouse gas emission abatement benefits gained from the biogas project are also incorporated into the extended exergy accounting framework. The benefits/outputs of biogas projects include: biogas energy output, economic profits gained by the utilization of biogas and its co-products, greenhouse gas emission abatement due to the substitution of traditional biomass and fossil fuels by biogas.

Exergy consumption associated with biogas production appears not only in the process of biogas fermentation but also in the processes of delivering semi-finished products and raw materials for the biogas project. The useful energy (exergy) consumed over the life cycle is represented by cumulative exergy analysis, including nonenergetic raw material consumption (e.g., chemical energy from ore). The unit of CExC is the MJ equivalent (MJ_eq). Here, the employment of cumulative exergy analysis aims to indicate resource depletion in the biogas project.

The economic input for the biogas project is the total investment for the biogas digesters to support the construction and operation, including all construction, transportation, and operation fees. Meanwhile, economic benefits can be quantified owing to the multiple uses of biogas digestate. Economic benefits can also be attributed to the fees saved by substituting biogas for conventional energy source and substituting biogas digestate for feedstock inputs. In addition, human labor should also be taken as an economic element that swears for the functioning of the biogas project.

In terms of greenhouse gas emissions occurred in the lifetime of the biogas project, except for the greenhouse gas directly emitted onsite during biogas production process, embodied greenhouse gas emissions generated in the production and delivery of raw materials (used as inputs of the biogas project) are taken into consideration. In the evaluation of the environmental performance of the biogas project, a tradeoff between lifetime greenhouse gas emissions and emissions avoided by substituting for conventional energy should be made.

2.4.2 Extended Exergy-Based Sustainability Indexes

Taking into account the resource, economic, and greenhouse gas emission implications of extended exergy analysis, a series of indicators can be presented to reflect the conversion efficiency, renewability, carbon emission loading, economic

benefits, and sustainability of biogas projects. The calculations of these indicators are shown in Eqs. (2.23)–(2.27).

(a) Resource depletion

The conversion efficiency or ε_P can be computed as the ratio of the useful output to the sum of the inputs that occurred to produce it (Wall 1977):

$$\varepsilon_P = \frac{\sum EO_j}{CExC} \quad (2.23)$$

where $\sum EO_j$ is the sum of useful resource outputs.

Renewability ($R\%$) is defined as the ratio of renewable exergy inputs to cumulative exergy inputs, i.e., the percentage of renewable energy that drives a process. In the long run, only high $R\%$ processes are sustainable.

$$R\% = E_R / CExC \quad (2.24)$$

where E_R is the renewable exergy input and CExC is the cumulative exergy input, which is the sum of renewable exergy inputs (E_R) and nonrenewable exergy inputs (E_{NR}).

(b) Greenhouse gas emission performance

Greenhouse gas emission intensity (CI) is used as the exergy equivalent to remove greenhouse gas emission (generated during the lifetime of the biogas digester) from the atmosphere divided by exergy output. CI can be a benchmark used to make tradeoffs between greenhouse gas emission and energy output.

$$CI = E_c / \sum EO_j \quad (2.25)$$

The economic return on investment (EROI) is the ratio of the economic profits gained from the biogas project to the sum of the economic investments delivered to produce it:

$$EROI = \frac{Y_C}{E_C} \quad (2.26)$$

where Y_C is the economic benefit gained by multiple utilization of biogas digestate and the substitution of conventional energy, and E_C is the exergy equivalent of the monetary inflow.

(c) Extended exergy-based sustainability indicator

Sustainable development meets the needs of economic development without compromising the environment. Taking into account both greenhouse gas emissions and economic elements in extended exergy analysis framework for biogas

Table 2.3 Evaluation indicator framework for biogas project

Destination layer	Criteria layer	Indicator layer	Explanation
Sustainable development	Environmental indicators	Increasing rate of organic matter	Increasing organic matter by returning biogas slurry, residue, and straw to the field
		SO ₂ reduction rate	Biogas as a substitution of coal to reduce SO ₂ emission
		CO ₂ reduction rate	Biogas as a substitution of coal and firewood to reduce CO ₂ emission
		Forest deterioration reduction rate	Biogas as a substitution of coal and firewood to slowdown forest deterioration
		Proportion of arable land taken by biogas digester	Arable land occupied by biogas digester construction
		Increase in animal excreta disposal rate	Improving residential environment quality through anaerobic fermentation
	Social indicators	Reduction in the rate of emigrate workers	More jobs and opportunities are provided by biogas projects
		Increase in labor productivity rate in rural areas	Surplus labor is fully used for maintenance of biogas digester
		Increase in the proportion of technical farmers	Enlarging the proportion of technical farmers through technical training on biogas technology
		Decrease in infection rate of parasitic disease	Influenced by the disposal of human and animal excreta
		Decrease in infection rate of intestine disease	Influenced by the disposal of human and animal excreta
	Economic indicators	Promotion in farmers' consuming level	Increase in income simulated the consumption
		Increasing rate of grain output per hectare	The use of organic fertilizer leads to the increase in grain output
		Increasing rate of pig breeding number	Biogas pool construction pulled the livestock breeding
		Increasing rate of fruit output per hectare	The developing mode of "pig–biogas–fruit" accelerated the development of fruit industry
		Proportion of construction cost	The proportion of pool construction costs in the whole expenditure

projects, the sustainability indicator SI can be expressed as the ratio of economic return on investment (EROI) to the greenhouse gas emission intensity (CI). The higher the index of sustainability, the lower the level of greenhouse gas emitted per unit of economic activity by the biogas project:

$$SI = EROI/CI \quad (2.27)$$

2.5 Analytic Hierarchy Process

The multiple benefits of biogas project in rural areas cover the following: increasing the food supply by producing more and better crops, fruits, and live stocks; improving the efficiency of agricultural production; and reducing the risk of soil erosion. Meanwhile, the elimination of parasites caused by the biogas fermentation process and biogas-based cooking instead of based on dung or wood can lead to positive effects on human health. However, the construction of biogas digesters may occupy former arable land in most cases and the construction costs are unaffordable for some farmers. In consideration of both the potential impacts of biogas exerted on sustainable development and the negative influences, a tradeoff between them and thereby an indicator system should be proposed. Here, the major impacts concerning social, economic, and ecological aspects caused by the application of biogas are identified and classified in Table 2.3.

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Biogas Systems in China

Chen, B.; Hayat, T.; Alsaedi, A.

2017, XXIII, 151 p. 41 illus., 5 illus. in color., Hardcover

ISBN: 978-3-662-55496-8