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The Application of Emergy Evaluation in Energy-Chemical Systems Incorporating Waste Influence

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In this paper, the energy-chemical systems incorporating waste treatment are analyzed using emergy analysis. Firstly, the system boundary with different types of waste is determined. Then the deficiency of traditional emergy-based indicator, environmental loading ratio (ELR), is discussed, and an alternative indictor ELR_W is given. In addition, to assess the impact of waste, the parameters for waste (W) and impact amplification coefficient (λ) are proposed for inclusion in traditional indicators. Finally, methanol synthesis (MEOH), Integrated Gasification Combined Cycle (IGCC) and poly-generation (PG) systems are analyzed by the modified indicators. The results show that the new indicators are reasonable to explain the environmental stress; IGCC has less economic competitiveness; MEOH gives the most pressures on the environment; the sustainability of PG is higher than MEOH and IGCC as well as the maximum tolerable value of waste negative effect reaches 4.33.

1. Introduction

Some acceptable evaluations indictors and frameworks, including energy analysis, exergy analysis and LCA (Life Cycle Assessment), have been used for providing decision-making in energy-saving and waste management (Cucek et al. 2011; Modarresi et al. 2011). In addition to the mentioned methods, the emergy analysis, first proposed by Odum (1988), is defined as follows: Emergy is the amount of available energy in units of one type of energy that is required to provide a given flow or storage of energy or matter. However, when dealing with energy-chemical systems which are different from ecosystems in stucture, emergy analysis needs to be modified and takes consideration of wastes (e.g., residues, waste water, and exhaust gases). Many researchers have applied emergy theory incorporating waste influence to industrial systems in recent years (Brown et al. 2002; Lou, et al. 2004; Yang et al. 2003), however, most of them ignores the potential negative effect of waste. Based on the reasonable determination of systems boundaries, the deficiency of traditional indicator ELR when applied to industrial systems is discussed and an alternative indictor ELR_W for overcoming them is also given. Moreover, the impact amplification coefficient (λ) proposed in this paper are used for investigating the negative effect of waste. Three cases of MEOH, IGCC and PG systems are analyzed by the proposed indicators.

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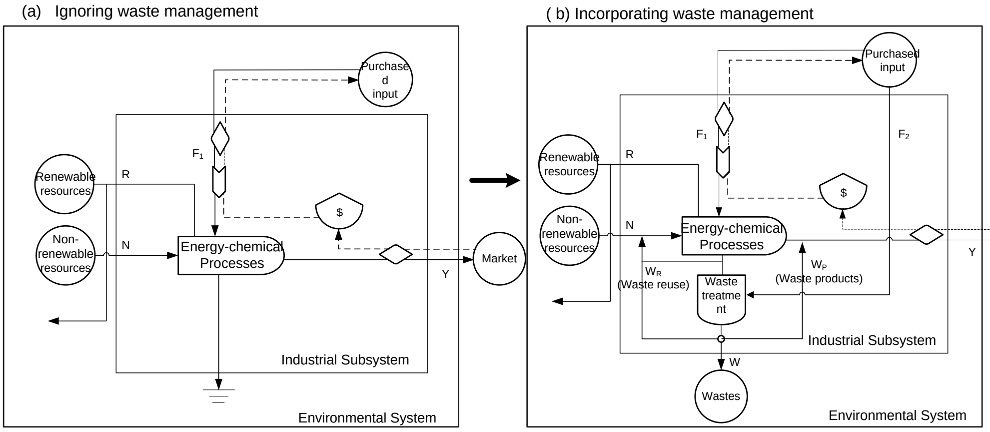
2. Emergy-based indicators in energy-chemical system

2.1 Determination of energy-chemical system boundary


(a) Ignoring waste management

(b) Incorporating waste management

Figure 1: Emergy flow diagram of an energy-chemical system

Evaluation methods based on traditional emergy analysis do not consider waste management, as shown in Figure 1a. In this paper, only four streams of input and output are taken into account, which are resources input, including renewable/no-renewable resources, supplemental emergy input, product output and waste for discharge.

2.2 Limitation of emergy-based indicators and its improvement

Several emergy-based indicators have been proposed, some of which are as follows.

$$EYR = \frac{Y}{F} = \frac{R+N+F}{F} \tag{1}$$

$$ELR = \frac{F+N}{R} \tag{2}$$

$$EIS = \frac{EYR}{ELR} \tag{3}$$

where R is renewable resources, N is nonrenewable resources, F is purchased input and Y is yield. Emergy yield ratio (EYR) denotes the competition ability or economic benefit of a process, and low value of EYR indicates weak competition and low economic benefit. Environmental loading ratio (ELR) is an indicator of the stress on the environment due to economic activity. Emergy index of sustainability (EIS) provides a simplistic indication of sustainability for a given process.

The application of traditional emergy analysis may result in an obvious defect that the emergy of renewable resources (R) is relatively low (Yang et al. 2003). Thus, the values of indicator ELR will become usually large. Meanwhile, as shown in Figure 1b, F_1, F_2 represent emergy input of investment on production and basic waste management cost, respectively. It is assuming that the waste from plant A is discharged without management, while waste from plant B is treated. As shown in equations 4 ~ 5, it is easy to draw the conclusion that $ELR_A < ELR_B$. Compared with plant A, plant B has a relatively higher environmental stress calculated by ELR, although the harmful waste from plant B has been treated. In a word, the traditional emergy-based indicator ELR is not reasonable and requires modification in order to incorporate waste treatment.

$$ELR_A = \frac{N+F_1}{R} \tag{4}$$

$$ELR_B = \frac{N+F_1+F_2}{R} \tag{5}$$

2.3 Alternative emergy-based indictors

The Alternative indictors EYR_W, ELR_W and EIS_W are illustrated as following (Mu et. al 2011):

$$EYR_w = \frac{R+N+F_1+F_2 - \lambda \sum_{i=1}^{n} W_i}{F_1+F_2} \tag{6}$$

$$ELR_w = \frac{N+F_2}{R+F_1+F_2 - \lambda \sum_{i=1}^{n} W_i} \tag{7}$$

$$EIS_w = \frac{EYR_w}{ELR_w} \tag{8}$$

where λ is the impact amplification factor; W is the emergy of waste; *i* denotes the *i*th type of waste and *n* is the total number of waste types.

For the alternative indictor ELR_W, the purchased emergy input (F) includes emergy input of investment for production processes (F_1) and basic waste management cost (F_2). F_2 is the cost for pollutants treatment in order to meet the basic requirements of environmental regulations. F_1 helps in reducing the environmental stress, and the higher fixed investment of an energy-chemical process, the smaller negative impact on environment. The impact of waste may far from its own emergy, so the value of parameter λ can be determined according to the influence of a waste the on environment.

3. Separate/ploy-generation energy-chemical systems

3.1 System description

Figure 2 illustrates flow diagram of MEOH, IGCC and PG systems. All of these systems adopt similar process technology, e.g., O_2-blown Texaco gasifier, Lurgi technology of methanol synthesis, and Rectisol process. In the MEOH system, about 98.6 % unreacted gas is recycled back and mixed with fresh syngas; while in the PG system (Jin et. al 2008), the syngas is sent to Lurgi methanol synthesis reactor without undergoing C/H adjusting of syngas, and about 75 % unreacted gas is recycled back to methanol synthesis reactor. Among these energy-chemical systems, total installed capacity of power generation unit is 200 MW, the maximum production capacity of MEOH synthesis unit is 25 wt /y.

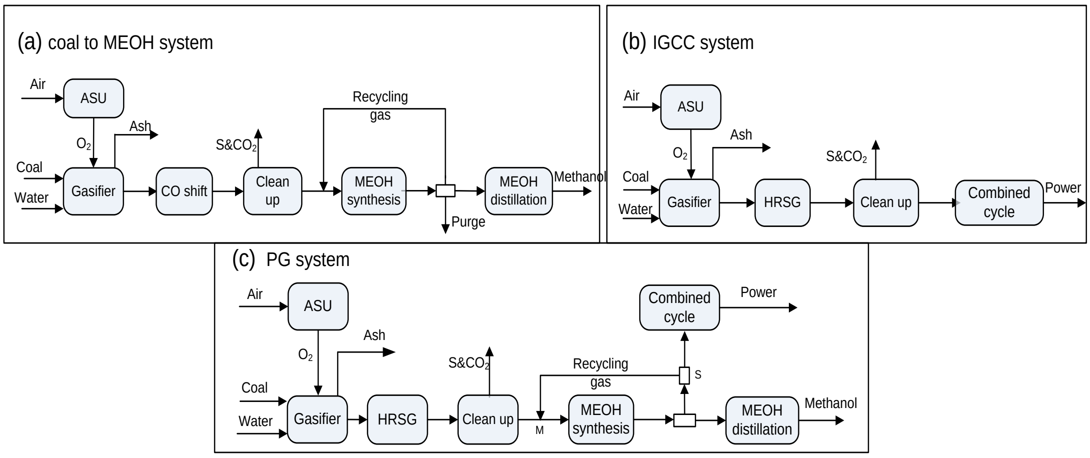


Figure2: Flow diagram of MEOH, IGCC, PG systems

3.2 System evaluation

Chapter 2 In this work, ASPEN Plus is used to simulate the material, energy and chemical balances of each process. Modelling of chemical reactions, thermodynamic property calculation methods and stream class selection, as well as process simulation and synthesis are completed based on previous studies reported in the literature (Zheng et al., 2005; Ong'iro et al., 1995; Emun et al., 2010). The results of emergy analysis are shown in Table 1~3.

Table 1: Emergy analysis of coal-based methanol synthesis (MEOH) system

	Items	Primary data	Transformity	Solar emergy /(sej)	Sum/(sej)
R	Air	1.57E+12/(g·y^{-1})	5.16E+07/(sej·g^{-1})	8.11E+19	8.18E+19
	Water	1.09E+12/(g·y^{-1})	6.60E+05/(sej·g^{-1})	7.17E+17	
N	Coal	1.04E+16/(J·y^{-1})	4.00E+04/(sej·J^{-1})	4.15E+20	5.98E+20
	Power	1.15E+15/(J·y^{-1})	1.60E+05/(sej·J^{-1})	1.84E+20	
F$_1$	Investment	5.35E+07/($·y^{-1})	7.35E+11/(sej·$$^{-1}$)	3.93E+19	3.93E+19
Y	MEOH	2.88E+11/(g·y^{-1})	2.39E+09/(sej·g^{-1})	6.88E+20	6.88E+20
	Sulfur	3.77E+09/(g·y^{-1})	1.83E+11/(sej·g^{-1})	6.88E+20	
F$_2$	Waste treatment cost	7.13E+05/($·y^{-1})	7.35E+11/(sej/$$^{-1}$)	5.24E+17	5.24E+17
W	CO$_2$	1.13E+11/(g·y^{-1})	5.16E+07/(sej·g^{-1})	5.85E+18	3.22E+19
	Ash	2.63E+10/(g·y^{-1})	1.00E+09/(sej·g^{-1})	2.63E+19	
	Waste water	1.09E+11/(g·y^{-1})	6.60E+05/(sej·g^{-1})	7.17E+16	

Table 2: Emergy analysis of Integrated Gasification Combined Cycle (IGCC) system

	Items	Primary data	Transformity	Solar emergy /(sej)	Sum/(sej)
R	Air	2.20E+12/(g·y^{-1})	5.16E+07/(sej·g^{-1})	1.13E+20	1.14E+20
	Water	1.44E+12/(g·y^{-1})	6.60E+05/(sej·g^{-1})	9.48E+17	
N	Coal	1.23E+16/(J·y^{-1})	4.00E+04/(sej·J^{-1})	4.93E+20	4.93E+20
F$_1$	Investment	6.76E+07/($·y^{-1})	7.35E+11/(sej·$$^{-1}$)	4.97E+19	4.97E+19
Y	Power	4.55E+15/(J·y^{-1})	1.35E+05/(sej·J^{-1})	6.15E+20	6.15E+20
	Sulfur	2.88E+09/(g·y^{-1})	2.14E+11/(sej·g^{-1})	6.15E+20	
F$_2$	Waste treatment cost	5.67E+05/($·y^{-1})	7.35E+11/(sej·g^{-1})	4.17E+17	4.17E+17
W	CO$_2$	1.87E+11/(g·y^{-1})	5.16E+07/(sej·g^{-1})	9.63E+18	4.10E+19
	Ash	3.12E+10/(g·y^{-1})	1.00E+09/(sej·g^{-1})	3.21E+19	
	Waste water	1.44E+11/(g·y^{-1})	6.60E+05/(sej·g^{-1})	9.48E+16	

Table 3: Emergy analysis of un-reacted syngas partial-cycling ploy-generation (PC/PG) system

	Items	Primary data	Transformity	Solar emergy/(sej)	Sum/(sej)
R	Air	3.69E+12/(g·y^{-1})	5.16E+07/(sej·g^{-1})	1.91E+20	1.92E+20
	Water	2.13E+12/(g·y^{-1})	6.60E+05/(sej·g^{-1})	1.41E+18	
N	Coal	2.07E+16/(J·y^{-1})	4.00E+04/(sej·J^{-1})	8.27E+20	8.27E+20
F$_1$	Investment	1.12E+08/($·y^{-1})	7.35E+11/(sej·$$^{-1}$)	8.22E+19	8.22E+19
Y	Power	4.55E+15/(J·y^{-1})	1.80E+05/(sej·J^{-1})	1.04E+21	1.04E+21
	MEOH	2.88E+11/(g·y^{-1})	2.82E+09/(sej·g^{-1})	1.04E+21	
	Sulfur	2.94E+09/(g·y^{-1})	2.48E+11/(sej·g^{-1})	1.04E+21	
F$_2$	Waste treatment cost	9.60E+05/(g·y^{-1})	7.35E+11/(sej·g^{-1})	7.06E+17	7.06E+17
W	CO$_2$	1.25E+11/(g·y^{-1})	5.16E+07/(sej·g^{-1})	1.08E+19	6.34E+19
	Ash	5.24E+10/($·y^{-1})	1.00E+09/(sej·g^{-1})	5.24E+19	
	Waste water	2.10E+11/(g·y^{-1})	6.60E+05/(sej·g^{-1})	1.41E+17	

1.1 Results and discussion

This section focuses on the changes of proposed emergy-based indictors under different impact amplification factor, and the results are shown in Table 4. The indictors of those systems based on traditional emergy analysis without waste treatment (λ=0) are also calculated.

Table 4: Effect of λ on the emergy-based indicators

	MEOH				IGCC				PG			
λ	0*	1	2	5	0*	1	2	5	0*	1	2	5
EYRw	18.05	13.25	12.24	10.32	13.08	12.39	8.67	9.01	13.22	12.78	11.82	9.56
ELRw	5.13	5.71	10.55	-8.01	2.86	3.98	5.72	-12.55	2.82	3.95	5.68	-20.82
EISw	3.67	2.32	1.16	-1.29	4.57	3.11	1.52	-0.72	4.69	3.24	2.08	-0.46
λ_{mt}	3.27				4.01				4.33			

* Calculation by traditional emergy-based indicators when λ=0.

As seen in Table 4, both the proposed emergy-based indictors (λ>1) of EYR_W and EISw are lower than the traditional emergy-based indictors, while the indictor ELR_W are higher than the traditional indictors. Such results indicate that the performance of the mentioned energy-chemical systems incorporating waste treatment is inferior to those of the traditional indictors. Those results are in accord with actual industrial processes. The proposed indictor EYRw decreases, even down to zero as expected, with increasing impact amplification coefficient (λ). Meanwhile, the relationship of EYRw is IGCC<PG<MEOH, which indicates that IGCC requires further improvement of economic competitiveness. ELRw will be turned negative as λ increases to a certain value. At the same time, the relationship of ELRw is PG<IGCC< MEOH, the PG system has advantage of lowest stress on the environment. EIS is able to characterize the degree of sustainability of energy-chemical systems. The mentioned systems have maximum tolerable (mt) value are λ_{mt} = 3.27, 4.01 and 4.33, respectively, When λ is lower than the λ_{mt}, both EIS_W and ELR_W become negative and then these systems are in unhealthy and unsustainable situations. It shows that poly- generation can strengthen sustainable development ability.

2. Conclusions

The newly developed emergy-based indictors can reasonably reflect the stress of waste in energy-chemical systems on the environment. For the three energy-chemical systems, PG system has the moderate economic competitiveness under the condition of lowest environmental stress and highest sustainability. The relationship between the impact amplification coefficient (λ) and emergy-based indictors of economic, environmental and sustainability has been investigated, thereby the maximum tolerable values of PG, IGCC and MEOH systems are also obtained. The PG system has best performance in diluting the hazards of waste on environment.

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