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Emergy Evaluation of Methanol and Naphtha to Aromatics Systems Combined with Renewable Power Generation

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Methanol to aromatics is proved to have better performance than traditional naphtha to aromatics in terms of aromatics demand increasing and the petroleum resources decreasing. The electricity source has a great impact on the performance of aromatics production systems according to the emergy evaluation. Basing on the emergy evaluation of different aromatics production systems and renewable power generation systems, the emergy indices of aromatics production systems are discussed when the electricity is generated from renewable resources. The sustainability levels of the systems are analysed when the emergy proportion of electricity is uncertain. The results show that all the methanol to aromatics systems will be sustainable when the hydropower is applied. When the biomass direct-fired power is used, the natural gas and coke oven gas-based systems show weak sustainability while the coal-based system will be unsustainable. For the situation that the electricity has uncertain emergy proportion, the coal, natural gas and coke oven gas-based systems will become sustainable when the renewable proportion of electricity is greater than 0.40, 0.20 and 0.20.

1. Introduction

Aromatics are important products in chemical industries and conventionally produced by catalytic reforming of naphtha. With petroleum reserves decreasing and aromatics demand increasing, new aromatics production methods should be developed (Singh et al., 2019). Nowadays, the methanol production is in excess and the route of methanol to aromatics shows good technical and economic benefits (Zhang et al., 2020). Further research on methanol to aromatics is essential to reduce the dependence on fossil fuels.

Methanol could be produced from coal (Chen et al., 2019), coke oven gas (COG) (Li et al., 2018), natural gas (Niziolek et al., 2016) and biomass (Ng and Sadhukhan, 2011). Among these, COG is proved to have better economic and environmental performance than coal and natural gas (Li et al., 2018) while coal to methanol system has the largest environmental impact (Chen et al., 2019).

The overall route of methanol to aromatics based on different raw materials has been studied by life cycle assessment (Jiang et al., 2020), indicating better economic and environmental performance of methanol to aromatics systems. Emergy evaluation (Ren and Feng, 2021) is performed to obtain the sustainability levels of the aromatics production systems, demonstrating that methanol to aromatics systems are more sustainable than naphtha to aromatics systems.

The previous studies analysed the techno-economic performance, environmental performance and sustainability of aromatics production based on different raw materials. However, the factors affecting the sustainability, for example, the types of the electricity resources, have not been analysed, as a lot of electricity is needed in the aromatics production process (Wang et al., 2020).

In this paper, the factors impacting the sustainability levels are analysed and the performance of the systems using electricity from different resources is discussed from the emergy perspective. The emergy is defined as the amount of available energy of one kind directly or indirectly used to make a service or product. The novelties of this paper are as follows. (1) The impact of renewable electricity on the sustainability of the aromatics production is analysed. The emergy indices of aromatics production systems are analysed when hydropower and biomass direct-fired power is utilised; (2) The sustainability of each methanol to aromatics system is discussed when the source of electricity are uncertain.

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2. Data and method

The research scale of this paper is described. The basis data for the discussion of different scenarios are provided.

2.1 Research boundary

The research boundary of this paper are aromatics production systems, as shown in Figure 1. Naphtha-to-aromatics and methanol-to-aromatics systems are considered. The raw materials of the methanol-to-aromatics systems include coal, coke oven gas (COG), natural gas and biomass. The electricity is initially regarded as non-renewable energy.

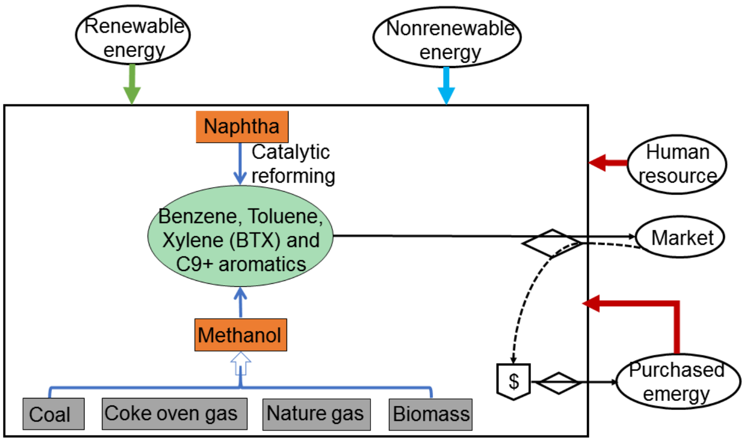

Figure 1: Different routes of aromatics production

2.2 Data collection

Table 1 shows the emergy data of different aromatics production systems (Ren and Feng, 2021). The electricity is initially considered to be from traditional thermal power station and belongs to the non-renewable emergy. Table 2 is different types of emergy values of the renewable power generation systems.

Table 1: Emergy data of different aromatics production systems

Items	Coal (sej)	COG (sej)	Natural gas (sej)	Biomass (sej)	Naphtha (sej)
R					
Biomass	-	-	-	7.26×10^{20}	-
Air	4.47×10^{20}	2.78×10^{20}	-	1.30×10^{20}	-
Water	2.52×10^{20}	7.40×10^{19}	7.49×10^{19}	5.56×10^{19}	3.34×10^{19}
Oxygen	-	-	1.79×10^{20}	-	-
N					
Naphtha	-	-	-	-	1.73×10^{21}
Electricity	2.44×10^{21}	1.92×10^{21}	7.21×10^{20}	1.46×10^{20}	2.21×10^{19}
Coal	3.57×10^{21}	3.11×10^{19}	1.10×10^{20}	-	-
Natural gas	-	-	2.19×10^{21}	-	-
F					
Capital costs	8.67×10^{19}	5.12×10^{19}	4.20×10^{19}	2.82×10^{20}	7.27×10^{18}
O&M costs	1.33×10^{20}	1.33×10^{20}	1.33×10^{20}	3.22×10^{20}	1.03×10^{20}
Utility	7.59×10^{20}	2.94×10^{20}	5.72×10^{19}	7.58×10^{19}	2.90×10^{19}
Y					
Total emergy	7.69×10^{21}	2.78×10^{21}	3.51×10^{21}	1.73×10^{21}	1.93×10^{21}

Table 2: Different types of emergy values in renewable power generation systems

Unit (sej)	CSP (Zhang et al., 2012)	Wind (Yang and Chen, 2016)	Tidal (Zhang et al., 2018)	Hydropower (Cui et al., 2011)	Geothermal (Buonocore et al., 2015)	PV (Paoli et al., 2008)	Biomass (Pang et al., 2017)
R	8.31×10^{16}	3.55×10^{19}	2.92×10^{18}	1.13×10^{21}	4.50×10^{19}	1.00×10^{14}	6.28×10^{18}
N	5.94×10^{16}	3.21×10^{16}	2.53×10^{18}	3.82×10^{20}	7.41×10^{18}	3.05×10^{13}	4.37×10^{17}
F	4.83×10^{17}	2.49×10^{20}	1.05×10^{19}	1.20×10^{20}	1.92×10^{19}	4.88×10^{15}	1.11×10^{19}

2.3 Method

The emergy indices mainly include emergy yield ratio (EYR), environmental loading rate (ELR) and sustainability index (ESI) (Odum, 1996).

The EYR (-) is the ratio of the total emergy output to the purchased emergy input, which represents the dependence of the system on the purchased emergy.

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

The ELR (-) indicates the pressure of the system on the environment in the production process. The use of non-renewable resources is the main reason for environmental deterioration. A high ELR (-) value means the environmental impact of a systems is high.

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

The ESI (-) is the ratio of EYR (-) and ELR (-). If the system has a higher production efficiency and less environmental pressure, there will be a high sustainability index. Generally, the system with ESI (-) higher than 1 is sustainable, but higher than 10 is a symbol of insufficient utilisation of resources.

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

The limitation of the method is that it is more inclined to consider the environmental performance and sustainability of different systems, but less about the economic performance and emissions.

3. Results

In this part, the proportions of different emergy types in methanol to aromatics systems and renewable power generation systems are compared.

3.1 Emergy proportions of methanol to aromatics systems

Figure 2 gives different types of emergy input proportions. According to Figure 2, the renewable emergy proportion of the biomass-based system is the highest. The natural gas-based methanol to aromatics system has the highest non-renewable emergy input proportion, which is mainly composed by natural gas, accounting for 62.40 %, followed by electricity (20.58 %).

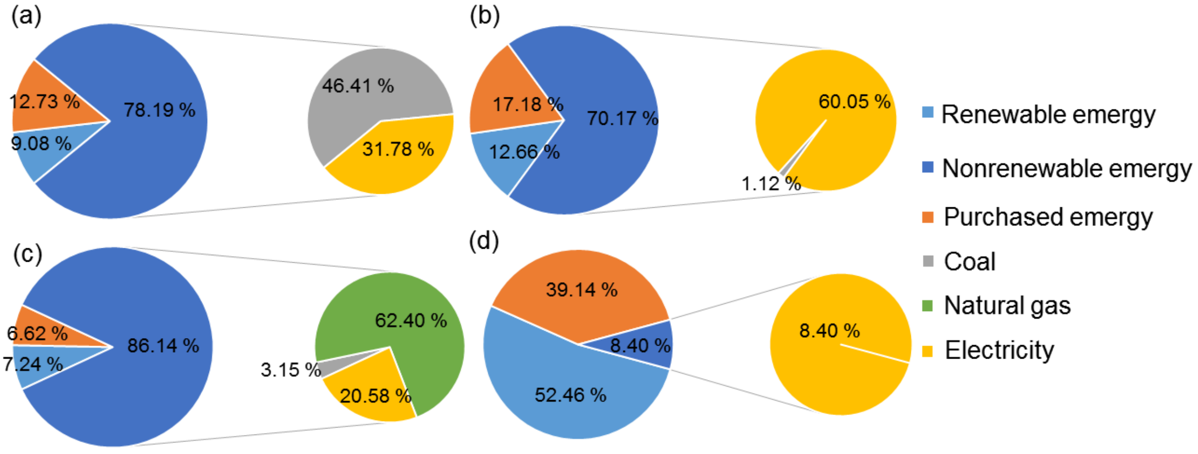

Figure 2: Different types of emergy input proportions: (a) Coal-methanol to aromatics system; (b) COG-methanol to aromatics system; (c) Natural gas-methanol to aromatics; (d) Biomass-methanol to aromatics

Basing on the above emergy analysis, the non-renewable emergy and purchased emergy are important factors affecting the sustainability. The environmental performance and sustainability of the system can be improved by reducing the proportion of non-renewable and purchased emergy. The purchased emergy can be reduced by decreasing the investment cost. As for the non-renewable emergy, it can be seen from Figure 2 that the coal and natural gas occupy a relatively high proportion of non-renewable emergy in the coal and natural gas-based systems, followed by electricity. The electricity accounts for the highest proportion of the non-renewable emergy in the COG and biomass-based systems. As coal and natural gas are raw materials for production and cannot be changed in the processes, the sustainability of the systems can be improved by changing the source of electricity, for example, using renewable electricity.

3.2 Emergy proportions of renewable power generation systems

The electricity generated from renewable resources have different types of resource inputs. The electricity from renewable resources should be composed of different types of emergy. Figure 3 shows the proportion of different forms of emergy in various renewable power generation systems. Among them, the hydropower system (Cui et al., 2011) has the largest renewable emergy input with proportion of 69.24 %, followed by the geothermal power system with the renewable emergy proportion of 62.87 %. The renewable emergy proportions of the power generation systems are ranging from 2.00 % to 69.24 %.

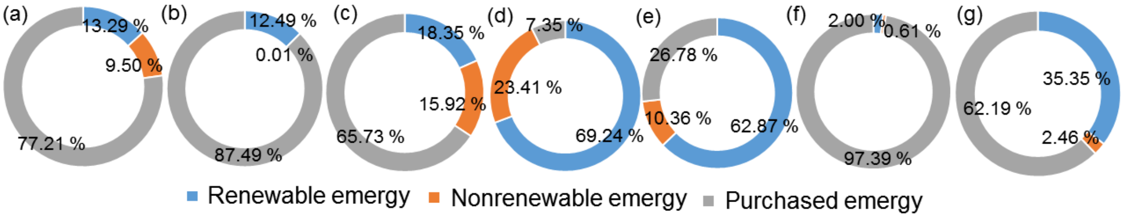

Figure 3: Different types of emergy proportions of renewable power generation systems: (a) Concentrated solar; (b) Wind; (c) Tidal; (d) Hydropower; (e) Geothermal; (f) Photovoltaic; (g) Biomass directly fired

4. Discussion

The emergy indices of methanol to aromatics systems are discussed when the hydropower and biomass direct-fired power are utilised as examples. The utilisation of other renewable power will be discussed uniformly in the situation that the emergy types proportions are uncertain.

4.1 Emergy indices under the utilisation of renewable electricity

The emergy results are shown in Figure 4(a) when the hydropower is utilised. All the methanol to aromatics systems are sustainable while naphtha to aromatics system is unsustainable, indicating a great development potential of the methanol to aromatics system when the renewable electricity is utilised.

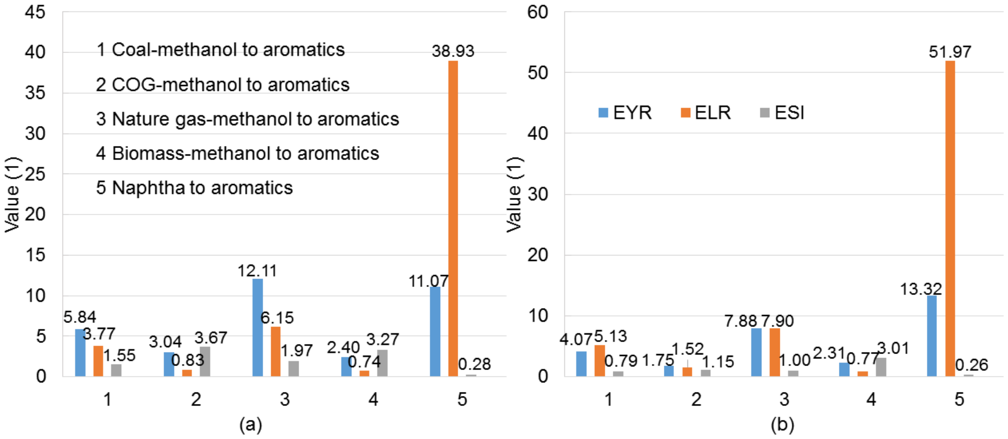

Figure 4: Emergy indices of the aromatics production systems (a): underutilisation of hydropower; (b): underutilisation of biomass directly-fired power

Comparing to the situation that electricity is regarded as non-renewable emergy (Ren and Feng, 2021), the sustainability of the COG-based system will surpass the biomass-based system. The reason is that a large amount of electricity is required in the production of COG, which leads to the larger electricity consumption of the COG-based system. The sustainability change of the COG-based system is greatly influenced by the electricity resources, demonstrating that the COG-based system is the worthiest of promotion under the premise of renewable electricity.

According to Figure 3, the renewable emergy proportion of geothermal power system (62.87 %) is close to the hydropower system (69.24 %), the situation of the utilisation of geothermal power will not be discussed. Next, the emergy indices of the systems will be discussed when the biomass direct-fired power is used. The emergy indices are shown in Figure 4(b), in which the order of the ELR (-) remains unchanged, while the EYR (-) of the COG-based system decreases obviously compared with the results under the utilisation of hydropower. The reason is that the purchased emergy of the biomass direct-fired power system is relatively high (62.19 %), which further increases the purchased emergy input of the COG-based system. The biomass-based methanol to aromatics system has the highest sustainability, followed by the COG and natural gas-based systems, while the system based on coal is unsustainable.

4.2 Sustainability changes with the renewable emergy proportion of electricity

The above analysis shows that the sustainability levels of methanol to aromatics systems are significantly affected by the renewable emergy proportion of electricity. The impact of the renewable emergy proportion of electricity on the sustainability is further studied.

MATLAB R2020a is used to generate a random matrix with 3 rows and 100 columns whose element size is in the range of 0-1, and the column sum is 1. Each row of elements represents the renewable, non-renewable and purchased emergy proportion of electricity. The emergy indices are calculated when the electricity with different types of emergy proportion is used.

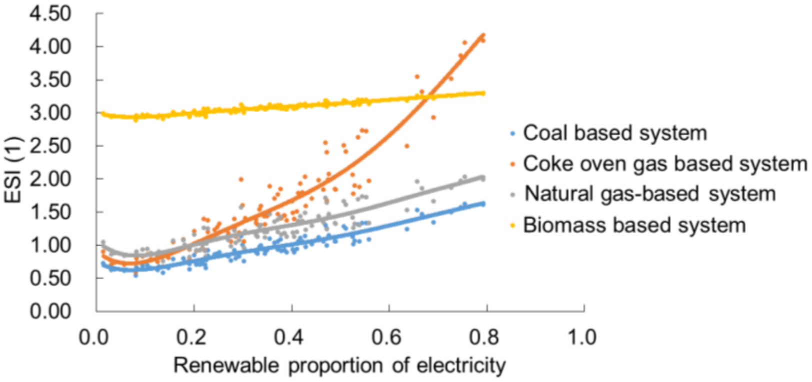

Figure 5: Sustainability indexes of the aromatics production systems changing with the renewable proportion of electricity

Figure 5 shows the sustainability variation with the renewable emergy proportion of electricity. The sustainability of the COG based methanol to aromatics system is less than that of the natural gas-based system when the renewable emergy proportion of electricity is less than 0.19 (-). When the renewable emergy proportion of electricity is more than 0.2 (-), the sustainability of the COG based system will exceed that of the natural gas-based system and the ESIs (-) of these two systems will be greater than 1, which means sustainable. The sustainability of the coal-based methanol to aromatics system is always less than other systems. The coal-based system will be a sustainable system when the renewable emergy proportion of electricity is more than 0.4 (-). Among all the systems, the sustainability of the biomass-based methanol to aromatics system changes slightly with the renewable emergy proportion of electricity. Remarkably, the sustainability of the COG-based system will exceed that of the biomass-based system when the renewable emergy proportion of electricity is greater than 0.68 (-). It indicates that the COG based system has a good development prospect in terms of sustainability and the sustainability of which can be greatly improved by using renewable electricity.

5. Conclusions

By analyzing the input emergy proportion of aromatics production systems, it is found that the source of electricity has a significant impact on the system performance. The emergy indices are compared when the renewable electricity is utilised. The results show that all methanol to aromatics systems will be sustainable and the COG-based system will have the highest sustainability when the hydropower is used. When the biomass direct-fired power is utilised, the natural gas and COG-based systems show weak sustainability while the coal-based system will be unsustainable. When the emergy proportion of electricity is uncertain, the coal-based system always has the lowest sustainability among the methanol to aromatics systems and it will become sustainable when the renewable emergy proportion of electricity is greater than 0.40 (-). The COG and natural gas-based systems will be sustainable when the renewable emergy proportion of electricity is higher than 0.2 (-). The sustainability of the COG based system will exceed that of the biomass-based system when the renewable proportion of electricity is more than 0.68 (-). In the future work, the combination of different raw materials for methanol production could be studied. The economic performance and emissions of different systems should be considered at the same time.

Nomenclature

COG – Coke Oven gas
ELR – Environmental loading rate
ESI – Sustainability index
EYR – Emergy Yield Ratio
F – Purchased emergy
N – Non-renewable emergy
R – Renewable emergy
sej – Solar equivalent joule

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