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Polygeneration system and sustainability: Multi-attribute decision-support framework for comprehensive assessment under uncertainties

Zhenfeng Wang [a], Guangyin Xu [a,*], Jingzheng Ren [b,**], Zhaoling Li [c], Baolong Zhang [b], Xusheng Ren [d]

[a] Collaborative Innovation Center of Biomass Energy-Henan Province, College of Mechanical and Electrical Engineering, Henan Agricultural University, Zhengzhou, Henan Province, China

[b] Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong Special Administrative Region

[c] Graduate School of Life and Environmental Science, University of Tsukuba, Tsukuba, Ibaraki, 305-8506, Japan

[d] Department of Chemistry and Chemical Engineering, Chongqing University, Chongqing, 400044, China

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A B S T R A C T

As an important energy-efficient production technology, polygeneration has attracted more and more attentions for its advantages of high energy efficiency, low production cost, and fewer emissions compared with the traditional industrial systems. The objective of this study is to develop a multi-attribute comprehensive assessment method for sustainability assessment of polygenerations under uncertainty conditions. Fuzzy best-worst network method which can incorporate the interdependences and interactions among the evaluation criteria has been developed for determining the weights of the criteria. Interval TOPSIS which can rank the alternative under uncertainties has been employed to rank the alternative polygeneration systems according to their sustainability performance. In order to illustrate the proposed method, an illustrative case including four industrial systems has been studied, and the results were also validated by interval grey relational analysis (GRA) method. Sensitivity analysis was also carried out to investigate the effects of the weights of the criteria on the sustainability ranking of the four polygeneration systems.

1. Introduction

With the rapid development of the world's economy, especially the growth in developing countries, people's living standard and consumption level have been rising significantly. Consequently, the demand of natural resources, minerals, and water increase rapidly and has excessed the renewability of the earth. Recently, humanity requires over 50% more than what the planet can regenerate, and this ratio will increase to 75% by 2020 if nothing will be done (Global Footprint Network, 2016). This also leaded to severe environmental pollution and degradation problems (Serra et al., 2009). Therefore, polygeneration technologies which can maximize the utilization of energy and minimize the pollution have been recognized as a promising pathway for resolving these problems.

Polygeneration is an important and energy-efficient production technology, which is the combination of two or more products and/or services production processes to maximize the thermodynamic potential of the raw material resources (Serra et al., 2009). Adams and Ghouse (2015) accurately defined polygeneration as "*A thermochemical process which simultaneously produces at least two different products in non-trivial quantities, but is not a petroleum refining process, a co-generation process, or a tri-generation process, and at least one product is a chemical or fuel, and at least one is electricity*". It is an integrated process to co-produce chemicals, fuels and electricity with multiple production systems (see Fig. 1) (Petchers, 2003; Smith, 2005; Liu et al., 2007). The purpose of polygeneration system is to increase the energy efficiency through making full use of natural resources, and further for decreasing the environmental burdens and production costs simultaneously.

* Corresponding author. Collaborative Innovation Center of Biomass Energy-Henan Province, College of Mechanical and Electrical Engineering, Henan Agricultural University, Zhengzhou, Henan Province, China.
** Corresponding author.
E-mail addresses: xgy4175@126.com (G. Xu), jzhren@polyu.eud.hk, renjingzheng123321@163.com (J. Ren).

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There are usually various types of polygeneration systems. For instance, they can be categorized into cogeneration system and trigeneration system according to the number of the incorporated industrial processes, and they can also be divided into different categories according to the products or the processes. The basic form of polygeneration is the combination of heat and power (CHP). Polygeneration is not a simple superposition of multiple energy systems, while it is an integrated and optimized coproduction system based on a special principle (Yi et al., 2017). To be specific, depending on the number of integrated production process, polygeneration can be classified as cogeneration systems, trigeneration systems (Serra et al., 2009; Wang et al., 2009a,b; Carvalho et al., 2012; Jradi and Riffat, 2014). According to the different products, or different types of production process, polygeneration can be divided into coal based polygernation system, natural gas based polygeneration system, and renewable sources based polygeneration systems and some others, i.e. drinking water or sugar as one of the products. Yi et al. (2017) presented three types of coal-based polygernation systems. For more information about some other new types of polygeneration systems, in the readers can refer to the work of Serra et al. (2009).

Accordingly, the decision-makers can usually have multiple choices when selecting the most suitable type of polygeneration system for achieving their targets, i.e. the production of electricity, heat, power, and drinking water, etc. The polygeneration systems usually have the advantages of high energy efficiency, low production cost and fewer emissions compared with the traditional separate production systems. Comparing with the traditional technology, the efficiency of a steam turbine for power generation is only 20–38%, while the efficiency in combined heat and power (CHP) system will be improved to 80–90% when the useful heat has also been produced (Rong and Lahdelma, 2016). However, different polygeneration systems perform different with respect to these advantages. Meanwhile, there are also some disadvantages in the polygeneration systems, i.e. high investment and complex installations architecture (Hu and Feng, 2013). Similarly, different polygeneration systems also need different capital costs and have different complexity in configurations. The disadvantage can be remedied by the more economic operation and environmental benefits in the long-term run (Heteu and Bolle, 2002). There are also some deficiencies in some specific production processes. For example, Bruno (2007) mentioned that the thermal energy storage in the polygeneration systems needs complex installations architecture, which usually loss heat and have poor performance at low temperature. Adams and Ghouse (2015) pointed out that many studies focusing on the determination of the optimum configuration of polygeneration by optimizing the best combination of the candidate routes, processes, and products. Accordingly, different combinations can form different polygeneration configurations which have different economic, environmental and technological performances.

The selection of the most suitable polygeneration system cannot merely account economic benefits, the environmental impacts and societal performances should also be incorporated in the decision-

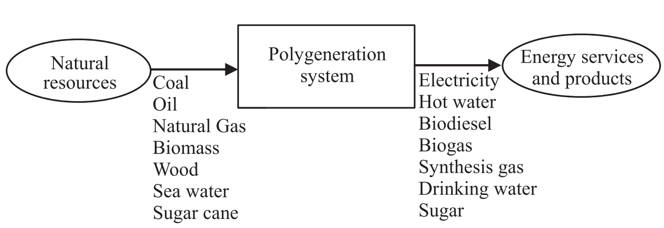

Fig. 1. Multi-resource and multi-product transformation process of polygeneration systems (Serra et al., 2009).

making process. Therefore, a multi-dimensional evaluation of polygeneration systems is of vital importance. Sustainability assessment as a typical multi-dimensional evaluation approach which can assess the economic, environmental and social aspects simultaneously was used as a comprehensive tool to evaluate the overall performances of the polygeneration systems.

Multi-attribute decision making (MADM), also called "multi-attribute decision analysis (MADA)" or "multi-criteria decision making (MCDM)", was widely used for technology evaluation and selection, i.e. sustainability assessment and comprehensive evaluation. Vivekh et al. (2016) used TOPSIS and PROMETHEE II method to have a multi-criteria evaluation of the desalination technologies by considering 11 criteria. Ren et al. (2015a) combined life cycle assessment, life cycle cost, and social life cycle assessment for investigating the environmental, economic, and social categories-the three pillars of sustainability, and VIKOR method was employed to rank the alternative technologies for bioethanol production. Similarly, MADM was also widely used for techno-economic evaluation or sustainability assessment of polygeneration systems. For instance, Yang et al. (2015) employed the House of Quality method for evaluating the polygeneration technologies based on low rank coal, in which a multi-hierarchy evaluation model including nineteen customer needs and ten technological characteristics was developed. Ng and Hernandez (2016) developed a multi-dimensional evaluation framework for decision-making on polygeneration systems by considering energetic, environmental and economic criteria simultaneously. Gangadharan et al. (2012) employed the embedding exergy analysis and inherent safety score for quantifying the efficiency and societal aspects to assess the sustainability of polygeneration systems. Khan et al. (2014) analyzed the technological and economic performances of polygeneration systems based on biogas by investigating mass flows and energy balance, levelized cost, and the payback period. Ng et al. (2013) investigated the techno-economic performances of polygeneration systems, and analyzed the effect of process configurations and operating conditions on the economic potential (EP) and risks. Wang et al. (2006) employed Analytic Hierarchy Process (AHP) to evaluate the sustainability of polygeneration systems. All these studies are significantly important for the decision-makers to select the most sustainable scenario among multiple alternative polygeneration systems; however, there are also some research gaps:

(1) The lack of the convenient methods for accurately collecting the opinions of the decision-makers, because the most commonly used method-AHP and various methods derived from AHP cannot accurately reflect the opinions of the decision-makers due to the vagueness and ambiguity existing in the opinions of the decision-makers. Moreover, all these methods determine the weights of the criteria/indicators based on the comparison matrix which has high requirement to ensure its consistency;
(2) The lack of the consideration of the independences, interdependences, and interactions among these criteria/indicators when calculating the weights of the criteria/indicators for sustainability assessment;
(3) The lack of the method for ranking the alternative polygeneration systems under uncertainty conditions. There are usually various uncertainties existing in sustainability assessment due to the lack of information/knowledge; thus, it is prerequisite to develop the multi-criteria decision making method which can address the decision-making matrix with uncertainty information.

In order to fill the above-mentioned research gaps, a novel multi-attribute decision making method was developed for