FUZZY OPTIMAL DESIGN MODEL FOR POLYGENERATION PLANT WITH BIOCHAR PRODUCTION FOR CARBON SEQUESTRATION

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Abstract: An efficient way for producing power, heat, and cooling while reducing CO_2 emissions is through trigeneration. The emitted CO_2 from trigeneration plant can be further reduced by producing biochar, which contributes negative carbon footprint to the system through sequestration of biomass carbon as char. This requires a gasification process to be added in the trigeneration system to produce biochar and syngas. The already complex nature of the trigeneration plant together with the added gasification process chain makes the capacity design of each of the components more challenging. In this study, a methodology for the optimal design of a polygeneration plant is shown using fuzzy optimization approach. The results of a case study show how the optimized capacities of each component are determined. The negative carbon footprint effect of the biochar production is observed in the case study results.

Keywords: Polygeneration, Biochar, Carbon Sequestration, Carbon Footprint, Fuzzy Optimization

1. INTRODUCTION

As of 2010, about 41% of the global carbon dioxide (CO_2) emission which accounts for 12.4 Gt/y is caused by electricity and heat production (IEA, 2012). One of the approaches in mitigating the continuous growth of CO_2 emissions while producing energy is through polygeneration, which efficiently converts various raw materials to generate simultaneously multiple energy streams such as electricity, heat, cooling, and other chemical products (Serra et. al., 2009; 2010, Carvalho et al., 2012). A trigeneration system is a type of a polygeneration which specifically produces power, heat, and cooling; it is also known as combined heat, cooling, and power (CHCP). Given the various benefits of using trigeneration system compared to conventional plants, it is still considered as a low carbon strategy.

McGlashan et al. (2012) reviewed five techniques for implementing negative carbon emissions. One of the viable strategies is through biochar production. Biochar is produced through gasification of biomass (Bridgwater, 2003). It contains about 60%-90% carbon (Guar and Reed, 1995) which, when stored underground results in negative net emissions effect. Biochar production through gasification also yields syngas which can be used to various applications. This study seeks to design optimally a polygeneration system which achieves carbon capture through biochar production.

A novel fuzzy optimization approach is proposed. This paper is organized as follows. First, information for each of the components of the polygeneration system is discussed in detail in the next section. Then, the formal problem statement is then discussed. After which, the fuzzy optimization model is described next. A case study is then solved to demonstrate the model. Finally, the conclusion of the paper and future possible studies are stated.

2. MOTIVATING EXAMPLE: POLYGENERATION

This paper demonstrates an example of a biomass-based polygeneration system which demonstrates a negative carbon emission footprint by producing biochar. The extended process matrix for the five components of the polygeneration system is seen in Table 1.

Table 1. Extended process matrix of the polygeneration system.

Extended Process Matrix	GT-HRSG	Boiler	Vapor Absorption Chiller	Vapor Compression Chiller	Gasification
Power (MW)	1	0	0	-0.2	0
Heat (MW)	1.2	1	-1.6	0	-3.17
Cooling (MW)	0	0	1	1	0
Biochar (kg/s)	0	0	0	0	0.17
Syngas (kg/s)	-0.95	-0.21	0	0	1
Biomass (kg/s)	0	0	0	0	-0.83

The polygeneration system consists of five main parts: gas turbine (GT) with heat recovery steam generator (HRSG), the utility boiler, vapor absorption chiller (VAC), vapor compression chiller (VCC), and gasification. Combined heat and power is generated from a small GT-HRSG with an efficiency in producing power and heat of η_{GTp} = 0.35 and η_{HRSGh} = 0.42, respectively (Serra et. al., 2009; Carvalho, 2012). The syngas consumption of the GT-HRSG per unit of electricity is assumed to be 0.95 kg/MJ. Additional steam is produced in a separate boiler having a thermal efficiency of η_{Bh} = 0.8 (Serra et. al., 2009; Carvalho, 2012). The syngas consumption of the boiler per unit of heat is assumed to be 0.21 kg/MJ. The calorific value of syngas consumed in the GT-HRSG and the boiler is 6 MJ/kg. The COP of the vapor absorption chiller in converting heat energy to cooling is COP_{VAC} = 0.625 (Serra et. al., 2009; Carvalho, 2012). A part of the power produced from the GT-HRSG unit is converted to cooling by a vapor compression chiller with a COP_{VCC} = 5.0. The gasification converts solid biomass to biochar and syngas through the high heat energy. The gasification process converts 0.83 kg solid biomass to 0.17 kg biochar and 1 kg syngas (Bridgewater, 2003) which requires 3.17 MJ/kg biomass (Tay, 2012).

The product streams of the polygeneration are electricity, heat, cooling, and biochar. The syngas produced from the gasification fully supports the requirements of the GT-HRSG and the boiler as seen in Figure 1. A negative value from Table 1 indicates that the stream is an input in the process, while a positive value denotes an output stream. An illustration of the polygeneration system flowsheet is shown in Figure 1.

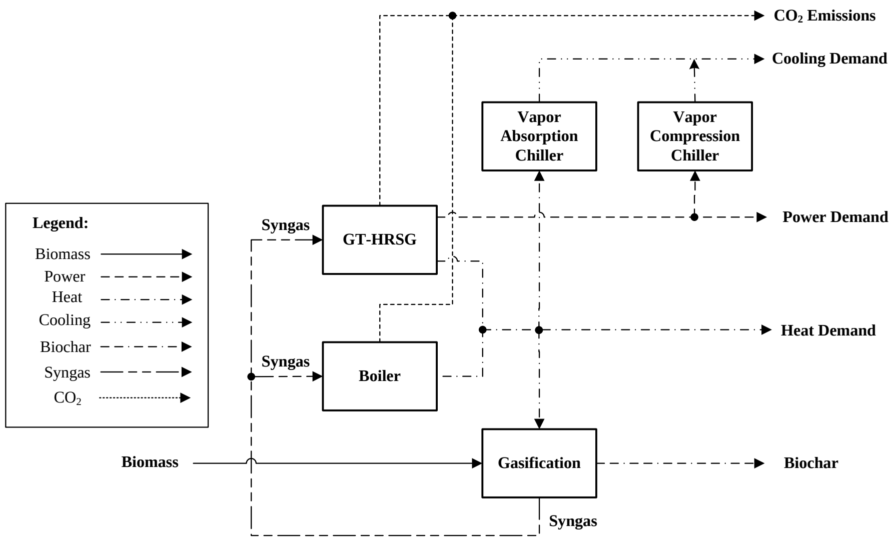

Figure 1. A generic polygeneration flowsheet.

3. PROBLEM STATEMENT

In working with systems with inherently complex structure and interdependency with each other such as the polygeneration, the problem arises in the identification of capacities and its optimal configuration. Note that the polygeneration does not only seek to maximize its production capacity to generate the required demands but also to minimize its environmental impact through quantification of its carbon footprint. The energy demands are exogenously defined based on specific requirements. We are given a biomass-based polygeneration system whose components' performance is described by process matrix of **A**, with an assumed trapezoidal energy demands **y**, and a carbon footprint vector **z**. The developed model seeks to achieve the optimal capacity **x**, given the trapezoidal demand limits ($\mathbf{y_a}$, $\mathbf{y_b}$, $\mathbf{y_c}$, and $\mathbf{y_d}$), while satisfying the negative carbon emission.

4. FUZZY OPTIMIZATION PROGRAMMING

A linear programming approach is introduced to assess the performance of a polygeneration plant with biochar production. Fuzzy mathematical programming is applied in optimization problems to allow varying satisfactory values between given limits (Zimmerman, 1978). The fuzzy membership function allows setting suitable limits for the product demands and carbon emissions. The optimization model is:

$$\text{maximize } \lambda \qquad \text{(Equation 1)}$$

subject to:

$$\mathbf{Ax} = \mathbf{y} \qquad \text{(Equation 2)}$$

$$\mathbf{y} \geq \mathbf{y_a} + \lambda(\mathbf{y_b} - \mathbf{y_a}) \qquad \text{(Equation 3)}$$

$$\mathbf{y} \leq \mathbf{y_d} + \lambda(\mathbf{y_c} - \mathbf{y_d}) \qquad \text{(Equation 4)}$$

$$\mathbf{z} = \mathbf{c}^{\mathbf{T}}\mathbf{y} \qquad \text{(Equation 5)}$$

$$\mathbf{z} \leq \mathbf{z_u} + \lambda(\mathbf{z_l} - \mathbf{z_u}) \qquad \text{(Equation 6)}$$

$$0 \leq \lambda \leq 1 \qquad \text{(Equation 7)}$$

where λ is the degree of satisfaction for the fuzzy membership functions; **A** is the process matrix; **x** is the process scaling vector; **y** is the net product output vector; $\mathbf{y_a}$, $\mathbf{y_b}$, $\mathbf{y_c}$, $\mathbf{y_d}$ are the product demand limits as shown in Figure 2, which describes the trapezoidal fuzzy membership function for the net product output **y**; **z** is the carbon footprint of the system; $\mathbf{c}^{\mathbf{T}}$ is the transposed carbon footprint coefficient vector (the superscript "T" indicates transposition of column vector **c**); $\mathbf{z_l}$ and $\mathbf{z_u}$ are the lower and upper carbon footprint boundaries for **z**, respectively.

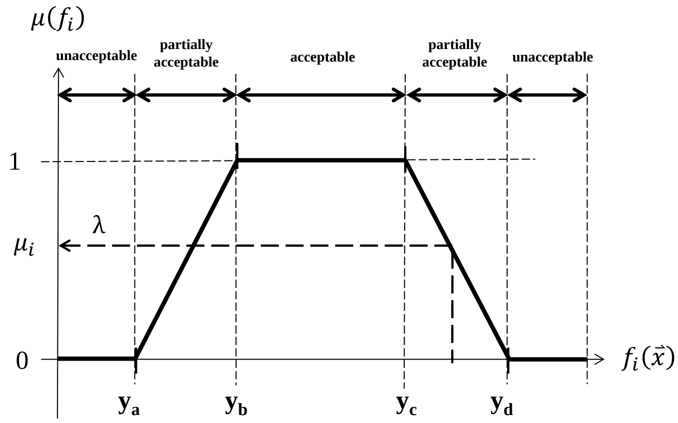

Figure 2. Piecewise fuzzy membership function for the net energy output.

5. CASE STUDY

This case study illustrates a biomass-polygeneration plant, which is shown in Figure 1, with the desired demand limits for each of the products as shown in Table 2. The efficiency of the GT-HRSG and the boiler, and the COP of the chillers are as stated earlier in the motivation example: polygeneration section. The carbon footprint coefficient for produced biochar is -0.73 kg CO_2/kg (Bridgwater, 2003). The CO_2 emission lower and upper limits are -30 kg/s and 30 kg/s, respectively. It is assumed that all syngas produced will be utilized to run both the GT-HRSG and the boiler. The model calculates the production of biochar which is not subject to exogenous constraints.

The result of the model yielded a λ value of 0.84 which partially satisfies the fuzzy membership goals. The calculated total carbon emission led to a negative carbon value of –20.11 kg/s assuming that the biomass feed is carbon neutral. The optimal configuration of the polygeneration plant is seen in Figure 3 together with the product streams. In Figure 3, it shows that the VCC was unutilized since it requires electricity to produce the desired cooling capacity. Thus, the power produced from the GT-HRSG was solely used to support the power demand. About 77% of the heat generated by both the boiler and the GT-HRSG was consumed in the gasification process to produce the required amounts of biochar and syngas. The syngas generated from the gasification is just enough to support the requirements of both the GT-HRSG and the boiler. The optimal **y** values are 30.8 MW power, 58.2 MW heat, 60.8 MW cooling, and 27.5 kg/s biochar. The calculated biomass requirement to operate the polygeneration plant is 134.5 kg/s.

Table 2. Product demand limits for each products.

Product Demand Limits	y_a	y_b	y_c	y_d
Power (MW)	5	10	30	35
Heat (MW)	10	20	50	100
Cooling (MW)	10	40	55	90

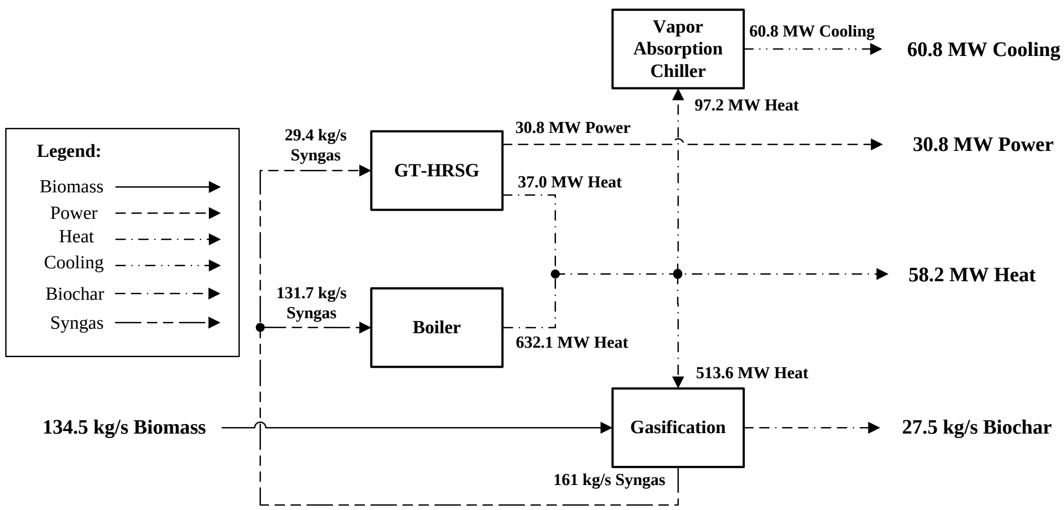

Figure 3. Optimal total capacity of the polygeneration for the case study.

6. CONCLUSION

A fuzzy linear optimization model has been developed for designing a biomass-based polygeneration system which accounts for a trapezoidal fuzzy demand for products. The model has been demonstrated in a case study where a negative carbon footprint was accounted by producing biochar for carbon sequestration. Future work can focus on complex polygeneration plants which includes multi-regional considerations together with economic potential. A holistic assessment of a polygeneration entails inclusion of land footprint and water footprint.

7. ACKNOWLEDGEMENT

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