A two-stage optimization approach for the synthesis of an integrated pulp and paper biorefinery

The 6th International Conference on Applied Energy – ICAE2014

A two-stage optimization approach for the synthesis of an integrated pulp and paper biorefinery

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Abstract

Pulp and paper mills (PPMs) generate large amount of wastewater with high chemical oxygen demand (COD) concentration. Recently, anaerobic digestion receives much attention for the treatment of PPM wastewater. Through anaerobic digestion treatment, biogas can be generated and converted to bioenergy via combined heat and power (CHP). However, there are limited studies on the systematic allocation of bioenergy from CHP to wastewater treatment (WWT) and PPM to form an integrated pulp and paper biorefinery (IPPB). Therefore, the current work explores the potential of energy integration in an IPPB through a two-stage optimization approach. In the first stage, an optimal cost effective WWT for the treatment of PPM wastewater is synthesized. Next, the generated biogas from WWT is converted into four different forms of bioenergy. The detail allocation of the generated bioenergy is then determined in the second stage optimization. A case study is solved to illustrate the proposed approach.

Pulp and paper; anaerobic digestion; wastewater treatment; combined heat and power; pathway optimization.

1. Introduction

Pulp and paper mills (PPMs) generate large amount of wastewater, in the range of 60-90 m^3/ton of pulp produced [1]. Thus, wastewater treatment (WWT) has been an integral part of pulp and paper production to ensure the treated wastewater complies with the regulated discharge policies. Various treatment systems are available, ranging from aerobic systems to anaerobic systems and combined anaerobic-

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aerobic systems. Note that all these treatment systems have high organic removal efficiency [2]. However, anaerobic systems have an additional advantage as biogas can be recovered from the treated wastewater [3]. The generated biogas can be utilized to produce bioenergy via gas combustion engine and gas boiler in a combined heat and power (CHP) plant or upgraded to biomethane [4, 5]. The generated bioenergy can then be used to supplement the energy demands in WWT and PPM.

In this work, potential for energy integration in an integrated pulp and paper biorefinery (IPPB) which consists of CHP, WWT and PPM is explored through a two-stage optimization approach. Based on the proposed approach, the first stage optimization involves the synthesis of an optimal cost effective WWT system. The generated biogas is then sent to CHP to be converted into four different forms of bioenergy. The bioenergy considered include high pressure, medium pressure and low pressure steams as well as power. The second stage optimization will address the detail allocation of bioenergy in an IPPB.

2. Problem Statement

The problem definition of an IPPB can be stated as follow: Wastewater, $i \in I$ generated from pulp and paper mill (PPM) is sent to wastewater treatment plant (WWT). In WWT, wastewater is treated with different treatment systems, $j \in J$. Through the treatment system, biogas is generated. The generated biogas can be used to produce primary energy, $e \in E$ via pathways $c \in C$ (i.e., gas engine or gas boiler). Then, primary energy can be further converted to secondary energy, $e' \in E'$ (i.e., steam and power) via pathways $c' \in C'$ (steam turbine).

3. Model Formulation

3.1. Wastewater Treatment Plant (WWT)

As mentioned previously, a cost effective WWT system is synthesized in the first stage of optimization. Thus, the optimization objective for the synthesis of WWT is given as minimize total annualized costs (TAC) of WWT. Due to the page limitation, readers can refer to the work by Leong [6] for detailed formulation of WWT systems.

3.2. Combined Heat and Power Plant (CHP)

In CHP, biogas produced at M^{BGT} from WWT is split into the potential pathway c at a flowrate of M^{BGS}_c.

$$M^{\mathrm{BGT}} = \sum^{C}(M^{\mathrm{BGS}}_c) \tag{1}$$

Primary energy is then generated at E^{PE}_{ce} from pathway c given a conversion factor of k_{ce}. The total production rate of primary energy e at E^{GENP}_e is expressed below

$$E^{\mathrm{PE}}_{ce} = M^{\mathrm{BGS}}_c \, \mathrm{k}_{ce} \qquad\qquad \forall c,e \tag{2}$$

$$E^{\mathrm{GENP}}_e = \sum^{C} E^{\mathrm{PE}}_{ce} \qquad\qquad \forall e \tag{3}$$

Next, flowrate of E^{GENP}_e is split for the conversion to secondary energy e' via pathway c' at $E^{\mathrm{PET}}_{ec'}$.

$$E^{\mathrm{GENP}}_e = \sum^{C} E^{\mathrm{PET}}_{ec'} \qquad\qquad \forall e \tag{4}$$

Secondary energy is generated at $E^{\mathrm{SE}}_{c'e'}$ from pathway c' given a conversion factor of $\mathrm{k}_{c'e'}$. The total production rate of secondary energy e' at $E^{\mathrm{GENS}}_{e'}$ from CHP can be expressed as

$$E^{\mathrm{SE}}_{c'e'} = \sum^{E} E^{\mathrm{PET}}_{ec'} \, \mathrm{k}_{c'e'} \qquad\qquad \forall c',e' \tag{5}$$

$$E^{\text{GENS}}{}_{e'} = \sum{}^{C'} E^{\text{SE}}{}_{c'e'} \qquad\qquad \forall e' \tag{6}$$

The total energy balance of WWT can be written as

$$E^{\text{WWT}}{}_{e'} + E^{\text{EXP}}{}_{e'} = E^{\text{GENS}}{}_{e'} + E^{\text{IMP}}{}_{e'} \qquad\qquad \forall e' \tag{7}$$

where $E^{\text{WWT}}{}_{e'}$, $E^{\text{EXP}}{}_{e'}$, $E^{\text{GENS}}{}_{e'}$ and $E^{\text{IMP}}{}_{e'}$ are energy consumption of WWT, exported energy, generated secondary energy and imported energy *e'* respectively.

3.3. Economic Analysis

The optimization objective is to minimize total annualized costs (TAC) of an IPPB

MINIMIZE TAC= TOC + AIC $\tag{8}$

where TOC and AIC are referred as total operational costs and annualized investment costs.

TOC is determined from the total imported energy subtracted by total exported energy and miscellaneous operational costs such as maintenance, insurance, personnel etc. as below

$$\text{TOC} = \text{AOT}\left(\sum{}^{\text{E'}} E^{\text{IMP}}{}_{e'} C^{\text{IMP}}{}_{e'} - \sum{}^{\text{E'}} E^{\text{EXP}}{}_{e'} C^{\text{EXP}}{}_{e'}\right) + C^{\text{IC}}(\text{TIC}) \tag{9}$$

where AOT is the annual operating time while $C^{\text{IMP}}{}_{e'}$ and $C^{\text{EXP}}{}_{e'}$ represents cost of imported energy and price of exported energy respectively. C^{IC} denotes the cost parameter for miscellaneous operations while TIC is the total investment costs of the synthesized IPPB.

Meanwhile, AIC is given by Eq (10) with a^{F} denoting annualization factor.

$$\text{AIC} = a^{\text{F}}(\text{TIC}) \tag{10}$$

4. Case Study

A case study is adapted from Haandel and Lubbe [4] to illustrate the proposed approach. Three WWT systems for PPM are proposed. System 1 represents conventional aerobic system with primary settling and sludge digestion post-treatment while System 2 is a combined anaerobic-aerobic system. Next, System 3 is similar with System 2 but with an additional sludge digestion post-treatment. PPM wastewater characteristics is retrieved from Pokhrel and Viraraghavan [1]. The wastewater flow rate is given as 15000 m^3/d with a COD load of 4870 mg/L. Meanwhile, the discharge limit for COD of the final treated wastewater is given as less than 350 mg/L.

4.1. Integrated Pulp and Paper Biorefinery (IPPB)

In the first stage optimization, the optimal cost effective WWT system is determined to be System 2 as seen in Table 1 (Column 2). Next, in the second stage, the optimization objective in Eq (8) is solved subjected to Eqs (1) – (7), (9) – (10). The results of an optimized IPPB can be viewed in Table 1 (Column 3). Through CHP, bioenergy in the form of steam and power is generated via a gas boiler. Upon comparison of TAC from the first stage optimization (USD 3.67 million/y) with IPPB, TAC of IPPB can be reduced to USD 2.27 million/y. Besides, the power generated from CHP is sufficient to cater the power demands of WWT. In addition, medium and low pressure steam is generated from IPPB which can be supplied to PPM.

Table 1. Optimization results of an integrated pulp and paper biorefinery (IPPB)

	WWT (1st Stage)	IPPB (2nd Stage)
Wastewater treatment system	System 2	System 2
Economic analysis ($\times 10^6$ USD/y)		
Total annualized cost, TAC	3.67	2.27
Annualized investment cost, AIC	1.65	1.69
Total operating cost, TOC	2.02	0.58
Biogas production (kg/d)	10801	10801
Power required in WWT (kW)	292	292
Power generated from biogas (kW)	--	1300
Imported power from grid (kW)	292	-
Exported power to grid (kW)	-	1008
Medium pressure steam (t/d)	-	37
Low pressure steam (t/d)	-	111

5. Conclusion

In this work, a two-stage optimization approach is introduced for the synthesis of an IPPB. The approach synthesizes an optimal WWT system in the first stage and the detail allocation of bioenergy in the second stage. The generated heat and power is prioritized to satisfy demands in WWT and PPM. Future work can address multi-objective optimization in the IPPB to consider simultaneous economic and environmental analysis.

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Biography

Lee Siu Hoong graduated with Bachelor of Chemical Engineering (Honours) from Monash University Malaysia in 2010. He returned to Monash University Malaysia in 2012 to pursue his postgraduate studies. His research focuses on the synthesis and optimization of an integrated pulp and paper biorefinery to achieve resource conservation.