Multi-objective Design of a Biomass-based Polygeneration for Iron and Steel Manufacturing

A T Ubando1,2, and W H Chen1,*

1Department of Aeronautics and Astronautics, National Cheng Kung University, Tainan 701, Taiwan
2Mechanical Engineering Department, De La Salle University, 2401 Taft Avenue, 0922 Manila, Philippines
E-mail: weihsinchen@gmail.com

Abstract. Iron and steel manufacturing is considered a major contributor to the global carbon emission and energy-intensive industry. To sustainably produce iron and steel, various approaches have been explored to generate the needed power to support the production while mitigating the carbon dioxide emission. One of the viable approaches is the integration of a biomass-polygeneration system to produce biochar and other energy streams needed by the iron and steel manufacturing plant. A polygeneration system is composed of a combination of various existing technologies which seeks to recover wasted energy and to reuse by-products through process integration, thus, improving the overall thermodynamic efficiency of the system. In designing such complex systems, multiple objectives should be considered to assimilate the real-life requirements of the system. However, recent studies on the design of polygeneration system for iron and steel industry used a single-objective approach which may not consider the trade-offs between multi-objectives. Hence, this study proposes to design a biomass-based polygeneration system using a multi-objective approach employing fuzzy linear programming (FLP) model. The FLP model allows partial satisfaction of multi-objectives through the use of linear membership functions. A case study is presented involving biochar production from torrefaction, pyrolysis, and gasification together with power and heat production. The results indicate the optimal polygeneration process network consisting of a gas turbine for the generation of power, a heat recovery steam generator attached to the gas turbine for the heat generation, a gasifier for syngas, and torrefaction for biochar production. The developed model aims to aid engineers and managers in cost-effectively integrating a biomass-based polygeneration system in iron manufacturing.

1. Introduction
The iron and steel manufacturing is considered as the backbone of economies across the globe. Iron and steel are considered an essential commodity and are used as raw materials for numerous industries. However, the industry is the main contributor to global carbon dioxide (CO2) emission [1], thus, in recent years it has felt the impact of CO2 emission taxes. The priority of the industry has shifted to capital acquisition and cost-cutting measures due to the price competitiveness and volatility of the economy especially in developing countries [2]. Iron production is a matured and well-established process, hence, the reduction of the energy requirement and its emissions is challenging.
One of the key alternatives to sustainably produce iron and steel is through biomass utilization. Biomass offers a clean and renewable substitute for fossil-based fuels. Recently, biomass has been found to be an important fuel or reducing agent in the production of iron and steel [3]. The utilization of biomass in the blast furnace to produce iron could potentially reduce the CO₂ emission by one-third compared to conventional means [4]. Biomass can be fed to the blast furnace in the form of bio-oil, biochar, and biomass-derived syngas [5] through thermochemical conversions such as gasification, pyrolysis, and torrefaction. Out of the three products, biochar shows the potential to partially substitute coal as a reducing agent in the blast furnace resulting in a competitive iron quality [6]. The three thermochemical processes convert biomass to biochar at varying yields. A sustainable approach in integrating biochar production while producing the needed energy requirements of the plant is through polygeneration. Polygeneration system is composed of various processes which produce multiple products from a number of raw materials. With the inter-connectivity and the tight integration of the processes in a polygeneration system, its design presents a challenging task. In recent years, polygeneration systems have been designed using a mathematical programming optimization approach [7]. The inclusion of biochar production in a polygeneration plant has shown the potential for negative carbon emission using a life-cycle based optimization method [8].

Recent works on integrating a polygeneration system with the iron and steel manufacturing using optimization approach are as follows. Ghanbari et al. [9] adopted a non-linear programming (NLP) model to integrate the top gas recycling and the cold oxygen injection in the blast furnace. The net present value of the iron and manufacturing plant is maximized and stands as the objective function [9]. Ghanbari et al. [2] employed mixed-integer non-linear programming (MINLP) approach to integrate polygeneration system in the iron and steel manufacturing. The objective function is to minimize the cost of producing hot liquid steel [2]. In designing a polygeneration system, real-life constraints must be considered. In most cases, real-life scenarios translate to involving multiple (multi-) objectives. However, both studies have not considered biochar as a raw material in the blast furnace and the potential selection of a cost-effective thermochemical process to produce the biochar. In addition, both studies proposed a single-objective approach in designing a polygeneration for iron and steel manufacturing. In the case of the iron and steel manufacturing, the acceptable product demand limits and targets range of the objectives are well defined within the plant as shown in the previous studies [2, 9]. The utilization of fuzzy set theory combined with mathematical programming approach offers a simple yet elegant method in solving for multi-objective problems compared to other methodologies [11]. The fuzzy linear programming (FLP) model employs the max-min aggregate which enables to solve multi-objective problems and provides a compromise solution among the objectives [13]. The FLP allows the use of partially acceptable values for a given objective represented by the partially acceptable threshold limits. Limited study was found in integrating an appropriate thermochemical conversion technology for biochar production system considering multiple objectives and applied on iron manufacturing. This study proposes a systematic approach in designing a polygeneration process network which allows multiple objectives such as maximizing the production of energy streams, minimizing capital cost, and meeting the biochar production levels. In addition, three thermochemical processes have been considered for the production of biochar. The objective of the study is to develop a multi-objective approach using FLP model in designing a biomass-based polygeneration system which produces power, heat, syngas, and biochar for iron manufacturing.

2. Problem Statement
The process matrix is defined by the various technologies considered in the polygeneration system. Each process is considered as a vector which consists of the energy and material streams represented as either raw material or a product of the process. A positive or negative value represents a raw material or product of the process, respectively. The product demand is defined by the manufacturing plant based on historical demand data and production level requirements. The product demand limits are represented by a demand profile such as maximizing the production level up to an acceptable level or in some cases targeting a specific production level with an acceptable demand range described by the support and the
core threshold limits [11]. A process scaling vector signifies the appropriate size of the process to produce the product stream requirements. A target capital cost target is defined by the plant owner’s which is described by an acceptable capital cost range bounded by an upper and lower limit [12]. The capital cost function is desired to approach the lower threshold limit so as to minimize the capital cost. The problem is to define the optimal process scaling vector and the product output of the polygeneration process network.

3. Model Development

The FLP model consists of the objective function shown in equation (1) such that it is satisfied with the constraints shown in equations (2-8).

\[
\text{Maximize } \lambda \quad (1)
\]

s.t.

\[
Ax = y \quad (2)
\]

\[
y \geq y^l + \lambda (y^u - y^l) \quad (3)
\]

\[
y \geq y^a + \lambda (y^b - y^a) \quad (4)
\]

\[
y \leq y^e + \lambda (y^b - y^e) \quad (5)
\]

\[
CC_T = CC \cdot x \quad (6)
\]

\[
CC_T \leq CC^u + \lambda (CC^l - CC^u) \quad (7)
\]

\[
0 \leq \lambda \leq 1 \quad (8)
\]

where the degree of satisfaction is \( \lambda \), the process matrix is \( A \), process-scale vector is \( x \), the net product output is \( y \), the upper and lower threshold limit of the required streams are \( y^a \) and \( y^l \), respectively. The desired core limit of the output demand stream is \( y^b \) bounded by the upper and lower support threshold limit of the required streams are \( y^e \) and \( y^a \), respectively. The overall capital cost is represented by \( CC_T \) with \( CC \) as the capital cost vector. The overall capital cost is bounded by a lower and upper limit represented by \( CC^l \) and \( CC^u \), respectively.

The objective function in equation (1) utilizes the max-min aggregation rule which attempts to simultaneously arrive in a solution approaching the desired limits of the multi-objectives [11]. Since most of the multi-objectives are naturally conflicting, the degree of satisfaction \( \lambda \) represents a partial satisfaction among the objectives, thus, signifying a compromise solution. The production level of the polygeneration system \( y \) is determined together with the scaling vector \( x \) through equation 2. In equation 2, the process matrix \( A \) is introduced as a conglomeration of the unit vectors of the considered processes in the polygeneration plant. The unit vectors of each process can be represented by an input-output stream diagram shown in figure 1. To maximize the product streams, a fuzzy membership function for maximization is used as shown in equation (3). However, some product streams require a firm product demand range. In such cases, linear membership function with a triangle-shape is used indicated in equations (4) and (5). The overall capital cost \( CC_T \) is the dot product of the capital cost vector and the process-scale vector adapted from Ubando et al. [12] indicated in equation (6). One of the objectives is to minimize the overall capital cost as described in equation (7). Lastly, equation (8) bounds the \( \lambda \)-values from 0 to 1. The model is solved using Lingo 12.0 with global optimizer coupled with MS Excel through object linking and embedding (OLE) on a computer with Core i7 and 4 GB of RAM.
4. Case Study

The polygeneration system considers an energy generating sub-system to generate the required power and heat in the manufacturing plant, and a biochar production sub-system which will provide biochar to the blast furnace. A gas turbine to generate power is considered. Attached to it is a heat recovery steam generator for the simultaneous conversion of heat is considered (GT-HRSG). In addition, an auxiliary boiler is considered to generate the added heat from the iron and steel manufacturing plant. While gasification, pyrolysis, and torrefaction are the three thermochemical technologies considered to produce the required biochar. The produced biochar will be fed to the blast furnace as a reduction agent for the iron production. The gasification and pyrolysis processes were considered since both produce biochar and biomass-based syngas. The generated syngas from these processes has the potential to fuel the boiler and the GT-HRSG. The torrefaction process was considered due to the improved biochar yield and quality [13]. Figure 1 describes the unit process of the considered technologies in the polygeneration process network.

![Diagram of the polygeneration system](image_url)

**Figure 1.** The unit process of each technology considered for the polygeneration system.

| Technology | Power (MW) | Heat (MW) | Biomass (t/h) | Syngas (t/h) |
|------------|------------|-----------|---------------|--------------|
| GT-HRSG    | 1.00       | 0.78      | 1.00          | 0.10         |
| Boiler     | 1.00       | 0.01      | 1.00          | 0.41         |
| Gasification | 1.00       | 0.04      | 1.00          | 1.59         |
| Pyrolysis  | 1.00       | 0.11      | 1.00          | 0.22         |
| Torrefaction | 1.00       | 0.01     | 1.00          | 0.74         |

**Table 1.** Capital cost for each process.

| Capital cost per process | CC (US$) |
|--------------------------|----------|
| GT-HRSG                  | 111,200  |
| Boiler                   | 22,500   |
| Gasification             | 210,000  |
| Pyrolysis                | 120,000  |
| Torrefaction             | 136,000  |

The polygeneration system is designed to support an existing iron manufacturing plant with production levels ranging from 120 t/h to 170 t/h which considers biochar as a reducing agent for iron production [3]. The iron production range translates to a partially acceptable biochar demand range from 10.52 t/h to 11.92 t/h with a highly desirable target of 10.80 t/h. As such, the demand target for the biochar production follows a triangular-shaped fuzzy membership function utilizing equations (4) and (5). The partially acceptable energy stream requirements by the iron manufacturing from the polygeneration are 0.75 to 2.00 MW for power, 0.00 to 0.50 MW for heat, and 0.00 to 0.30 MW for syngas. Power, heat, syngas demand streams follow a fuzzy membership function for maximization,
thus, using equation (3). The manufacturing owner considers a partially acceptable capital cost ranging from US$ 1 to 3 Million and is desired to be minimized. The capital cost vector is shown in table 1.

The results yielded an objective function of $\lambda = 0.26$ with an optimal polygeneration process network exhibited in figure 2. The technologies selected are GT-HRSG to produce both power and heat, gasification for the syngas and biochar, and torrefaction to produce mainly biochar. The power produced by the GT-HRSG is allocated for the consumption of the iron and steel manufacturing plant. A fraction of the heat generated from the GT-HRSG is allocated for the heat requirement of the gasification and torrefaction processes. The remaining heat from the GT-HRSG is utilized for the use of the iron and steel manufacturing plant. The major portion of the syngas produced by the gasification process is supplied to the GT-HRSG while the remaining portion is distributed to the iron and steel manufacturing plant. The biochar generated by both the torrefaction and gasification process is then fed to the blast furnace as a reduction agent for the production of iron. The majority of the biochar produced came from the torrefaction process. As shown in figure 2, the boiler and pyrolysis were not chosen to produce the needed product streams in the process network. The resulting capital cost is US$ 2.49 Million which falls within the acceptable target range of the plant owner’s.

![Figure 2. The resulting optimal polygeneration process network.](image)

With the recent biomass utilization in the iron and steel making industry and its benefits [3], the integration of biomass-based processes through polygeneration system enables energy efficient and cost-effective production of multiple product streams. A systematic approach to designing a biomass-based polygeneration system has been presented in this study through the developed FLP model considering multiple objectives.

5. Conclusion
A biomass-based polygeneration system has been designed for the iron and steel manufacturing plant employing the developed fuzzy linear programming model which simultaneously produces power, heat, syngas, and biochar. The biochar produced from the polygeneration system is then used as a reductant.
for the iron production in the blast furnace. The developed model aims to minimize the overall capital cost, maximize the generation of power, heat, and syngas, and to produce biochar given the desired target with a partially acceptable range. The results provided the optimal configuration of the polygeneration system selecting the use of the GT-HRSG for the generation of heat and power, the gasifier for the production of syngas, and the torrefaction for the production of biochar. The study presents a systematic approach to designing a biomass-based polygeneration for iron manufacturing which considers multiple objectives and provides an efficient and cost-effective approach in producing multiple energy streams. The study is aimed to aid engineers and managers in integrating biomass processes in iron manufacturing through polygeneration process network. Future studies include the minimization of the carbon footprint of the polygeneration system for iron and steel manufacturing.

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