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# Mathematical Programming Model of Biomass-To-Electricity Generation: A Case Study in Suphan Buri Province

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## Abstract

Multi-biomass types and a huge amount of biomass storage are the strategies a biomass power plant normally applied to deal with the periodic supply and uncertainty problems of biomass feedstock for a continuous biomass-to-electricity generation throughout the year. However, continuous increasing of biomass feedstock cost could not be avoided as well as an inherent issue of biomass degradation during storage is difficult to recognize its impacts on feedstock cost. Moreover, efficiently managing the logistics issues related to biomass-to-electricity generation is not a trivial task. Therefore, the mathematical programming model well known as systematic integration method was proposed in this work for helping a power plant to understand degradation effect on feedstock cost and better manage logistics operations related to biomass-to-electricity generation. The developed models were applied to the power plant in Suphan Buri province for two scenarios; the problem with and without consideration of biomass degradation during storage. Linear programming models were obtained and the results showed the total cost of degraded model was higher than non-degraded model at 102.1 million baht or 19.3%. Nevertheless, further development and validation of the model when bring the model to the real application for the case study will be the next step of this work.

Keywords: Mathematical programming model, biomass-to-electricity generation, Suphan Buri Province

## 1 Introduction

Biomass is one of the alternative energy sources which is organic material made from plants and animals. Plant biomass contains energy from the sun by absorption process called photosynthesis and can be burnt as fuels to generate the electricity via combustion or gasification popularly used in biomass power plants (McKendry, 2002**).** Types of biomass can be divided into 4 main types by source including agricultural residues (such as rice straw, sugarcane trash, and corn stover) industry residues (such as bagasse, rice husk, and sawdust), forest residues (such as woodchips, bark, and branches) and human and animal wastes (Mafakheri and Nasiri, 2014).

Biomass supply chain is the flow of biomass material from suppliers that passes through the processes to be the final product that can be divided into 3 parts; the upstream, biomass that left from agriculture, industry or forestry will be pre-processed and transported from suppliers to store in power plant before convert to electricity at the midstream, and then the electricity was sent to the end customer at the downstream. Generally, biomass-to-electricity generation at a power plant contains 3 main processes: biomass procurement, storage and conversion. All these processes are related to decision making of quantity, quality and flow of biomass feedstock.

Making a decision providing the right quantity and quality including the smooth flow of feedstock at a right time to generate electricity is not a trivial task due to the fact of naturally own characteristic and uncertainty characteristic of biomass. Biomass is generally high in moisture, low in bulk density, degradable organic material and own different shapes and sizes which require diverse machines and equipment for handling and transportation. Uncertainty of biomass is related to availability and price. Biomass availability and price cause from many different factors such as soil and weather condition, seasonality of biomass, land availability, availability and reliability of biomass suppliers, policy incentive and energy demand.

Due to a challenge associated to decision making for effectively managing the logistics issues related to biomass-to-electricity generation; therefore, this research work is interested to study the logistics issues of biomass-to-electricity generation by selecting the power plant located in Suphan Buri province of Thailand as the case study.

From a field study survey, multi-biomass types and huge amount of biomass storage are the strategies the biomass power plant normally employed to deal with the periodic supply and uncertainty problem of biomass feedstock for a continuous generation of biomass-to-electricity throughout the year. However, continuous increasing of feedstock supply cost could not be avoided as well as the degradation issue of biomass during storage was not explicitly recognized on how it impacts on the total feedstock cost.

Therefore, the mathematical programming model well-known as a systematic integration method to design and analyze the biomass supply chain will be proposed for the case study. Mathematical programming is one of the best developed and most utilized branches of operation research. It consists of an objective function to be minimized or maximize under a set of functions called constraints encompassing relationships of all variables and parameters in equation forms (Ba et al., 2016). Depending on the characteristics of variables, objective function and constraints, these models can be divided into four categories (Atashbar et al., 2016): linear programming (LP), integer programming, Mixed-integer programming (MILP) and nonlinear programming (NLP).

There are a number of papers which applied mathematical programming models to different parts of bioenergy supply chain. Dunnett et al. (2007) developed MILP of a biomass to heat supply chain that represent the processes of harvesting, densification, drying, storage and transportation which applied 12-month operational cycle. They compared scenarios between single harvest period (SHP) and multi harvest period (MHP) models, the results showed the MHP model saved the total cost about 14.9% compared with the SHP model. Akhtari et al. (2014) developed linear programming (LP) model to minimize the delivery cost which determine the optimal flow of biomass. Each node including biomass source points, terminal storages, and heating plants of the forest supply network. The optimal results showed biomass should be chipped at supply sources, while woodchips should be sent to terminal storage or directly to the power plant. Tan et al. (2017) studied direct combustion power generation focusing on the collection, transportation, storage and generation processes. A nonlinear multi-objective optimization model was developed to determine the optimal quantity of electricity generation and to maximize profits related to all variables such as acquisition quantity, biomass price and blending ratio. The optimal result showed the best integrated efficiency was achieved when the biomass electricity on-grid price was 0.65 Yaun $kWh^{-1}$.

In addition, degradation process of biomass during storage is an unavoidable problem especially for the ambient storage practice employed at the case study resulting in material loss of biomass and later adding a cost to biomass feedstock. Many research works studied the degradation process of biomass during different storage conditions and methods. Santos et al. (2011) evaluated the difference of treated bagasse as basic, dry and wet. The highest loss of heating value was found 52.2% in the wet bagasse after stored 150 days. Lois-Correa et al, (2010) studied baled bagasse piles in 3 different conditions; wet raw bagasse (~ 50% M.C.), wet depithed bagasse which pith was removed (~50% M.C.) and pre-dried depithed bagasse (~25% M.C.). The result showed the lowest dry fiber loss was 6.5% in pre-dried depithed bagasse at 120 days, while wet raw and wet depithed bagasse rapidly rise to 24.7% and 20.2%, respectively within 30 days and after that the loss remained stable. Not only for bagasse, Searcy and Hess, (2010) measured deterioration of woodchip (51% M.C.) in the timber industry, found the loss rate 2.2% per month, averaged over six months and it was generally much higher in the first few weeks than later.

Because the moisture content in biomass is the one factor that supports the growth rate of microbial that use fiber as food, the drying process (<20% moisture) which reduce the moisture content of biomass become a choice to decrease the degradation of biomass (Purchase et al., 2014). Smith et al. (2013) measured moisture content and dry matter loss of baled corn stover and sorghum that were stored outdoor with 3 types of uncovered, tarp-covered and wrapped stacks. The conclusion found that the stack configuration, orientation and coverage methods can improve moisture management and preservation.

From above all mentioned; therefore, the objective of this research work aims to develop mathematical model of operations related to biomass-to-electricity generation with the propose for helping the power plant to understand degradation effect on feedstock cost and better manage logistics operations related to biomass-to-electricity generations. In the following sections, Section 2 represents logistics operations regarding to biomass-to-electricity generation of the case study and its related mathematical models was proposed in Section 3. Then, the implementation of the model to the case study will be provided in Section 4 and finally conclusion in Section 5

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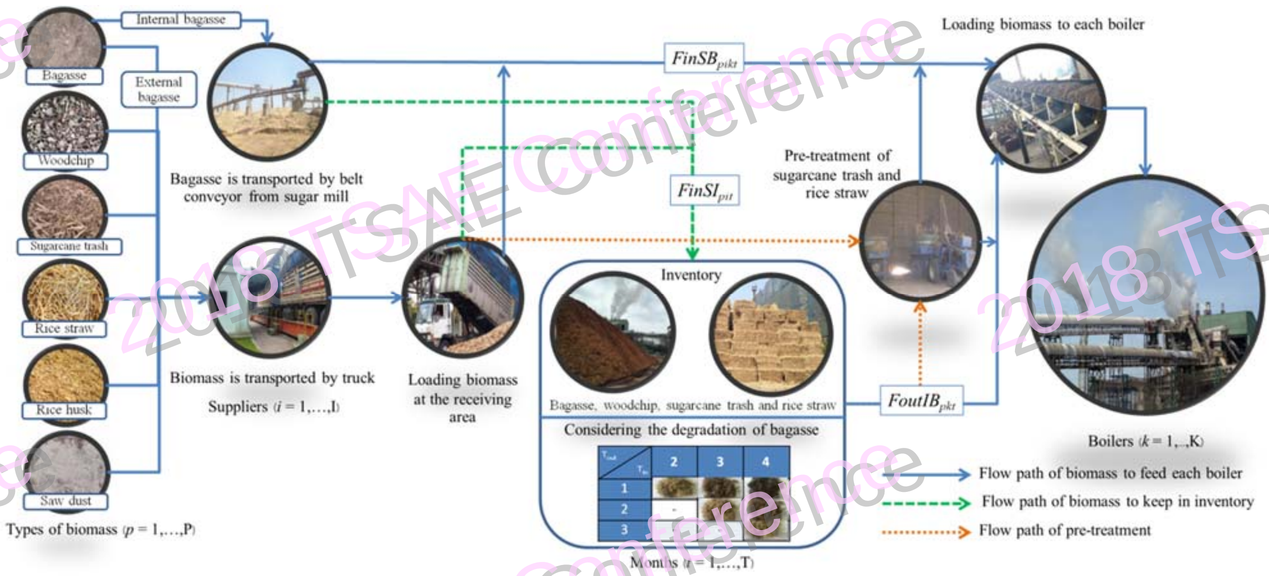


Figure 1 Material flow diagram of biomass-to-electricity generation at the power plant

## 2 Logistics operations of biomass–to-electricity generation

From a field study conducted at the power plant, bagasse which is the residue left from sugar mill located nearby the power plant has been used as a main feedstock to produce electricity via direct combustion process at boilers installed at the power plant. Nevertheless, availability of bagasse at the nearby sugar mill is not enough as a whole feedstock to produce electricity throughout the year as committed in the Power Purchase Agreement (PPA) issued by EGAT. Moreover, short seasonal period of bagasse available locally in Suphan Buri province during late November to April is another burden to rely only on bagasse as a feedstock to produce electricity.

Currently, woodchip, sugarcane trash, rice husk, rice straw and saw dust have been chosen as alternative feedstocks at the power plant. Many factors procurement team of the company applied to choose other types of biomass as an alternative feedstock such as % moisture content, heating value, available quantity, quality, price and availability area as well as social responsibility issue.

Figure 1 shows the logistics operations regarding to biomass-to-electricity of the power plant. Six types of biomass are purchased from suppliers to generate electricity at the power plant; bagasse, the main feedstock, is available from 2 sources; internal bagasse transported by belt conveyor from nearby sugar mill, and external bagasse transported by truck from other sugar mill located in other provinces. Due to a huge amount of bagasse required to produce electricity, some arrived bagasse at the power plant will be separated to directly feed boiler and to the inventory. Ambient storage at an open-air area is provided as a storage site at the company. Please note that stored bagasse will deteriorate using this storage method (Darr and Shah, 2012).

For alternative feedstocks, they are transported by truck and pickup truck to the plant and then a truck load biomass at the receiving area which will later be chosen which station will be proceeded next depending on a type of biomass. For example, sugarcane trash and rice straw will be sent to de-baling station before further process to the boiler. Rice husk and saw dust will directly feed to the boiler to avoid self-ignition process. Woodchip somehow will immediately feed to the boiler or go to the storage site depending on available quantity and the production plan. In the following section, mathematical models regarding to this logistics operations will be developed.

## 3 Mathematical models

In this work, two mathematical models were developed. One called non-degraded model formulated under the assumption which none of any type of biomass is deteriorate during storage. This assumption tends to synchronize with understanding of operation at the power plant. Another one called degraded model was formulated under the assumption which a huge storage of bagasse will be subject to deterioration. This assumption synchronizes with the reviewed literature. In the following, nomenclature, objective function and constraints of both models will be defined.

**Nomenclature**

*Sets*

$p \in P$- Types of biomass that used in biomass power plant ($p \in$ {bagasse, woodchip, sugarcane trash, rice straw, rice husk, saw dust})

$i \in I$ – set of supply lists ($i \in \{1,\ldots,I\}$)

$k \in K$ – set of boilers ($k \in \{1,2,3\}$)

$t \in T$ – set of time periods ($t \in \{1,\ldots,12\}$)

$o \in O$ – set of time periods to identify a degradation ratio when bagasse is used at time $o$ ($o \in \{1,\ldots,12\}$)

*Parameters*

$BS_{pit}$ – available biomass $p$ from supplier $i$ in month $t$ (ton)

$CPB_{pit}$ – cost of purchased biomass $p$ from supplier $i$ in month $t$ (baht ton$^{-1}$)

$CTin_{pt}$ – cost of transfered biomass $p$ to keep in the inventory in month $t$ (baht ton$^{-1}$)

$CTout_{pkt}$ – cost of transfered biomass $p$ from inventory to feed boiler $k$ in month $t$ (baht ton$^{-1}$)

$DB_{to}$ – degradation ratio of bagasse during storage period from month $t$ to month $o$ (decimal fraction)

$EB_k$ – efficiency of boiler $k$ (decimal fraction)

$EG_{kt}$ – electricity generation demand at boiler $k$ in month $t$ (kJ)

$HV_{pt}$ – heating value of biomass $p$ in month $t$ (kJ ton$^{-1}$)

$IntI_p$ – quantity of biomass $p$ at initial period in the inventory of degraded model (ton)

$CapI_p$ – inventory capacity of biomass $p$ (ton)

$MR_{kt}$ – minimum ratio of required bagasse at boiler $k$ in month $t$ (decimal fraction)

*Decision variables*

$FinSB_{pikt}$ – quantity of purchased biomass $p$ from supplier $i$ in month $t$ to feed at boiler $k$ (ton)

$FinSI_{pit}$ – quantity of purchased biomass $p$ from supplier $i$ in month $t$ to keep in the inventory (ton)

$FoutIB_{pkt}$ – quantity of biomass $p$ taken from the inventory to feed at boiler $k$ in month $t$ (ton)

$SB_{pt}$ – quantity of stored biomass $p$ in month $t$ (ton)

$FinDI_t$ - quantity of initial bagasse without deterioration keeping in the inventory in month $t$ of degraded model (ton)

$FoutDI_{to}$ – quantity of degraded bagasse taken out from the inventory after storage from month $t$ to month $o$ (ton)

$RB_{kt}$ - ratio of bagasse to total required biomass at boiler $k$ in month $t$ (decimal fraction)

### *3.1 Objective function*

Total cost in Eq. (1) to be minimized includes sum of purchased biomass cost and transfer biomass cost.

*Total cost = purchased biomass cost + transfer biomass cost* (1)

Eq. (2) and Eq. (3) refer to cost of purchased biomass (PBC) and transfer biomass cost (TBC), respectively.

$$PBC = \sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{t=1}^{T}((CPB_{pit}) * ((\sum_{k=1}^{K} FinSB_{pikt}) + FinSI_{pit})) \qquad (2)$$

$$TBC = \sum_{p=1}^{P}\sum_{t=1}^{T}(CTin_{pt} * (\sum_{i=1}^{I} FinSI_{pit})) + \sum_{p=1}^{P}\sum_{k=1}^{K}\sum_{t=1}^{T}(CTout_{pkt} * FoutIB_{pkt}) \qquad (3)$$

### *3.2 Constraints*

Eq. (4) is sum of feed biomass and stored biomass that must equal or less than available biomass from suppliers in each month.

$$\sum_{k=1}^{K} FinSB_{pikt} + FinSI_{pit} \le BS_{pit}\,;\forall i \in I, p \in P, t \in T \tag{4}$$

At first month, quantity of feed biomass must equal or less than initial biomass available in inventory shown in Eq. (5).After that quantity of feed biomass depends on quantity of stored biomass available in months *t*-1 Eq. (6).

$$\sum_{k=1}^{K} FoutIB_{pkt} \le IntI_p; \forall p \in P, t = 1 \tag{5}$$

$$\sum_{k=1}^{K} FoutIB_{pkt} \le SB_{p,t-1}; \forall p \in P, t = 2,3,\dots,12 \tag{6}$$

The material balance of stored biomass at *t*=1 is represented in Eq. (7) while at other time periods are represented in Eq. (8).

$$SB_{pt} = IntI_p + \sum_{i=1}^{I} FinSI_{pit} - \sum_{k=1}^{K} FoutIB_{pkt}; \forall p \in P, t = 1 \tag{7}$$

$$SB_{pt} = SB_{p,t-1} + \sum_{i=1}^{I} FinSI_{pit} - \sum_{k=1}^{K} FoutIB_{pkt}; \forall p \in P, t = 2,3,\dots,12 \tag{8}$$

Sum of quantity of purchased biomass and initial biomass in the inventory must less than or equal to maximum inventory capacity as represented in Eq. (9) for period *t*=1. At other time periods (*t*>1), sum of quantity of purchased biomass and stored biomass must less than or equal maximum inventory capacity as represented in Eq. (10).

$$\sum_{i=1}^{I} FinSI_{pit} + IntI_p \le CapI_p\ ; \forall p \in P, t = 1 \tag{9}$$

$$\sum_{i=1}^{I} FinSI_{pit} + SB_{p,t-1} \le CapI_p\ ; \forall p \in P, t = 2,3,\dots,12 \tag{10}$$

The power plant use bagasse as the main feedstock mixed with other biomass such as woodchip, sugarcane trash, rice husk, rice straw and saw dust to generate electricity. Therefore, Eq. (11) represents the minimum ratio of bagasse feedstock required by the existing conversion technology installed at the power plant.

$$RB_{kt} \ge MR_{kt}; \forall k \in K, t \in T \tag{11}$$

Eq. (12) uses to balance between heating value of bagasse and electricity generation demand required by each boiler.

$$\sum_{p=1}^{P} (EB_k * HV_{pt} * (\sum_{i=1}^{I} FinSB_{pikt} + FoutIB_{pkt})) \ge EG_{kt} * RB_{kt};\ \forall k \in K, t \in T, p = 1 \tag{12}$$

For alternative biomass, Eqs. (13) - (15) use to balance between heating value of alternative biomass usage and electricity generation demand in each boiler.

$$\sum_{p=1}^{P} (EB_k * HV_{pt} * (\sum_{i=1}^{I} FinSB_{pikt} + FoutIB_{pkt})) \ge EG_{kt} * (1 - RB_{kt});\ k = 1, p = 2,5,6, \forall t \in T \tag{13}$$

$$\sum_{p=1}^{P} (EB_k * HV_{pt} * (\sum_{i=1}^{I} FinSB_{pikt} + FoutIB_{pkt})) \ge EG_{kt} * (1 - RB_{kt}); k = 2, p = 2,5,6, \forall t \in T \tag{14}$$

$$\sum_{p=1}^{P} (EB_k * HV_{pt} * (\sum_{i=1}^{I} FinSB_{pikt} + FoutIB_{pkt})) \ge EG_{kt} * (1 - RB_{kt}); k = 3, p = 3,4, \forall t \in T \tag{15}$$

### *3.3 Additional constraints for degraded model*

The following constraints will be employed only in the degraded model. Eq. (16) is applied to determine the availability of bagasse at initial time before deterioration. When time period *t*=1 and Eq. (17) applied when time period *t*>1.

$$FinDI_t = \sum_{i=1}^{I} FinSI_{pit} + IB_p; p = 1, t = 1 \tag{16}$$

$$FinDI_t = \sum_{i=1}^{I} FinSI_{pit}; p = 1, t = 2,3,\dots,12 \tag{17}$$

Eq. (18) represents the material balance of usage of degraded bagasse.

$$FinDI_t - \sum_{o=1}^{O} FoutDI_{to} \ge 0; \forall t \in T, o > t \tag{18}$$

Eq. (19) is applied to limit that bagasse will not be taken out from inventory when time period *o*=1. Eq. (20) represents the balance of amount of degraded bagasse left when it is taken-out to feed boilers.

$$FoutIB_{pko} = 0; \forall k \in K, p = 1, o = 1 \tag{19}$$

$$\sum_{t=1}^{T} \left(\frac{100 - DB_{to}}{100}\right) * FoutDI_{to} = \sum_{k=1}^{K} FoutIB_{pko}; \forall t \in T, o > t, p = 1 \tag{20}$$

All decision variables value must equal or more than zero.

## 4 Implementation of the models

In this section, the developed models in Section 3 were implemented assuming a maximum capacity of the power plant is 110 MW. Model assumptions, parameters and computational results will be shown and discussed as follows.

### *4.1 Model assumptions*

The following model assumptions were applied in the models. All assumptions can be explained below.

1). Six types of biomass were applied; bagasse is the main feedstock. Woodchip, sugarcane trash, rice straw, rice husk and saw dust are alternative feedstock to produce electricity.

2). Operation period considered on monthly basis for 1 year; in the real situation, available bagasse comes to the plant at late November, so these models will count December as a starting month.

3). For the degraded model, only bagasse will be assumed to decompose which is relevant to the real practice of huge storage pile of bagasse at the power plant.

4). There is no deterioration for external bagasse even when it is purchased during off-seasonal periods.

### *4.2 Model parameters*

For parameters applied in the model, some have been obtained from a field study; some have been modified from the literature. Table 1 shows parameters of each biomass applied to the model which were adapted from data of the case study. From Table 1, bagasse is the main feedstock but has the lowest heating value (HV) while sugarcane trash has the highest HV. Availability period of most biomass is seasonal except woodchip and sawdust which can be purchased all year round. Inventory capacity, the maximum amount of each stored biomass in the power plant will not include rice husk and saw dust which is relevant to the real practice of the case study. The usage ratio of bagasse as a main feedstock must be more than or equal to 0.5 of all biomass usage; therefore, the sum of other biomass usage must less than or equal to 0.5. For the purchased price of each biomass, internal bagasse is at the lowest price while rice husk is at the highest price. Transfer biomass cost is the estimated cost which accounts for moving biomass into or moving biomass from the inventory by rented tractors.

Table 2 represents deterioration rate of internal bagasse in percentage applied in the degraded model. The deterioration rate depends on storage period of bagasse as the period starts from when the bagasse is purchased (period *t*) till the bagasse is used (period *o*) to produce electricity. The percentage of degraded bagasse starts at 6% loss for storage period of one month, and increase to 3% loss in the following periods till the highest loss is 36% if bagasse was stored from the first month (*t*=1) until the final month (*o*=12). The percentage employed in Table 2 was adapted from the literature (Dunnett et al., 2007).

Table 3 shows parameters applied in each boiler including the efficiency and amount of electricity generation in each month adapted from data of the case study. Note that the third boiler will be operated only 3 months per year relevant to the real data of the case study.

Table 1 Parameters of each biomass

| | Heating value (kJ kg$^{-1}$) | Available period of biomass | Inventory capacity (ton) | Ratio of biomass usage to generate electricity | Purchased price (baht ton$^{-1}$) | Transfer biomass cost (baht ton$^{-1}$) |
|---|---|---|---|---|---|---|
| Bagasse (internal) | 7,300 | November-April | 544000 | ≥ 0.5 | 400 | 20 |
| Bagasse (external) | | May-October | | | 1,000 | |
| Woodchip | 8,700 | All year | 100000 | Sum of ratio ≤ 0.5 | 1,300 | |
| Sugarcane trash | 12,800 | December-April | 20000 | | 1,000 | |
| Rice straw | 11,200 | March-July and October-December | 20000 | | 1,000 | |
| Rice husk | 12,700 | March-July and October-December | - | | 1,700 | |
| Saw dust | 9,700 | All year | - | | 1,400 | |

Table 2 The percentage of degraded bagasse in each period (%)

| time period *o* / time period *t* | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 6 | 9 | 12 | 15 | 18 | 21 | 24 | 27 | 30 | 33 | 36 |
| 2 | 🟥 | 6 | 9 | 12 | 15 | 18 | 21 | 24 | 27 | 30 | 33 |
| 3 | 🟥 | 🟥 | 6 | 9 | 12 | 15 | 18 | 21 | 24 | 27 | 30 |
| 4 | 🟥 | 🟥 | 🟥 | 6 | 9 | 12 | 15 | 18 | 21 | 24 | 27 |
| 5 | 🟥 | 🟥 | 🟥 | 🟥 | 6 | 9 | 12 | 15 | 18 | 21 | 24 |
| 6 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 6 | 9 | 12 | 15 | 18 | 21 |
| 7 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 6 | 9 | 12 | 15 | 18 |
| 8 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 6 | 9 | 12 | 15 |
| 9 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 6 | 9 | 12 |
| 10 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 6 | 9 |
| 11 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 🟥 | 6 |

Table 3 Parameters of each boiler

| | Efficiency of each boiler | Electricity generation in each month (Tj) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| Boiler 1 | 0.3 | 88.2 | 88.2 | 88.2 | 88.2 | 88.2 | 88.2 | 88.2 | 88.2 | 88.2 | 88.2 | 88.2 | 88.2 |
| Boiler 2 | 0.3 | 88.2 | 88.2 | 88.2 | 88.2 | 88.2 | 88.2 | 88.2 | 88.2 | 88.2 | 88.2 | 88.2 | 88.2 |
| Boiler 3 | 0.3 | 100.8 | 100.8 | 100.8 | - | - | - | - | - | - | - | - | - |

### *4.3 Computational results*

Two LP models were solved to minimize total cost in LINGO 11 (LINGO, 2018). The result in Table 4 showed that the total cost of the degraded model was higher than the non-degraded model as 102.1 million baht or 19.3%. The most increasing costs come from the purchasing of the alternative biomass which an amount of each purchased biomass was presented in Table 5. From both models, bagasse was mostly used at 1,043,829.4 ton and 1,041,752.7 ton, for non-degraded and degraded model respectively. This belongs to the fact that bagasse is a main feedstock required at boilers of the power plant. Apparently, increasing usage of woodchip, sugarcane trash and saw dust become important when bagasse deteriorates (degraded model) which affect the total feedstock cost. In addition, Table 5 showed the models inherently ranking the usage of alternative biomass types due to their heating value, price, as well as theirs availability which this generally become a difficult task for making a decision by an operator at the power plant.

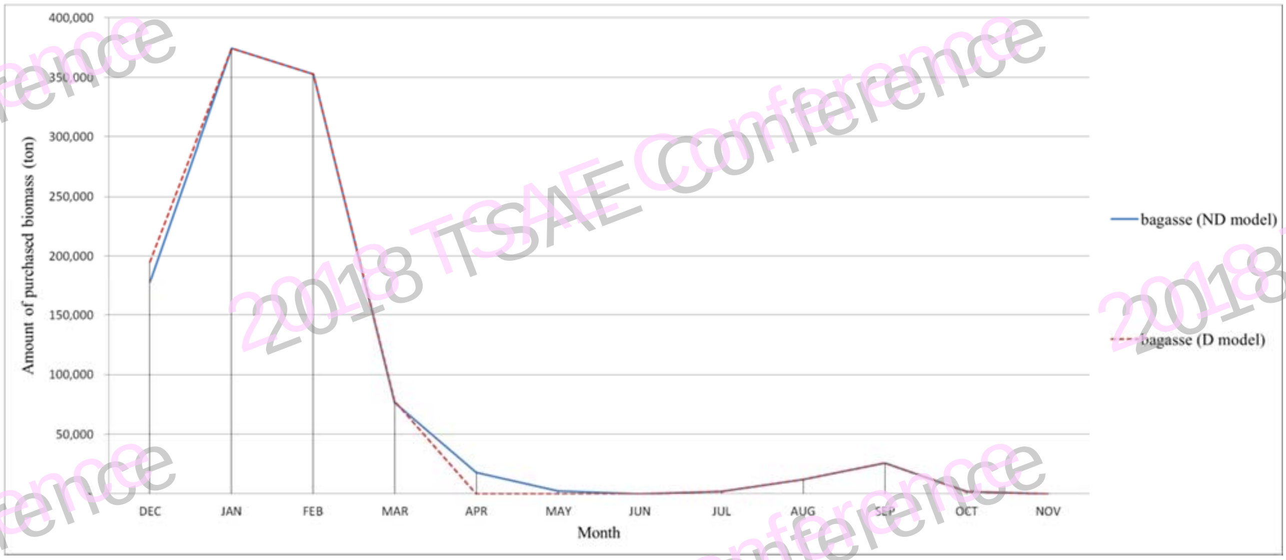
Figure 2 and 3 showed the difference of management practice of purchased bagasse and alternative biomass in each month compared between non-degraded model (ND) and degraded model (D), respectively. In Figure 2, both models showed insignificant difference of purchased bagasse because bagasse is a main feedstock needed at boilers and most of bagasse comes from nearby sugar mill which the price is very cheap. Nevertheless, some difference found due to the deterioration effect. Also, Figure 3 elaborates the additional amount of alternative biomass required due to deterioration effect of the degraded model in each month as shown in Table 5.

Table 4 The results of operating costs (Million baht)

| | Purchased biomass cost | Transfer biomass cost | Total cost |
|---|---|---|---|
| Non-degraded model | 507.3 | 21.8 | 529.1 |
| Degraded model | 610.1 | 21.1 | 631.2 |

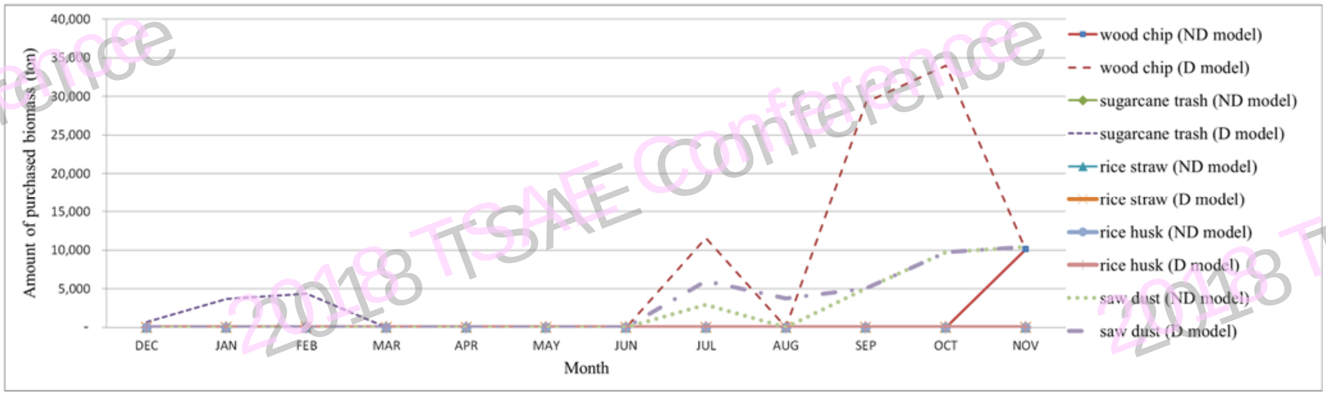
Table 5 Amount of each purchased biomass (ton) of each model

| Types of biomass | Non-degraded model | Degraded model |
|---|---|---|
| Bagasse | 1,043,829.4 | 1,041,752.7 |
| Woodchip | 10,096.2 | 84,946.9 |
| Sugarcane trash | - | 8,810 |
| Rice straw | - | - |
| Rice husk | - | - |
| Saw dust | 28,125 | 34,906.3 |



| Purchased biomass ($\times10^3$ ton) | DEC | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **bagasse (ND model)** | 177.90 | 374.26 | 352.81 | 76.68 | 17.84 | 2.27 | - | 2.20 | 11.90 | 25.84 | 2.15 | - |
| **bagasse (D model)** | 194.95 | 374.26 | 352.81 | 77.67 | - | - | - | 2.20 | 11.90 | 25.84 | 2.15 | - |

Figure 2 The optimum amount of purchased bagasse in non-degraded and degraded model within 12 months



| Purchased biomass ($\times10^3$ ton) | DEC | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **woodchip (ND model)** | - | - | - | - | - | - | - | - | - | - | - | 10.10 |
| **woodchip (D model)** | - | - | - | - | - | - | - | 11.61 | - | 29.23 | 34.02 | 10.10 |
| **sugarcane trash (ND model)** | - | - | - | - | - | - | - | - | - | - | - | - |
| **sugarcane trash (D model)** | 0.70 | 3.72 | 4.40 | - | - | - | - | - | - | - | - | - |
| **rice straw (ND model)** | - | - | - | - | - | - | - | - | - | - | - | - |
| **rice straw (D model)** | - | - | - | - | - | - | - | - | - | - | - | - |
| **rice husk (ND model)** | - | - | - | - | - | - | - | - | - | - | - | - |
| **rice husk (D model)** | - | - | - | - | - | - | - | - | - | - | - | - |
| **saw dust (ND model)** | - | - | - | - | - | - | - | 2.93 | - | 5.02 | 9.74 | 10.43 |
| **saw dust (D model)** | - | - | - | - | - | - | - | 5.98 | 3.74 | 5.02 | 9.74 | 10.43 |

Figure 3 The optimum amount of purchased alternative biomass in non-degraded and degraded model within 12 months

## 5 Conclusions

Two mathematical programming models were proposed and developed in this work as degraded and non-degraded model. Linear programming models were obtained and the results showed the total cost of degraded model is higher than non-degraded model at 102.1 million baht or 19.3%. Both models provided an insight analysis to help operators at the power plant for better understanding the degradation effect on feedstock cost and better manage a feedstock supply. Nevertheless, further development and validation of the models when bring the models to the real application for the case study will be the next step of this work.

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## 7 References

Akhtari, S., Sowlati, T., & Day, K. (2014). Optimal flow of regional forest biomass to a district heating system. *International Journal of Energy Research*, *38*(7), 954-964.

Atashbar, N. Z., Labadie, N., & Prins, C. (2016). Modeling and optimization of biomass supply chains: A review and a critical look. *IFAC-PapersOnLine, 49*(12), 604-615.

Ba, B. H., Prins, C., & Prodhon, C. (2016). Models for optimization and performance evaluation of biomass supply chains: An Operations Research perspective. *Renewable Energy*, *87*, 977-989.

Darr, M. J., & Shah, A. (2012). Biomass storage: an update on industrial solutions for baled biomass feedstocks. *Biofuels*, *3*(3), 321-332.

dos Santos, M. L., de Lima, O. J., Nassar, E. J., Ciuffi, K. J., & Calefi, P. S. (2011). Estudo das condições de estocagem do bagaço de cana-de-açúcar por análise térmica. *Quim. Nova*, *34*(3), 507-511.

Dunnett, A., Adjiman, C., & Shah, N. (2007). Biomass to heat supply chains: applications of process optimization. *Process Safety and Environmental Protection*, *85*(5), 419-429.

LINGO. (2017). Optimization modeling software. Available at: https://www.lindo.com/. Accessed on 20 February 2018.

Lois-Correa, J., Flores-Vela, A., Ortega-Grimaldo, D., & Berman-Delgado, J. (2010). Experimental evaluation of sugar cane bagasse storage in bales system. *Journal of applied research and technology*, *8*(3), 365-375.

Mafakheri, F., & Nasiri, F. (2014). Modeling of biomass-to-energy supply chain operations: applications, challenges and research directions. *Energy Poli1cy*, *67*, 116-126.

McKendry, P. (2002). Energy production from biomass (part 1): overview of biomass. *Bioresource technology*, *83*(1), 37-46.

McKendry, P. (2002). Energy production from biomass (part 2): conversion technologies. *Bioresource technology*, *83*(1), 47-54.

Purchase, B. S., Rosettenstein, S., & Bezuidenhoudt, D. V. (2014). Challenges and potential solutions for storage of large quantities of bagasse for power generation. *Intern. Sugar J*, *116*, 592-602.

Searcy, E. M., & Hess, J. R. (2010). Uniform-format feedstock supply system: A commodity-scale design to produce an infrastructure-compatible biocrude from lignocellulosic biomass. *EXT-1020372: Idaho National Laboratory*.

Smith, W. A., Bonner, I. J., Kenney, K. L., & Wendt, L. M. (2013). Practical considerations of moisture in baled biomass feedstocks. *Biofuels*, *4*(1), 95-110.

Tan, Q., Wang, T., Zhang, Y., Miao, X., & Zhu, J. (2017). Nonlinear multi-objective optimization model for a biomass direct-fired power generation supply chain using a case study in China. *Energy*, *139*, 1066-1079.