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The development of multi-objective optimization model for excess bagasse utilization: A case study for Thailand

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Abstract

In this paper, a multi-objective optimization model is proposed as a tool to assist in deciding for the proper utilization scheme of excess bagasse produced in sugarcane industry. Two major scenarios for excess bagasse utilization are considered in the optimization. The first scenario is the typical situation when excess bagasse is used for the onsite electricity production. In case of the second scenario, excess bagasse is processed for the offsite ethanol production. Then the ethanol is blended with an octane rating of 91 gasoline by a portion of 10% and 90% by volume respectively and the mixture is used as alternative fuel for gasoline vehicles in Thailand. The model proposed in this paper called “Environmental System Optimization” comprises the life cycle impact assessment of global warming potential (GWP) and the associated cost followed by the multi-objective optimization which facilitates in finding out the optimal proportion of the excess bagasse processed in each scenario. Basic mathematical expressions for indicating the GWP and cost of the entire process of excess bagasse utilization are taken into account in the model formulation and optimization. The outcome of this study is the methodology developed for decision-making concerning the excess bagasse utilization available in Thailand in view of the GWP and economic effects. A demonstration example is presented to illustrate the advantage of the methodology which may be used by the policy maker. The methodology developed is successfully performed to satisfy both environmental and economic objectives over the whole life cycle of the system. It is shown in the demonstration example that the first scenario results in positive GWP while the second scenario results in negative GWP. The combination of these two scenario results in positive or negative GWP depending on the preference of the weighting given to each objective. The results on economics of all scenarios show the satisfied outcomes.

Keywords: Bagasse; LCIA; Multi-objective optimization; Ethanol; GWP

1. Introduction

The present worldwide economic development tends to increase the emission of greenhouse gases (GHGs). As a developing country, Thailand is expected to be a major contributor of atmospheric carbon dioxide (CO_2)

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build-up and a potential target for the deployment of biomass-based technologies in the near future.

Sugarcane industry is one of the major agro-industries in Thailand. The residual left from the juice extraction is bagasse which is a kind of lignocellulosic biomass. Typically, the left-over bagasse after the juice extraction is about 30% by weight of the crushed sugarcane (Therdyothin, 1992). All of the bagasse left from sugar mills is burnt in the boiler to generate high-pressure steam, the major portion of which is used in the sugar production process. While the excess high-pressure steam is used to drive the power generator in order to produce electricity to be sold to the electricity generating authority of Thailand (EGAT). The equivalent amount of bagasse that contributes to electricity is called "excess bagasse". Fig. 1 shows a simplified diagram of the typical processes of the sugar industry. The amount of excess bagasse from the sugar mills is usually about 12% of the total bagasse (Payne, 1991).

Several researches have been conducted and shown that not only can bagasse, which is lignocellulosic biomass, be utilized as renewable fuel source for the electricity generation but it is also desirable as the feedstock for ethanol production. The excess bagasse can be utilized in a bioconversion process to produce ethanol. The produced ethanol can then be blended with gasoline to produce an E10 which is a blending of 90% of the 91 octane rating gasoline and 10% of the ethanol by volume. E10 is currently used as an alternative fuel for gasoline vehicles in Thailand. With the current climate change and oil crisis, when the environmental and economic aspects are concerned, a better choice of using excess bagasse may be to produce ethanol rather than electricity. This statement has been supported by the trend of researches on energy conducted in the United States where the development of ethanol from lignocellulosic feedstock as an alternative to conventional petroleum transportation fuels has attracted more interest and been promoted. Wooley et al. (1999) developed the process design and economic analysis for predicting the cost and benefit of lignocellulosic biomass derived ethanol. However, their research did not include the study of environmental effects. On the progress of environmental study, corn and lignocellulosic biomass derived ethanol has been the subject of life cycle analysis (NREL, 1993; Wang et al., 1998; Wang et al., 1999). There have also been a series of studies estimating the life cycle energy balance of ethanol derived from corn and lignocellulosic biomass (Lorenz and Morris, 1995; Shapouri et al., 1995; Wang et al., 1999; Farrell et al., 2006). The conclusion drawn from those studies was that the corn and lignocellulosic biomass derived ethanol technology reduces the emission of GHGs to the atmosphere. Wang et al. (1999) concluded that 12.4%–26.4% GHGs emission reduction per volume of ethanol used as E10 was obtained from corn derived ethanol and 83.6%–143.8% GHGs emission reduction per volume of ethanol used as E10 was obtained from lignocellulosic biomass derived ethanol. Moreover, the higher fossil energy ratio, which is the ratio of the final fuel product energy to the fossil energy input, was also obtained. It was reported that the energy contained in ethanol and other products in the corn processing facility is 38% more than the energy used to grow and harvest corn and produce energy products (Lorenz and Morris, 1995). These data agreed with the studies by Wang et al. (1999), Shapouri et al. (1995) and Farrell et al. (2006). However, there was still rebuttal. Pimentel and Patzek (2005) reported that corn derived ethanol and lignocellulosic biomass derived ethanol require 29% and 45%–57% more fossil energy than the fuel produced respectively. However, the study of Pimentel and Patzek (2005) did not state any value of the co-products (Farrell et al., 2006). Furthermore, the data used were too old and unrepresentative of the current processes (Graboski, 2001). Kadam (2002) recently developed the environmental life cycle analysis of bagasse-derived ethanol in Mumbai, India. Global warming potential, depletion of natural resources, acidification potential, eutrophication potential, human toxicity

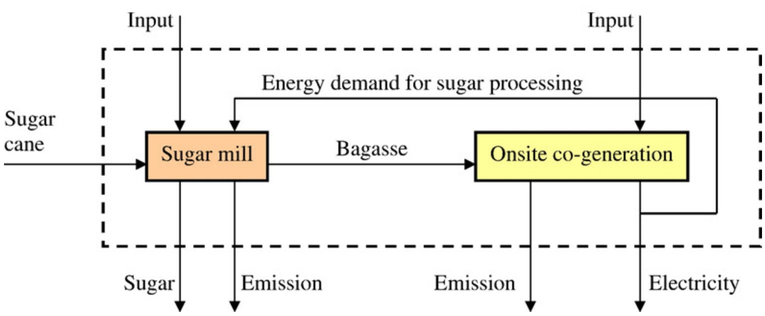

Fig. 1. Typical processes of the sugar industry.

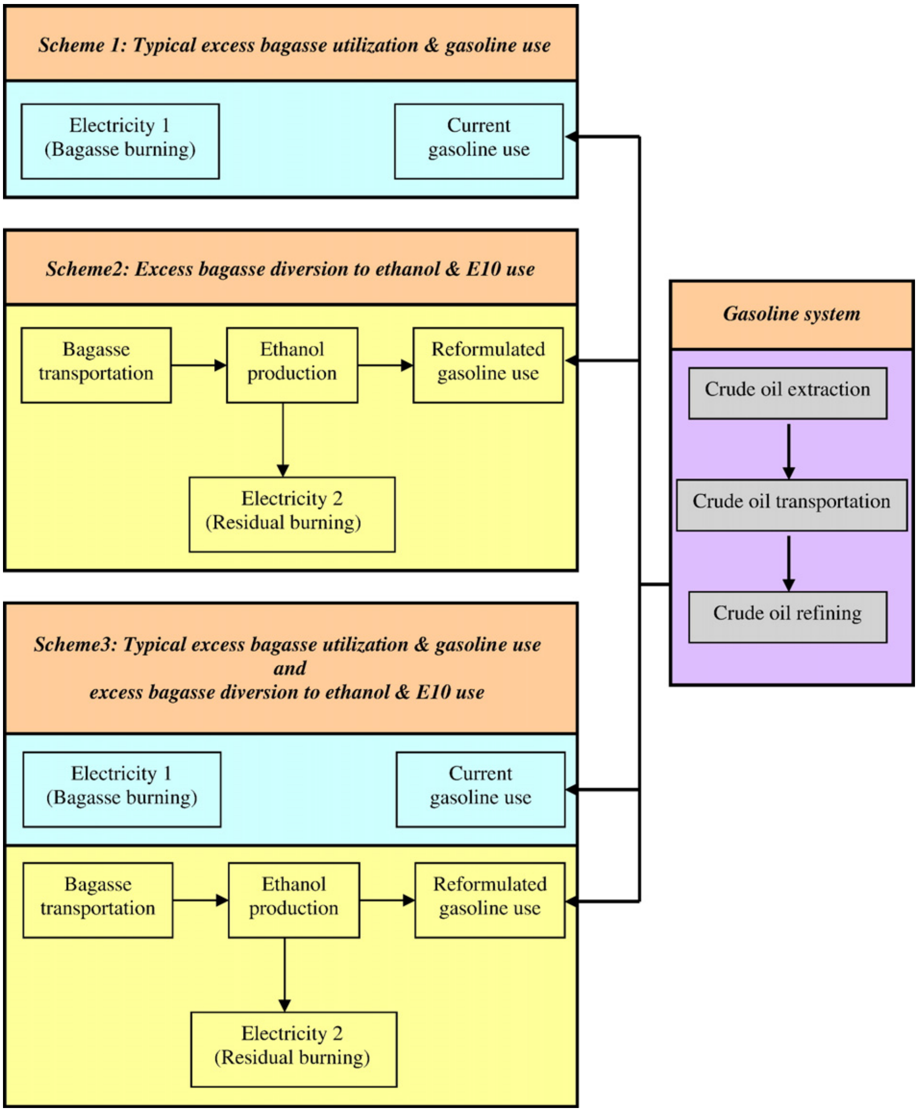

Fig. 2. Structure of the studied model (adapted from Kadam, 2002).

potential, and air odor potential were included in the life cycle assessment (LCA). The results showed significant environmental improvement. However, the effect on economics was not taken into consideration. The selection of the ethanol plant size was not mathematically optimized and the selection of the location of the ethanol plant was not considered.

This study develops and tests a multi-objective optimization model in order to assist the decision-making for the proper utilization scheme of excess bagasse generated in the sugarcane industry in Thailand. The selection of location and the size of the excess bagasse-derived ethanol plants, which imply the portion of excess bagasse from each sugar mill to be burnt on site and the remaining excess bagasse from each sugar mill which needs to be sent to the ethanol plant in order to produce ethanol offsite, are taken into account. These selections are conducted by considering both the advantage and disadvantage on the GWP and economic basis.

2. Proposed methodology

2.1. Problem model

The structure of the studied model is categorized as shown in Fig. 2 and the flow scheme for the excess bagasse utilization and management system is schematically shown in Fig. 3. It is shown in the model that the excess bagasse coming from each sugar mill can be utilized in 3 schemes (Fig. 2). First, the excess bagasse is

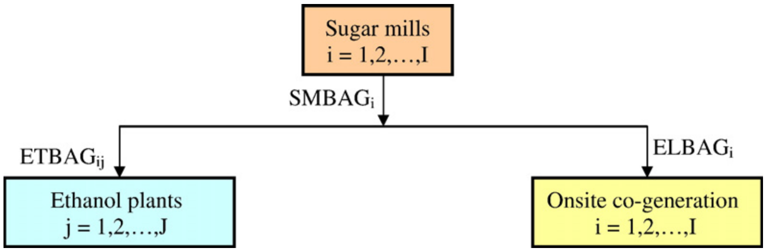

Fig. 3. Excess bagasse utilization and management system for sugar mills.

fed to burn in the onsite boiler to produce high-pressure steam and subsequently produce electricity as practiced in Thailand nowadays. Second, the excess bagasse is sent to produce ethanol in offsite ethanol plant/plants. Third, the excess bagasse from each sugar mill is utilized both for the generation of electricity onsite and the production of ethanol offsite at the optimal proportion. In the second and third schemes, the produced ethanol is blended with gasoline to produce E10 and used as an alternative fuel for gasoline vehicles in Thailand. This research effort is directed towards the development and test of the multi-objective optimization model in order to assist in deciding for the proper utilization scheme of excess bagasse generated in sugarcane industry in Thailand. The selection of the location and size of the excess bagasse-derived ethanol plants, which implies the portion of excess bagasse from each sugar mill to be burnt onsite and the remaining excess bagasse from each sugar mill which needs to be sent to each ethanol plant in order to produce ethanol offsite, are taken into account. These selections are done by considering both the advantage and disadvantage on the GWP and economic basis. The problem is rather complicated and the multi-objective optimization is chosen to assist in solving this problem. The selection of location and size of the ethanol production plants, the allocation of excess bagasse from each sugar mill to the corresponding ethanol plant and the calculation of benefit on GWP and economics are involved.

2.2. Model formulation for environmental system optimization

The studied model is considered a multi-objective optimization, since it seeks an optimal solution between two objectives. This multi-objective optimization model is proposed in this section. The method called "Environmental System Optimization" (ESO), used for determining the optimal solution for deciding on the excess bagasse utilization has been developed. ESO comprises the life cycle impact assessment of the global warming potential (GWP) and the associated cost followed by the multi-objective optimization. ESO involves the selection of the location and size of the ethanol production plants. It also allocates the excess bagasse from each sugar mill to the corresponding ethanol plant and calculates for the benefit on GWP and economics. The GWP and economic criteria are simultaneously taken into account. The GWP objective includes the impact of the emission of all GHGs, especially CO_2, on the global warming potential. The economic objective involves cost and benefit. Basic mathematical expressions for indicating GWP and economics for all processes for excess bagasse utilization in both schemes 1 and 2 are analyzed and modeled in the objective function. The multi-objective optimization process is then performed to determine the optimal excess bagasse utilization scheme. The nomenclatures used in the model formulated are listed as follows;

BCCOST	cost of base case ethanol plant
BCSIZE	size of base case ethanol plant
BGWP	GWP due to burning excess bagasse in all sugar mills
D_{ij}	distance between sugar mill i and ethanol plant j ($i=1,\ldots,I$; $j=1,\ldots,J$)
E10GWP	offset GWP due to the utilization of produced ethanol as E10 fuel
EBCOST	cost of excess bagasse burnt in all sugar mill
EECON	economic effects from the utilization of excess bagasse in scheme 1
EELBFIT	benifit from selling electricity generated from burning of excess bagasse burnt in all sugar mill
EFB	emission factor for burning of excess bagasse in sugar mill
EFE10	offset emission factor for the utilization of produced ethanol as E10 fuel
EFEL	offset emission factor for the electricity producein sugar mill
EFET	emission factor for the production of ethanol from excess bagasse
EFT	emission factor for the transportation of excess bagasse
EGWP	GWP due to the utilization of excess bagasse in scheme 1
$ELBAG_i$	amount of excess bagasse burnt in sugar mill i ($i=1,\ldots,I$)
ELGWP	offset GWP due to the generation of electricity by burning of excess bagasse in all sugar mill
ELP	unit price of electricity

ELPF	electricity generation factor for burning excess bagasse in sugar mill
$ETBAG_{ij}$	amount of excess bagasse from sugar mill *i* processed in ethanol plant *j*;
ETGWP	GWP due to the ethanol production
ETP	price of ethanol
ETPF	excess bagasse-derived ethanol factor
exp	scaling exponent
N	maximum number of ethanol plant
PBCOST	cost of excess bagasse
PBFIT	benefit obtained from the utilization of excess bagasse in scheme 2
PCOST	cost occurring from the utilization of excess bagasse in scheme 2
PECON	economic effects from the utilization of excess bagasse in scheme 2
PELBFIT	benefit from selling of electricity gained from burning of ligneous residue (waste from the ethanol production process).
PEPCOST	cost of ethanol production
PETBFIT	benefit from selling produced ethanol
PGWP	GWP due to the utilization of excess bagasse in scheme 2
PTCOST	cost of excess bagasse transportation
$SMBAG_i$	excess bagasse available in sugar mill *i*
TGWP	GWP due to the transportation of excess bagasse from each sugar mill to corresponding ethanol plant
U	value of objective function
UCT	unit transportation cost of excess bagasse per km
UPB	unit price of excess bagasse
W_{GWP}	weighting to GWP
$W_{economic}$	weighting to economics
XELPF	electricity generation factor from ethanol production plants
y_{ij}	0–1 variable representing the presence or absence of excess bagasse transported from sugar mill I to ethanol plant *j*
z_j	0–1 variable representing the presence or absence of ethanol plant *j*

2.2.1. Formulation of the objectives

In general, the conventional optimization mainly involves the economic function. However, in this paper, the GWP objective is also taken into account. The optimization is then transformed into multi-objective problem. Therefore, the objective function of the proposed model developed in this paper consists of two terms, which are GWP and economics as defined in Eq. (1).

$$\min U = W_{\mathrm{GWP}}(\mathrm{EGWP} + \mathrm{PGWP}) + W_{\mathrm{economic}}(\mathrm{EECON} + \mathrm{PECON}). \quad (1)$$

2.2.1.1. Formulation of the mathematical model for GWP. The GWP has been used in this paper to account for the emission of all GHGs (IPCC, 1994). The GWP requires the complete set of life cycle inventory (LCI) of GHGs emission for the entire life cycle of a products, processes and activities.

For the utilization of excess bagasse in scheme 1, there are 2 GWP components involved. One is the GWP due to burning excess bagasse in onsite industrial boiler to generate electricity (BGWP). The other is the offset GWP due to electricity production (ELGWP). The mathematical relation is formulated as shown in Eq. (2).

$$\mathrm{EGWP} = \mathrm{BGWP} + \mathrm{ELGWP}. \quad (2)$$

BGWP and ELGWP are the multiplication of the quantity of excess bagasse used for generating electricity and emission factors as expressed in Eqs. (3) and (4).

$$\mathrm{BGWP} = \sum_{i=1}^{I} \mathrm{EFB} \times \mathrm{ELBAG}_i \quad \forall i \quad (3)$$

$$\mathrm{ELGWP} = \sum_{i=1}^{I} \mathrm{EFEL} \times \mathrm{ELBAG}_i \quad \forall i. \quad (4)$$

For the utilization of excess bagasse in scheme 2, there are 3 GWP components. They are the GWP due to the transportation of excess bagasse from each sugar mill to the corresponding ethanol plant, the GWP due to the ethanol production and the offset GWP due to the utilization of produced ethanol as E10 fuel in gasoline vehicle. The expression is shown in Eq. (5).

$$\mathrm{PGWP} = \mathrm{TGWP} + \mathrm{ETGWP} + \mathrm{E10GWP}. \quad (5)$$

The functions of the GWP due to the transportation of excess bagasse from each sugar mill to the corresponding ethanol plant, the GWP due to ethanol production and the offset GWP due to the utilization of produced ethanol as E10 fuel are formulated as shown in Eqs. (6)–(8).

$$\mathrm{TGWP} = \sum_{j=1}^{J} \sum_{i=1}^{I} \mathrm{EFT} \times \mathrm{D}_{ij} \times \mathrm{ETBAG}_{ij} \times y_{ij} \quad \forall i, \forall j \quad (6)$$

$$\mathrm{ETGWP} = \sum_{j=1}^{J} \sum_{i=1}^{I} \mathrm{EFET} \times \mathrm{ETBAG}_{ij} \times y_{ij} \quad \forall i, \forall j \quad (7)$$

$$\mathrm{E10GWP} = \sum_{j=1}^{J} \sum_{i=1}^{I} \mathrm{EFE10} \times \mathrm{ETBAG}_{ij} \times y_{ij} \quad \forall i, \forall j. \quad (8)$$

2.2.1.2. Formulation of the mathematical model for economics. The economic effects of the utilization of excess bagasse in scheme 1, covering the cost of the excess bagasse and the benefit from selling the generated electricity, are formulated as shown in Eqs. (9)–(11).

$$\mathrm{EECON} = \mathrm{EBCOST} - \mathrm{EELBFIT} \quad (9)$$

$$\mathrm{EBCOST} = \sum_{i=1}^{I} \mathrm{UPB} \times \mathrm{ELBAG}_i \quad \forall i \quad (10)$$

$$\mathrm{EELBFIT} = \sum_{i=1}^{I} \mathrm{ELP} \times \mathrm{ELPF} \times \mathrm{ELBAG}_i \quad \forall i. \quad (11)$$

For the excess bagasse utilization in scheme 2, the economic effects evaluated from the cost and benefits are formulated as shown in Eq. (12).

$$\mathrm{PECON} = \mathrm{PCOST} - \mathrm{PBFIT}. \quad (12)$$

The cost comprises the total cost of excess bagasse, cost of the ethanol production and cost of the excess bagasse transportation. The ethanol production cost includes the plant capital cost, the fixed operating cost (labor cost) and the variable costs (including the cost of material, electricity and other utility). The ethanol production processes are referenced from NREL simulation (Wooley et al., 1999). However, the economic analysis has been done on only one plant size which is considered the base case size in this paper. Nevertheless, the important thing is to take into account the effect of plant size (economies of scale) by substituting the cost calculated for the base case ethanol plant size with the equation that recalculates the cost with the function of size using the power law type of equation for the scaling factor (Wooley et al., 1999). These are mathematically defined in Eqs. (13)–(16).

$$\mathrm{PCOST} = \mathrm{PBCOST} + \mathrm{PTCOST} + \mathrm{PEPCOST} \quad (13)$$

$$\mathrm{PBCOST} = \sum_{j=1}^{J} \sum_{i=1}^{I} \mathrm{UPB} \times \mathrm{ETBAG}_{ij} \times Y_{ij} \quad \forall i, \forall j \quad (14)$$

$$\mathrm{PTCOST} = \sum_{j=1}^{J} \sum_{i=1}^{I} \mathrm{UCT} \times D_{ij} \times \mathrm{ETBAG}_{ij} \times Y_{ij} \quad \forall i, \forall j \quad (15)$$

$$\mathrm{PEPCOST} = \mathrm{BCCOST} \times \left(\left(\sum_{j=1}^{J} \sum_{i=1}^{I} \mathrm{ETBAG}_{ij} \times Y_{ij} \right) / \mathrm{BCSIZE} \right)^{\exp} \quad \forall i, \forall j. \quad (16)$$

The benefits are gaining from selling of the produced ethanol and the electricity obtained from burning ligneous residue. The benefits functions are formulated as shown in Eqs. (17)–(19).

$$\mathrm{PBFIT} = \mathrm{PETBFIT} + \mathrm{PELBFIT} \quad (17)$$

$$\mathrm{PETBFIT} = \sum_{j=1}^{J} \sum_{i=1}^{I} \mathrm{ETP} \times \mathrm{ETPF} \times \mathrm{ETBAG}_{ij} \times Y_{ij} \quad \forall i, \forall j \quad (18)$$

$$\mathrm{PETBFIT} = \sum_{j=1}^{J} \sum_{i=1}^{I} \mathrm{ELP} \times \mathrm{XELPF} \times \mathrm{ETBAG}_{ij} \times Y_{ij} \quad \forall i, \forall j. \quad (19)$$

2.2.2. Formulation of constraints

Based on ESO, the next step is to formulate the constraints. All of the mathematical models presented in Eqs. (1)–(19) are subjected to performed under the following constraints.

$$\sum_{j=1}^{J} \mathrm{ETBAG}_{ij} \times Y_{ij} + \mathrm{ELBAG}_i = \mathrm{SMBAG}_i \quad \forall i \quad (20)$$

$$y_{ij} = \begin{cases} 1 \text{ if sugar mill } i \text{ has to send its excess bagasse to ethanol plant } j \\ 0 \text{ otherwise} \end{cases} \quad \forall i, \forall j \quad (21)$$

$$\sum_{j=1}^{J} y_{ij} \le 1 \quad \forall i \quad (22)$$

$$z_j = \begin{cases} 1 \text{ if ethanol plant } j \text{ is open} \\ 0 \text{ otherwise} \end{cases} \quad \forall j \quad (23)$$

$$y_{ij} <= z_j \quad \forall i \quad (24)$$

$$\sum_{j=1}^{J} z_j \le N. \quad (25)$$

The first constraint is derived from the mass balance of the excess bagasse. Eqs. (21) and (22) indicate the 0–1 variable representing the presence or absent of excess bagasse transported from sugar mill i to ethanol plant j. Eq. (23) indicates the 0–1 variable representing the presence or absence of ethanol plant j. Eq. (24) forces the excess bagasse from a sugar mill sent to an ethanol plant one by one. Finally, Eq. (25) is developed to set the maximum number of ethanol plant. This number is set by taken the availability of excess bagasse into consideration.

3. Demonstration example

The following example is chosen to illustrate the applicability of ESO for the sugar mills in the Northeastern

Table 1
Excess bagasse from each sugar mill

No.	Factory	Excess bagasse (tons/year)
1	Burirum sugar mill	36 408
2	Sahareong sugar mill	34 150
3	Reum–Udom sugar mill	68 129
4	Kasetphon sugar mill	52 631
5	Kumpawapee sugar mill	52 303
6	Khon–Kaen sugar mill	87 092
7	Mitrphuwieng sugar mill	90 239
8	Roumkasettrakorn–Utsahakam sugar mill	104 983
9	Utsahakamkorat sugar mill	89 330
10	Angwean(ratchasima sugar mill	89 592
11	N.Y. sugar mill	61 628
12	Utsahakamnamtan–Esarn sugar mill	36 663
13	Mitr–Kalasin sugar mill	61 259
Total		864 406

Thailand. In this section the computation of ESO is performed to illustrate the benefit of the model developed. The sensitivity analysis of the model is also performed in order to study the effects of the change in the preferences of the weightings given to each objective which is beneficial to the policy maker.

3.1. Description of the example problem

The example selected covers the whole area of North-eastern Thailand where 13 sugar mills are located. Based on the production year 2002–2003 (Product Development Department, 2003), the excess bagasse from each sugar mill has been calculated and tabulated in Table 1.

For the typical situation, the amount of the excess bagasse has been used for generating electricity. This process releases GHGs which contribute to the GWP of about 582 177 tons of CO_2 equivalent. An alternative option was considered for utilizing excess bagasse for ethanol production. The locations of all sugar mills of the study area are shown in Fig. 4. The potential locations of the ethanol plants can be computed by the center of gravity method (Krajewski et al., 2006) and are also presented in Fig. 4.

Fig. 5 presents the simplified locations of sugar mills and the potential locations of ethanol plants. This figure is converted from the map in Fig. 4 to provide the better image and fit the network analysis in this study. It consists 19 nodes. 13 nodes represent the locations of sugar mills and 6 nodes represent the potential locations of ethanol plants. The node information is given in Table 2.

The data used in the model for the example described in Section 3.1 are divided into two sets, which are the data related to the GWP and economics. The GWP related data result from considering several factors. The analysis of all factors follows the LCIA method. The economics related data also result from considering several factors. The analysis of all factors follows the life cycle approach. There is a lot of information accounted during the analysis and synthesis of data in the model. The information including their sources for

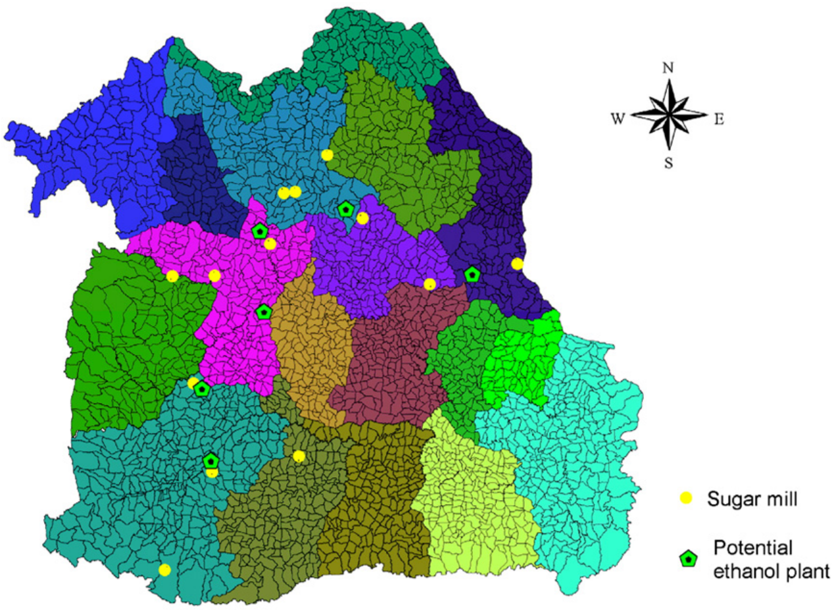

Fig. 4. Locations of all sugar mills and potential locations of the ethanol plants.

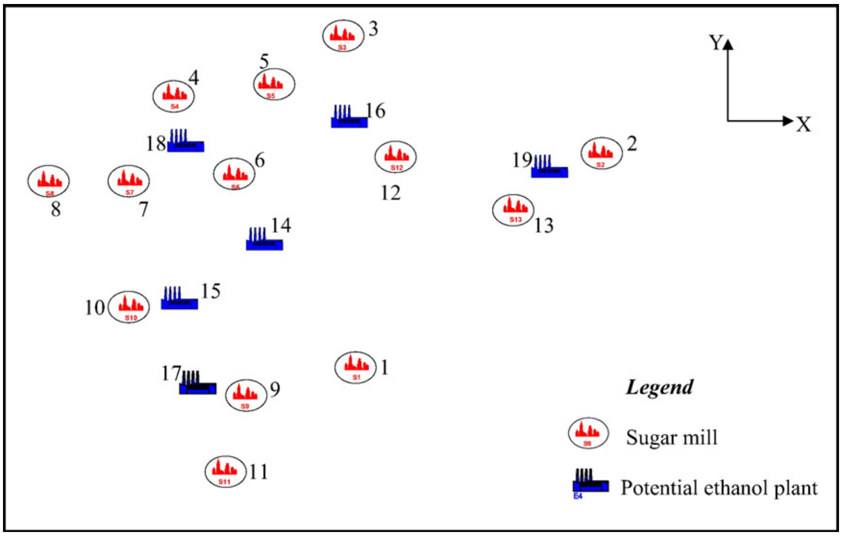

Fig. 5. Simplified locations of all sugar mills and potential locations of ethanol plants.

both the data related to the GWP and economics is summarized in Tables 3 and 4 respectively.

3.2. Results

The demonstration example was solved using LINGO software V4.0. The computations were performed on a personal computer with Intel Pentium M processor 1.5 GHz, 512 MB RAM with operating system windows XP. The example problem has been solved for the following 4 sets of joint functions of GWP and economics: (a) weighting to GWP: 0.0 and weighting to economics: 1.0; (b) weighting to GWP: 0.3 and weighting to economics: 0.7; (c) weighting to GWP: 0.7 and weighting to economics: 0.3; and (d) weighting to GWP: 1.0 and weighting to economics: 0.0. Fig. 6 shows the results of the selected potential site for ethanol plant obtained for various combinations of weighting given to GWP and economics. The results for all the sets of the optimization show that 1 ethanol plant has been chosen and node 18 has been selected to be the ethanol plant. All of the excess bagasse from any sugar mill should be transported to an ethanol plant if it is forced to send excess bagasse to produce ethanol. The effects of variation on weightings to GWP and economics on solution including the GWP and economic effects of the typical situation are calculated by the displacement method (Wang et al., 1999) taking into account the credits of electricity and ethanol produced. The results are summarized in Table 5. A compromise solution can be obtained by judiciously choosing the weightings to GWP and economics.

In the typical situation, the excess bagasse is burnt in the boiler to generate high-pressure steam. The high-pressure steam is used to drive the power generator to produce electricity. From the analysis, the emission of GHGs contribute to the GWP of about 582 177 tons of CO_2 equivalent, while the economic effect is equal to zero in case we sell the excess bagasse at the price equivalent to the benefit gained from the electricity

Table 2
The node information

Node no.	Name	Coordinate (m)	
		X	Y
1	Burirum sugar mill	293 242	1 678 359
2	Sahareong sugar mill	468 600	1 835 090
3	Reum–Udom sugar mill	315 571	1 921 008
4	Kasetphol sugar mill	281 789	1 891 616
5	Kumpawapee sugar mill	290 452	1 891 106
6	Khon–Kaen sugar mill	270 289	1 850 238
7	Mitrphuwieng sugar mill	226 078	1 825 535
8	Roumkasettrakorn–Utsahakam sugar mill	192 738	1 825 183
9	Utsahakamkorat sugar mill	225 524	1 669 230
10	Angwean (ratchasima sugar mill)	209 762	1 738 722
11	N.Y sugar mill	186 544	1 590 141
12	Utsahakamnamtan–Esarn sugar mill	344 192	1 871 650
13	Mitr–Kalasin sugar mill	398 050	1 818 803
14	Potential ethanol plant 1	265 864	1 797 221
15	Potential ethanol plant 2	215 484	1 737 343
16	Potential ethanol plant 3	326 515	1 869 306
17	Potential ethanol plant 4	220 654	1 675 311
18	Potential ethanol plant 5	260 784	1 860 526
19	Potential ethanol plant 6	423 302	1 824 633

Table 3
Information of GWP related data

Processes	Information	Sources of information
Electricity generation from burning of excess bagasse	▪ Electricity generation from burning of excess bagasse in onsite industrial boiler	1. EPA (1995)
	▪ Electricity generation from conventional technologies practicing in Thailand	2. EGAT (2005)
		3. SimaProV5.1
Transportation of excess bagasse	▪ Transportation of excess bagasse from sugar mills to the potential ethanol plant by 10 wheels truck with trailer (dimension of each cabin 5.5(*W*)×2.3(*L*)×2.5(*H*) m^3)	1. Japan Transport Cooperation Association, 2004
	▪ Crude oil extraction and transportation	2. SimaProV5.1
	▪ Crude oil refining	
	▪ Diesel transportation and stock at fuel station including fueling to vehicle	
	▪ Tailpipe emission	
	▪ Truck average speed of 60 km/h	
Ethanol production	▪ Lignocellulosic biomass to ethanol process utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis	1. Kadam (2002)
		2. Wooley et al. (1999)
		3. Aden et al. (2002)
		4. SimaProV5.1
Utilization of ethanol as E10 fuel	▪ A blended of octane rating of 91 gasoline and ethanol and with a portion of 90% and 10% by volume respectively (E10)	1. Kadam et al. (1999)
	▪ Utilization of E10 as an alternative fuel for gasoline vehicle in Thailand.	2. SimaProV5.1
	▪ Crude oil extraction and transportation	
	▪ Crude oil refining	
	▪ Gasoline transportation and stock at fuel station including fueling to vehicle	

SimaProV5.1 is LCA software developed by Pre Consultants, The Netherlands.

produced. In case (a): the result from optimization suggests that all of the excess bagasse from 4 sugar mills should be sent to produce ethanol. These four sugar mills are node nos. 4, 6, 7 and 8. The size of the ethanol plant is 917.65 tons of bagasse per day. The ethanol plant can produce 138 566 L of ethanol per day. The GWP occurrence is about 326 957 tons of CO_2 equivalent (−29 635 tons of CO_2 equivalent for ethanol

Table 4
Information of economics related data

Processes	Information	Sources of information
Electricity generation from burning of excess bagasse	▪ Electricity generation from burning of excess bagasse in onsite industrial boiler	1. Therdyothin (1992)
	▪ Calculation for price of excess bagasse equivalent to amount of the electricity generated.	2. PEA (2005)
	▪ Average price of electricity	
Transportation of excess bagasse	▪ Capital cost of truck with trailer	1. Truck and trailer supplier
	▪ Cost for maintenance.	2. Japan Transport Cooperation Association (2004)
	▪ Cost of fuel consumed during transportation	3. PTT (2006)
	▪ Crew cost	
Ethanol production and utilization of ethanol as E10 fuel	▪ The base case size for ethanol plant of 2000 dry metric tons of excess bagasse per day	1.Kadam (2002)
	▪ Cost of base case including capital cost and operation and maintenance cost	2.Wooley et al. (1993)
	▪ Scaling exponent of 0.7	3.Aden et al. (2002)
	▪ Bagasse-derived ethanol production	4.PTT (2006)
	▪ By-product electricity production (burning ligneous residual)	5.PEA (2005)
	▪ Price of ethanol	
	▪ Price of the 91 octane rating gasoline	
	▪ Average price of electricity	

The data of the cost of the truck and trailer including fuel consumption was taken from local truck and trailer suppliers or international suppliers which hold office in Thailand.

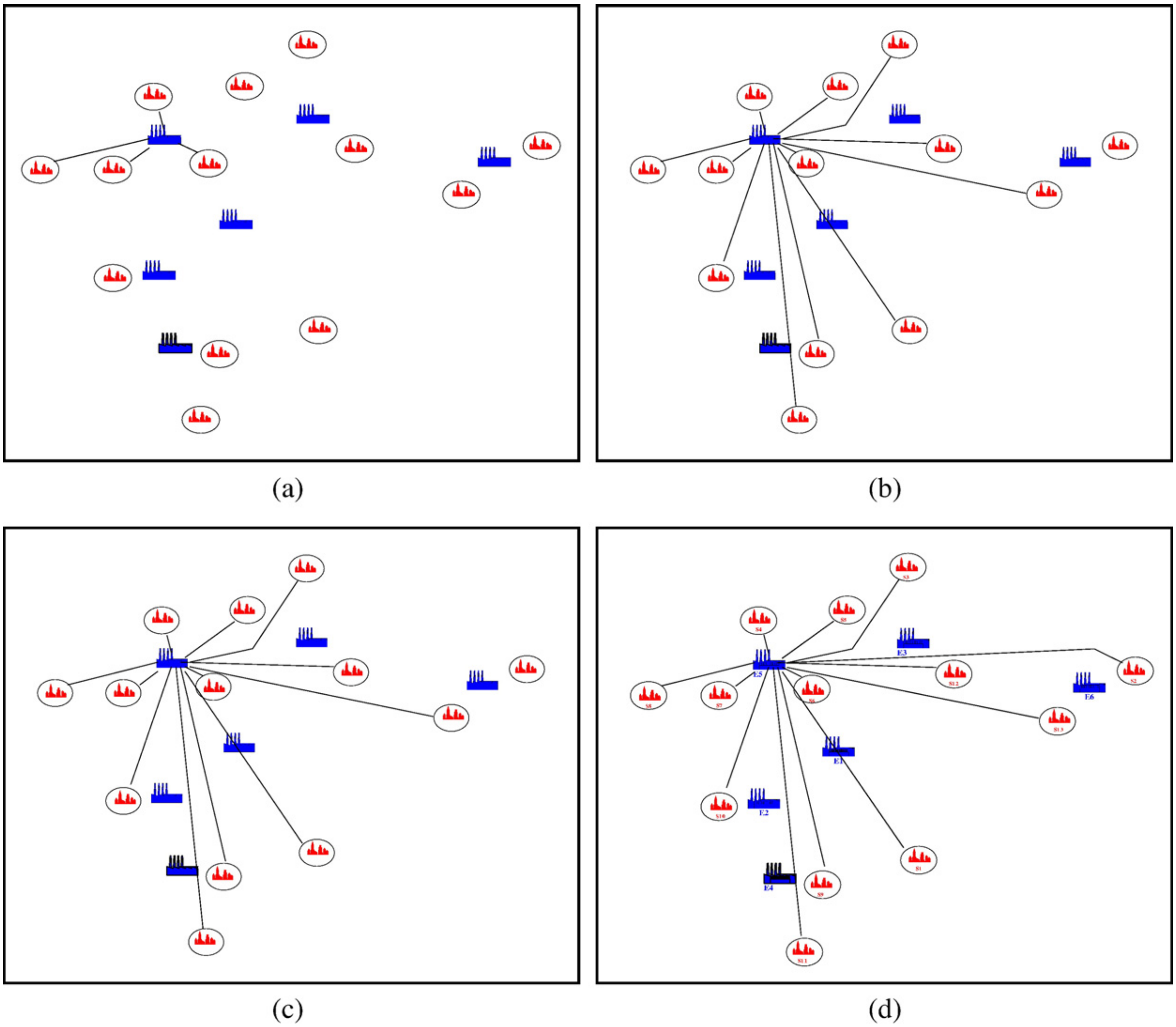

Fig. 6. Effects of variation on weightings to economics and GWP.

production and 356 592 tons of CO_2 equivalent for electricity production) or 43.84% reduction compared to the typical situation. The reduction of GWP is due to the GHGs emission credit from the production of ethanol. The benefit obtained is 1.14 million US$ per year. In cases (b) and (c): the results are similar. All of the excess

Table 5
Results from optimization

Case	W_{GWP}	$W_{economic}$	Total GWP (tons of CO_2 equivalent/year)			Total economics (million US$/year)	Plant size	
			Ethanol production	Electricity production	Total		(tons of bagasse/day)	(L/day)
Typical situation	–	–	0	582 177	582 177	0	0	0
a	0.0	1.0	−29 635	356 592	326 957	−1.14	917.65	138 566
b	0.3	0.7	−59 015	23 000	−36 015	−11.21	2 274.67	343 476
c	0.7	0.3	−59 015	23 000	−36 015	−11.21	2 274.67	343 476
d	1.0	0.0	−60 423	0	−60 423	−11.92	2 368.24	357 604

bagasse from all sugar mills except the sugar mill at node no. 2 (Sahareong sugar mill) should be sent to produce ethanol. The size of the ethanol plant is 2274.67 tons of bagasse per day. The ethanol plants can produce 343 476 L of ethanol per day. The GWP occurrence has become negative — about −36 015 tons of CO_2 equivalent (−59 015 tons of CO_2 equivalent for ethanol production and 23 000 tons of CO_2 equivalent for electricity production) or 106.19% reduction compared to the typical situation. The occurrence of negative GWP is due to the GHGs emission credit from the production of ethanol. The benefit obtained is 11.21 million US$ per year. Case (d) is the best case. All of the excess bagasse from all sugar mills should be sent to produce ethanol. The size of the ethanol plant is 2368.24 tons of bagasse per day. 357 604 L of ethanol can be produced per day. The GWP occurrence, which is due to the GHGs emission credit from the ethanol production only, has become negative — about −60 423 tons of CO_2 equivalent or 110.38% reduction compared to the typical situation. The benefit obtained is 11.92 million US$ per year.

From the results, it can be concluded that the excess bagasse-derived ethanol technology absorbs GHGs from the atmosphere. Although the production of ethanol releases GHGs to the atmosphere, the GHGs emission credit obtained from the ethanol and co-product energy is higher. This is mainly because the produced ethanol displaces the conventional gasoline used in vehicles, hence reducing the GHGs emission due to the production of conventional gasoline. Moreover, the tailpipe GHGs emission from the vehicles using E10 is lower than the tailpipe GHGs emission from the vehicles using conventional gasoline. Furthermore, electricity is also gained from burning ligneous residual left from the ethanol production. Hence the GHGs emission credit is also obtained as it displaces the electricity in the grid. On the other hand, the onsite production of electricity from burning excess bagasse has shown the opposite outcomes since it results in positive GHGs emission. Though the GHGs emission credit is obtained from the electricity generated from burning excess bagasse as it displaces the electricity in the grid, the GHGs emitted from burning excess bagasse itself is far more than the GHGs emission credit. It can also be summarized that the total GWP and the total economics of the system are related in the same direction. Nevertheless, the extent of similar directions and relationships will depend upon the configuration of the network such as the locations of sugar mills, potential ethanol plants and other attributes of the network. Other attributes of the network are the amount of excess bagasse left in sugar mills and the unit cost of several parameters (e.g. gasoline, excess bagasse, electricity, etc.). The optimization results shown in Table 5 may vary on a case to case basis. The purpose of demonstrating the example problems is to show the capabilities of the developed model as a tool for analyzing various management options.

4. Discussion and conclusion

Not only can the excess bagasse be utilized as the renewable fuel source for electricity generation but it is also desirable as the feedstock for the ethanol production. It is concluded from the study that the excess bagasse-derived ethanol technology results in GWP reduction. With the current climate change and oil crisis, when the environmental and economic aspects are concerned, a better choice of using excess bagasse may be to produce ethanol rather than electricity. In this case, there are a number of options and possibilities for excess bagasse utilization and it is not obvious which of them represents the optimal solution. Therefore, the significant technique of multi-objective optimization is necessary, and has been chosen for this work. The tool called "Environmental System Optimization" (ESO) has been developed to assist in deciding for the proper utilization scheme of excess bagasse generated in sugarcane industry in Thailand. ESO comprises the life cycle impact assessment of global warming potential (GWP) and the associated cost followed by the multi-objective optimization. ESO involves the selection of location and size of the ethanol production plants. It also allocates the excess bagasse from each sugar mill to the corresponding ethanol plant and calculates for the benefit on GWP and economics. The GWP and economic criteria are simultaneously taken into account. The GWP objective includes the impact of the emission of all GHGs, especially CO_2, on global warming potential. The economic objective involves cost and benefit. Multi-objective optimization used in ESO provides a more effective approach to environmental system management by offering a number of alternative optimal solutions and enabling decision-makers to identify and choose the best practicable environmental options for excess bagasse utilization in Thailand. A demonstration example for the whole area of North-eastern Thailand is presented to illustrate the advantage of the methodology which may be used and beneficial to the policy maker. It is obvious that the methodology is successfully performed to satisfy both environmental and economic objectives over the whole life cycle of the system.

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