การวิเคราะห์การใช้ประโยชน์จากชานอ้อยส่วนเกินที่เหมาะสมแบบหลายวัตถุประสงค์ โดยมุ่งเน้นผลกระทบต่อภาวะโลกร้อน: กรณีศึกษาสำหรับประเทศไทย

นายบรรชา บุดดาดี

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต
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MULTI-OBJECTIVE OPTIMIZATION MODEL FOR EXCESS BAGASSE UTILIZATION FOCUSING ON GLOBAL WARMING POTENTIAL: A CASE STUDY FOR THAILAND

Mr. Bancha Buddadee

A Dissertation Submitted in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy Program in Environmental Management
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Thesis Title	MULTI-OBJECTIVE OPTIMIZATION MODEL FOR EXCESS BAGASSE UTILIZATION FOCUSING ON GLOBAL WARMING POTENTIAL: A CASE STUDY FOR THAILAND
By	Mr. Bancha Buddadee
Field of Study	Environmental Management
Thesis Advisor	Associate Professor Dr. Wanpen Wirojanagud
Thesis Co-advisor	Dr. Rapeepan Pitakaso

Accepted by the Graduate School, Chulalongkorn University in Partial Fulfillment of the Requirements for the Doctoral Degree

……………………………………………… Dean of the Graduate School
(Assistant Professor M.R. Kalaya Tingsabadh, Ph.D.)

THESIS COMMITTEE

……………………………………………… Chairman
(Manaskorn Rachakornkij, Ph.D.)

W. Wirojanagud
……………………………………………… Thesis Advisor
(Associate Professor Wanpen Wirojanagud, Ph.D.)

……………………………………………… Thesis Co-advisor
(Rapeepan Pitakaso, Ph.D.)

Sompon K.
……………………………………………… Member
(Assistant Professor Somporn Kamolsiripichaiporn, Ph.D.)

……………………………………………… Member
(Associate Professor Nurak Grisdanurak, Ph.D.)

……………………………………………… Member
(Assistant Professor Sompop Sanongraj, Ph.D.)

บรรชา บุดดาดี : การวิเคราะห์การใช้ประโยชน์จากชานอ้อยส่วนเกินที่เหมาะสมแบบหลายวัตถุประสงค์โดยมุ่งเน้นผลกระทบต่อภาวะโลกร้อน: กรณีศึกษาสำหรับประเทศไทย (MULTI-OBJECTIVE OPTIMIZATION MODEL FOR EXCESS BAGASSE UTILIZATION FOCUSING ON GLOBAL WARMING POTENTIAL: A CASE STUDY FOR THAILAND) อ.ที่ปรึกษา: รศ.ดร.วันเพ็ญ วิโรจนกูฏ, อ.ที่ปรึกษาร่วม : ดร.ระพีพันธ์ ปิตาคะโส, 167 หน้า.

วัตถุประสงค์ของการศึกษานี้เพื่อวิเคราะห์ และพัฒนาแบบจำลองทางคณิตศาสตร์ของการหารูปแบบเงื่อนไขที่เหมาะสมของการใช้ประโยชน์จากชานอ้อยที่เกินความต้องการของอุตสาหกรรมน้ำตาลในประเทศไทย โดยพิจารณาข้อดี ข้อเสียทั้งทางด้านสิ่งแวดล้อม และทางด้านเศรษฐศาสตร์ในเวลาเดียวกัน ในการศึกษานี้ได้ทำการวิเคราะห์รูปแบบการใช้ประโยชน์ของชานอ้อยส่วนเกินใน 2 รูปแบบ โดยรูปแบบที่ 1 ซึ่งเป็นรูปแบบที่ดำเนินการในปัจจุบันคือการเผาชานอ้อยส่วนเกินในหม้อต้มเพื่อผลิตไอน้ำ สำหรับใช้ในการผลิตกระแสไฟฟ้าก่อนขายให้แก่การไฟฟ้าฝ่ายผลิตแห่งประเทศไทย ส่วนรูปแบบที่ 2 คือการนำชานอ้อยส่วนเกินไปผ่านกระบวนการหมักเพื่อผลิตเอทานอล และนำเอทานอลที่ได้มาผสมกับน้ำมันแก๊สโซลีนในอัตราส่วนเอทานอล 10 % โดยปริมาตรเพื่อให้ได้น้ำมันแก๊สโซฮอล (E10) และใช้เป็นเชื้อเพลิงสำหรับรถยนต์ สำหรับใช้ทดแทนน้ำมันแก๊สโซลีนที่มีค่าออคเทน 95 แบบจำลองที่พัฒนาขึ้นนี้ถูกตั้งชื่อว่า “Environmental System Optimization” ประกอบด้วยการวิเคราะห์ผลกระทบต่อภาวะโลกร้อนของการใช้ประโยชน์จากชานอ้อยส่วนเกินทั้งสองรูปแบบดังกล่าว การวิเคราะห์หาต้นทุนที่ต้องใช้ และผลประโยชน์ที่ได้รับ โดยการวิเคราะห์ตลอดทั้งวงจรชีวิตของผลิตภัณฑ์ หลังจากนั้นได้ทำการหาความสัมพันธ์ทางคณิตศาสตร์ของตัวแปรทั้งหมดที่เกี่ยวข้อง เพื่อจัดทำแบบจำลองทางคณิตศาสตร์ของระบบ และทำการแก้ปัญหาโดยใช้โปรแกรมคอมพิวเตอร์ในการหาแนวทางที่เหมาะสมสำหรับการใช้ประโยชน์จากชานอ้อยส่วนเกินของอุตสาหกรรมน้ำตาลในประเทศไทย จากการพัฒนาแบบจำลองทางคณิตศาสตร์ และการทดสอบในกรณีตัวอย่างของโรงงานน้ำตาลทั้งหมดที่มีในภาคตะวันออกเฉียงเหนือของประเทศไทยพบว่า แบบจำลองที่พัฒนาสามารถแก้ปัญหาได้อย่างมีประสิทธิภาพโดยสามารถหารูปแบบการใช้ประโยชน์จากชานอ้อยส่วนเกินสำหรับโรงงานน้ำตาลในภาคตะวันออกเฉียงเหนือของประเทศไทยได้ ซึ่งคำตอบที่ได้พบว่าช่วยลดผลกระทบของโลกร้อนได้ และมีความคุ้มค่ากับการลงทุน นอกจากนี้แบบจำลองยังสามารถกำหนดค่าถ่วงน้ำหนักของผลกระทบต่อภาวะโลกร้อนและผลกระทบทางเศรษฐศาสตร์ เพื่อหาค่าความอ่อนไหวของผลกระทบทั้งสองแบบจำลองทางคณิตศาสตร์ที่ได้จากการศึกษานี้ยังสามารถประยุกต์ใช้ในด้านการวางแผนและนโยบายด้านพลังงานและผลกระทบต่อภาวะโลกร้อนสำหรับผู้กำหนดนโยบายได้

สาขาวิชา การจัดการสิ่งแวดล้อม ลายมือชื่อนิสิต....................
ปีการศึกษา 2550 ลายมือชื่ออาจารย์ที่ปรึกษา....................
ลายมือชื่ออาจารย์ที่ปรึกษาร่วม....................

4589699020 : MAJOR ENVIRONMENTAL MANAGEMENT
KEY WORD: BAGASSE / LIFE CYCLE ASSESSMENT (LCA) / MULTI-OBJECTIVE OPTIMIZATION / ETHANOL / GLOBAL WARMING POTENTIAL

BANCHA BUDDADEE : MULTI-OBJECTIVE OPTIMIZATION MODEL FOR EXCESS BAGASSE UTILIZATION FOCUSING ON GLOBAL WARMING POTENTIAL: A CASE STUDY FOR THAILAND. THESIS ADVISOR : ASSOC. PROF. WANPEN WIROJANAGUD, Ph.D., THESIS COADVISOR : RAPEEPAN PITAKASO, PhD., 167 pp.

In this research, a multi-objective optimization model is proposed as a tool to assist in deciding for the proper utilization scheme of excess bagasse produced in sugar 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 the second scenario, excess bagasse is processed for the offsite ethanol production. Ethanol is then blended with 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 facilitate in finding out the optimal proportion of the excess bagasse to be 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 satisfactory outcomes.

Field of study Environmental Management Student's signature ....

Academic year 2007 Advisor's signature W. Wirojanagud

Co-advisor's signature ....

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Finally, I wish to dedicate my dissertation specifically to my parents who have given me both physical and mental health and my wonderful wife for her love, wholehearted understanding, encouragement, and patient support throughout my entire study.

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ABBREVIATIONS AND SYMBOLS

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
CH4GWP	GWP due to processing of by-product methane
CO2GWP	GWP due to CO_2 emitted from ethanol production process
CXET	x coordinate of potential ethanol plant
$CXSM_i$	x coordinate of sugar mill i (i = 1,……,I)
CYET	y coordinate of potential ethanol plant
$CYSM_i$	y coordinate of sugar mill i (i = 1,……,I)
D_{ij}	distance between sugar mill i and ethanol plant j (i = 1,……,I ; j = 1,……,J)
DSGWP	GWP due to production of diesel
E10GWP	offset GWP due to the utilization of produced ethanol as E10 fuel
E10USEGWP	GWP due to tailpipe emission from vehicle using E10
EBCOST	cost of excess bagasse burnt in all sugar mills
EECON	economic effects from the utilization of excess bagasse in scheme 1
EELBFIT	benefit from selling electricity generated from burning of excess bagasse in all sugar mills
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 produced in 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,……,I)

ELGWP1	offset GWP due to the generation of electricity by burning of excess bagasse in all sugar mills
ELGWP2	offset GWP due to the generation of electricity from burning of ligneous residual
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
GASGWP	offset GWP due to tailpipe emission from vehicle using current gasoline fuel
GASPROGWP	offset GWP due to production of current gasoline fuel
LIMEGWP	GWP due to production of lime
N	maximum number of ethanol plant
NH3GWP	GWP due to production of ammonia
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
TGWP1	GWP due to tailpipe emission from the truck with trailer used to transport the excess bagasse
TGWP2	GHGs emission due to the production of diesel consumed in by the truck with trailer used in excess bagasse transportation
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

CHAPTER I

INTRODUCTION

1.1 Motivations

Worldwide economic development tends to increase emissions of greenhouse gases (GHGs). As a developing country, Thailand is expected to be a major contributor on atmospheric carbon dioxide (CO_2) build-up and is potential targets for the deployment of biomass-based technologies in the near future.

Sugar industry is one of the major agro-industries in Thailand. The residual left from the juice extraction of sugarcane is the bagasse which is 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 mill is burnt in boiler to generate high-pressure steam. The major portion of high-pressure steam produced is used in sugar production process. While the excess high-pressure steam is used to drive the power generator in order to produce electricity and sell to the Electricity Generating Authority of Thailand (EGAT). The equivalent amount of bagasse that contributes to electricity is called “excess bagasse”. Figure 1-1 shows a simplified diagram of the typical process of the sugar industry. The amount of the excess bagasse from the sugar mills is usually about 12% of the total bagasse (Payne, 1991).

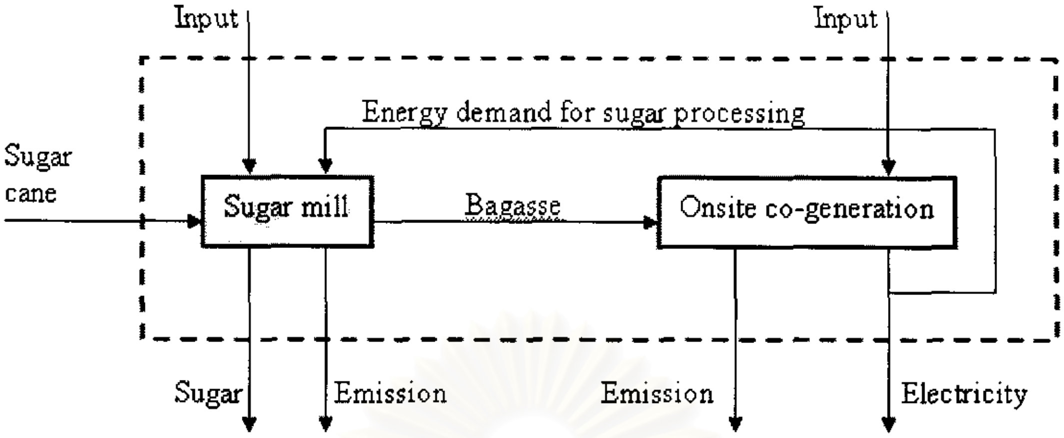


Figure 1-1 Typical processes of the sugar industry.

Several researches have been conducted and shown that bagasse which is lignocellolusic can be utilized not only as renewable fuel source for electricity generation but also as feedstock for ethanol production. The excess bagasse biomass can be utilized in a bioconversion process to produce ethanol. The produced ethanol can then be blended with gasoline to produce E10 which is a blending of 90% of gasoline and 10% of ethanol by volume. E10 is currently used as an alternative fuel for gasoline vehicle in Thailand. With the current climate change and oil crisis, when the environmental and economic aspects are concerned, the production of ethanol instead of electricity from excess bagasse may be a better choice. This statement has been supported by the ongoing energy researches conducted in the United States where the production 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 process design and economic analysis for predicting the cost benefits of lignocellulosic biomass derived ethanol. However, their research did not include the study of the environmental effects. For the progress on environmental study, lignocellulosic biomass derived ethanol has recently been the subject of life cycle analysis (NREL, 1993; Wang et al., 1997; Wang et al., 1998). There are a number of studies estimating the life cycle energy balance of ethanol derived from corn (Morris and Ahmed, 1992; Shapori et al., 1995). Kadam (2002) recently developed environmental life cycle analysis of bagasse-derived ethanol in Mumbai, India. Global warming potential, depletion of natural resources, acidification potential, eutrophication potential, human toxicity potential, and air odor potential were included in the life cycle assessment (LCA). The results showed significant environmental improvement. However, the economic effects have not taken into consideration. The ethanol plant size was not mathematically optimized and the location of ethanol plant was not considered.

1.2 Objectives

The overall objective is to support the development of robust methodology for utilizing the excess bagasse left-over from the sugar industry in Thailand in the most appropriate manner. The sub-objectives are as followed:

1. To determine the global warming potential (GWP), cost and benefit due to the utilization of excess bagasse from sugar industry in Thailand
2. To determine the alternative option for utilization of the excess bagasse from sugar industry in Thailand (bagasse derived fuel ethanol) and its corresponding GWP, cost and benefit.
3. To optimize the most appropriate option for utilization of the excess bagasse left from sugar industry in Thailand considering both advantage and disadvantage on GWP, cost and benefit.

1.4 Scope of Study

The goal of this study is to develop and test a multi-objective optimization model in order to find an appropriate utilization scheme of excess bagasse generated in sugar industry in Thailand. The selection of location and size of the excess bagasse derived ethanol plants, which imply to the portion of excess bagasse from each sugar mill to be burnt on site and the remain excess bagasse from each sugar mill which is needed to be sent to the ethanol plant in order to produce ethanol off site, are taken into account. These selections were done by considering both advantage and disadvantage on GWP and economic parameters. To achieve the goal of this study, the following studies were undertaken.

1. The analysis of the greenhouse gases (GHGs) emission and their impacts of global warming potential (GWP), cost and benefit of the existing operating conditions of the sugar mills in Thailand when the excess bagasse is used

for onsite electricity production using the concept of life cycle impact assessment (LCIA) and life cycle cost analysis respectively.

2. The analysis GHGs emission and their impacts of GWP, cost and benefit which might be occurring if excess bagasse is processed for the offsite ethanol production including its further use in E10 production, using the concept of life cycle impact assessment (LCIA) and life cycle cost analysis respectively.
3. The development of the optimization model in the context of life cycle impact assessment (LCIA) coupled with economic consideration for the utilization of excess bagasse left-over from sugar industry in Thailand.
4. The optimization and testing of the developed optimization model in order to determine the most appropriate option for utilization of the excess bagasse.

1.5 Expected Outcomes

1. The data of life cycle impact assessment on global warming potential and associated cost and benefit of excess bagasse utilization.
2. An optimization methodology to seek the best option for utilizing excess bagasse available in Thailand.
3. A guide for the policy makers in setting up the national strategy for utilization of excess bagasse in Thailand.

CHAPTER II

BACKGROND AND LITERATURE REVIEW

This chapter provides theoretical background and review on sugar industry, bagasse utilization technology, life cycle impact assessment, and multi-objective optimization.

2.1 Sugar industry

The sugar industry is one of the major agro-industries. Sugarcane, the raw material for sugar industry, is currently grown under a wide range of conditions, in tropical and sub-tropical regions. The production of the top 11 sugar-growing countries is shown in Table 2-1.

Table 2-1 Top 11 sugar-growing countries

Production Ranking	Country	Production (tons)
1	Brazil	386,232,000
2	India	290,000,000
3	China	93,900,000
4	Thailand	74,071,952
5	Pakistan	52,055,800
6	Mexico	45,126,500
7	Colombia	36,600,000
8	Australia	36,012,000
9	Cuba	34,700,000
10	USA	31,178,130
11	Philippines	25,835,000
	Total	**1,105,711,382**

From World Alliance for Decentralized Energy, 2004

It can be seen from Table 2-1 that sugar industry in Thailand plays an important role in the global market. Typically, the processes for sugar industry in Thailand are separated into four main steps, namely, cane preparation, milling, clarification-evaporation-crystallization and refining (Therdyothin, 1992). Each step is briefly described as follows.

(1) Cane preparation

The sugarcane stalks transported to the mills by trucks are firstly weighed, then cut into chips by knives before going through the shredder which shreds the sugar cane chips into a fluffy mass.

(2) Millings

The shredded cane chips are fed into a series of mills (generally 2-7 mills) along the mill tandem. More mills result in better extraction of sugar from the cane. Some mills use more than one tandem to increase their milling capacity and flexibility. The juice from the first and second mills, called mixed juice, is fed to the boiling house while the juice from other subsequent mills are fed back into the former mills to make it more concentrated. During the milling process, water is sprayed into fibrous cane to enhance the extraction process. Normally, the weight of juice delivered from milling section is approximately equivalent to the cane crushed. The fibrous residue or bagasse from the milling house is used to produce steam in boilers while the juice passes through the boiling house. The average moisture content of bagasse leaving the milling house is approximately 50% on wet weight basis.

(3) Clarification-Evaporation- Crystallization

In the boiling house, where clarification, evaporation, and crystallization take place, the mixed juice is preheated by steam heaters up to 65°C and its pH is adjusted to 7 by liming. The limed juice is then heated by another set of steam heaters. Steam used in these heaters can be the bleed steam from evaporators or exhaust steam from the milling or generator turbine. A flocculent is added into the boiled limed juice to improve settling and the impurities precipitated from the treated juice are separated as a cane mud in the clarifiers. The clarified juice from clarifiers is heated up before feeding into a series of evaporators. The evaporators can have none or one to two pre-heaters with 4-5 evaporation effects. The fluid delivered from evaporator, called raw syrup, is fed to a vacuum pan for crystallization.

(4) Refining

The raw sugar is mingled with hot concentrated syrup to remove the molasses film surrounding the crystals. After that the mingled syrup, called magma, is spun in the centrifuge and the sugar crystals obtained are washed with hot water. The sugar is then dissolved in hot water. The raw sugar liquor is carbonated by the reaction between lime milk and carbon dioxide. The impurity that is precipitated from carbonated liquor is separated by rotary pressure leaf filters. The filtered liquor is fed to a decolorizing process, boiled in vacuum pans and crystallized after seeding with fine powered sugar crystals. Finally, the refined sugar crystals are dried to eliminate the moisture before packing for sale.

Beside of the revenue obtained from sugar, there are a number of methods for utilizing of the by-products or waste coming from sugar mill that would increase revenues for sugar industry.

(1) Alcohol-fuelled vehicles

Molasses and bagasse left-over from sugar mills can be the raw materials for ethanol production plant. Brazil already encourages the use of alcohol as vehicle fuel. The new promoting programs in France, Mexico, Canada, Sweden, Australia, India, Colombia and China indicate favorable markets for ethanol fuels. The USA is potentially a large market in the future. In country like Thailand, vehicle fuels are blended with bio-ethanol with low proportion (10% by volume).

(2.) Bagasse-based cogeneration

Bagasse is typically use in the co-generation to produce electricity. The expansion of bagasse-based cogeneration nowadays increases the value of electricity exported by sugar mills and consequently increases the revenues for sugar mills.

These programs can also be implemented through the Kyoto Protocol's Clean Development Mechanism (CDM).

2.2 Bagasse Utilization Technologies

2.2.1 Co-generation

The fibrous residue (bagasse) left after the extraction of juice is burned in the boiler for process heat and electricity demand, while the surplus can be used to generate some extra electricity in onsite cogeneration. The process of bagasse cogeneration is shown in Figure 2-1.

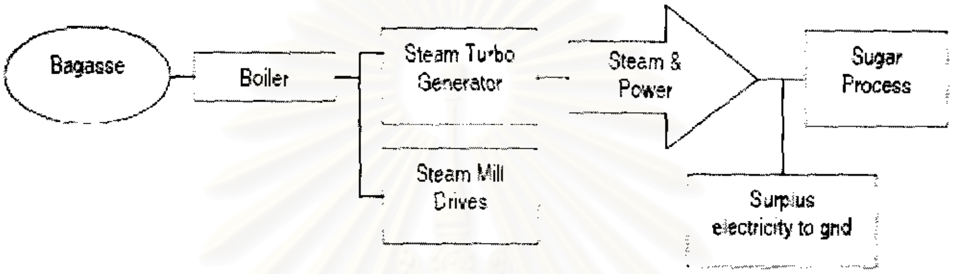


Figure 2-1 Process of bagasse cogeneration

Bagasse cogeneration was pioneered in Mauritius and Hawaii. By 1926-27, 26% of Mauritius' and 10% of Hawaii's electricity generation was from sugar factories (WADE, 2004).

Brazil is the world's largest sugar producer and exporter (Table 2-1). The development of bagasse cogeneration was initially prompted by the 1970s oil crises, when Brazil was highly dependent upon petroleum. Sugar mills were then encouraged to generate electricity for their own consumption. Bagasse cogeneration is being further encouraged through projects qualifying for the Kyoto Protocol's Clean Development Mechanism (CDM). However, with the feed-in tariffs and other policy incentives, producers may find that there are fewer advantages arising from CDM opportunities. Proposals under the CDM may therefore decrease in the future (WADE, 2004).

Indian sugar mills are currently self-sufficient in energy, already using bagasse to meet their steam and power requirements. As only 20-30% of all bagasse is used for these purposes, this suggests that the remaining 2/3 of bagasse is currently being "wasted" as it is being incinerated for disposal purposes rather than energy recovery (Kadam, 2002). Since the early 1990s, in recognition of the advantages of bagasse cogeneration relative to current regimes of centralized generation in India, several governmental, national and international agencies and financial institutions have been acting to promote and develop cogeneration power projects in Indian sugar mills. In addition to its wider benefits, bagasse cogeneration is seen as a potential means of meeting India's renewable energy targets (WADE, 2004).

All of the sugar mills in Thailand use steam turbine in their cogeneration. The system capacity varies from 1 MW in small sugar mills to 25 MW in the large sugar mills. This system can generate electricity higher than what they need to operate the mill (Therdyothin, 1992). The excess electricity is sold to the Electricity Generating Authority of Thailand (EGAT).

2.2.2 Ethanol production

With the current climate change and oil crisis, when the environmental and economic aspects are concerned, the production of ethanol in stead of electricity from an excess bagasse might be a better choice. 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 become more interested and is promoted. Wooley et al. (1999) developed process design and economic analysis for predicting the cost benefits of lignocellulosic biomass derived ethanol. Bagasse, which is lignocellolusic biomass, is not only considered as raw material in cogeneration but could be also considered a valuable feedstock to ethanol production.

The production of ethanol from biomass requires the following basic steps: pretreatment to hydrolyze the hemicellulose, hydrolysis of cellulose to produce glucose, fermentation of sugars to ethanol, and ethanol recovery. There are different process configurations, both enzyme based and nonenzyme based, that can be used to achieve the overall goal. In the nonenzyme based approach, acid is used for both hemicellulose and cellulose hydrolysis, and the mode is separate hydrolysis and fermentation (SHF); both six-carbon (hexoses, i.e., glucose, mannose, and galactose) and five-carbon sugars (pentoses, i.e., xylose and arabinose) are fermented to ethanol. In the enzymatic approach, dilute-acid pretreatment is used to hydrolyze the hemicellulose portion. The saccharification (hydrolysis) of cellulose to cellobiose and eventually to glucose is catalyzed by the synergistic action of cellulase and β-glucosidase enzymes. The mode of operation used is simultaneous saccharification and cofermentation (SSCF); cofermentation refers to the fermentation of both six-carbon and five-carbon sugars to ethanol (Wooley et al., 1999). The following two specific biomass-to-ethanol conversion technologies are currently interested (Kadam, 2000).

2.2.2.1 Enzyme-based process

The flow diagram for the enzyme-based process is shown in Figure 2-2. The enzyme-based process consists of the following basic unit operations.

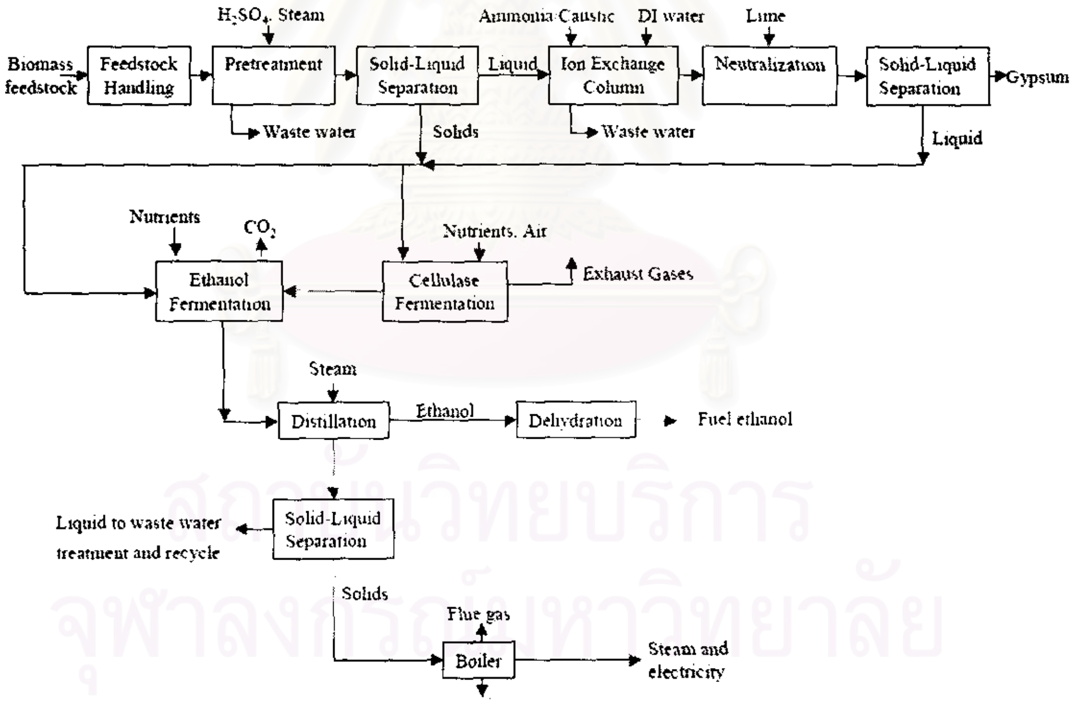


Figure 2-2 Biomass-to-ethanol technologies: enzyme-based process (Kadam, 2000)

(1) Feedstock Preparation and Pretreatment

The biomass is milled to an average size of 15 mm. A screw feeder conveys the biomass from the storage bunker to the acid impregnator. Dilute sulfuric acid and low-pressure steam are also fed to the acid impregnator. The acidic slurry is discharged from the acid impregnator into the pretreatment reactor. High-pressure steam and additional dilute sulfuric acid are fed to the reactor where hemicellulosic sugars are hydrolyzed to their respective monomers and/or oligomers (temperature ranges from 160°.180°C, liquid phase acid concentration ranges from 0.7%.1.0% wt.). The hydrolyzed mash is discharged from the acid hydrolysis reactor into a lower-pressure flash drum where cooling quenches the reactions. The hydrolyzate is separated from the solids in a solid-liquid separation step. The hydrolyzate is then pumped to the neutralization and detoxification tank using continuous ion exchange that employs a weak-base anion resin. The process primarily removes acetic acid and other organic species that could be toxic to the microorganisms used during fermentation. Lime is used to neutralize the detoxified hydrolyzate; the neutralization reaction produces calcium sulfate, which is removed in a solid-liquid separation step. The neutralized hydrolyzate is pumped through a heat exchanger where, using cooling tower water, it is cooled to fermentation temperature. The hydrolyzate and solids from the solid-liquid separation step are then pumped to the ethanol fermentation section.

(2) Cellulase Production

Cellulase production is by *T. reesei* using a slipstream of pretreated biomass as a carbon source. The fermentation is conducted in fed-batch mode at 28°C and pH 5. For a low-cost product such as ethanol, the enzyme need not be processed to any great extent to be useful. Whole broth from cellulase fermentation is actually more effective for the SSCF process. In this process, the whole fermentation broth is used as a source of cellulase enzyme. Because enzyme production is via the fed-batch mode and the SSCF is a continuous process, a surge storage tank is necessary. It is assumed that cellulase production using pretreated bagasse as substrate is feasible.

(3) Fermentation

The SSCF process using cellulase enzymes and a recombinant *Zymomonas mobilis* converts cellulose and five-carbon sugars to ethanol and CO_2. Cellulase catalyzes the hydrolysis of cellulose to glucose. A recombinant xylose-fermenting yeast, recombinant *E. coli* and *Klebsiella oxytoca* are also possible choices. The SSCF operation takes place in continuous anaerobic fermenters. Gravity drives the flow of fermentation broth between fermenters. Fermentation exhaust gases consisting of carbon dioxide and ethanol vapor are sent to the vent scrubber for ethanol recovery. The SSCF broth is pumped to the distillation section.

(4) Distillation and Ethanol Dehydration

Ethanol is separated from the fermentation beer by conventional distillation technology and is dehydrated using molecular sieve technology. The still bottoms are collected and the 99.7% ethanol is sent to fuel storage. The lignin residue is further dewatered in a solid-liquid separation step. The liquid stream is sent to wastewater treatment and the recycle loop.

(5) Ligneous Residue

The dewatered ligneous residue is burned on-site to cogenerate steam and electricity that can be used by the process. Excess electricity is generated, which can be sold to the grid.

2.2.2.2 Two-Stage Dilute Acid Process

The flow diagram for the two-stage dilute acid process is shown in Figure 2-3. The enzyme-based process consists of the following basic unit operations.

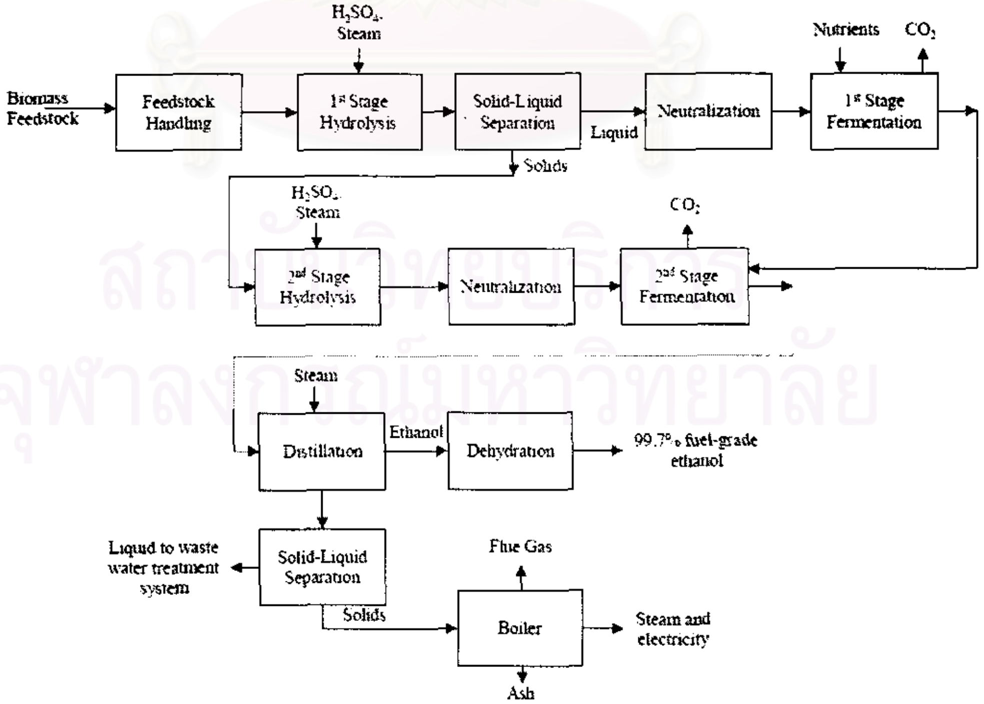


Figure 2-3 Biomass-to-ethanol technologies: two-stage dilute acid process (Kadam, 2000)

(1) First-Stage Hydrolysis

Prior to acid hydrolysis, the biomass is milled to an average size of 15 mm. The feedstock is then mixed with dilute sulfuric acid at a concentration of 0.70% and soaked at 50°C for 3 hours. In the first hydrolysis, the acid-impregnated biomass is heated to 180°.185°C for 3-5 minutes in a digester (hydrolyzer) to hydrolyze the hemicellulose; some cellulose hydrolysis also takes place in this step. The resulting slurry is pressed to obtain a liquid stream, which is sent to neutralization. Residual acid in the sugar stream is neutralized by adding lime, which forms a gypsum precipitate. Gypsum is removed in a solid-liquid separation step. The liquid stream is sent to first-stage fermentation.

(2) Second-Stage Hydrolysis

The solids remaining after the first hydrolysis and solid-liquid separation are again acid-impregnated at the same conditions. In the second hydrolysis step, acid-impregnated material is heated for 3-5 minutes at 200°.210°C to effect further cellulose hydrolysis. The resulting slurry is neutralized by adding lime. This stream is sent to second-stage fermentation without separating out the gypsum.

(3) Fermentation

A recombinant *Z. mobilis* is used to ferment both six-carbon and five-carbon sugars to ethanol and CO_2. (A recombinant xylose-fermenting yeast, rDNA *E. coli* or *K. oxytoca* can also be used.) First- and second-stage fermentations are carried out in continuous, anaerobic fermenters. The flow of fermentation broth between fermenters is facilitated by gravity. Fermentation off gases, containing mostly CO_2 and ethanol vapor, are sent to the vent scrubber for ethanol recovery. The fermentation broth is sent to the distillation section.

(4) Distillation and Ethanol Dehydration

Ethanol is separated from the fermentation beer by conventional distillation technology and is dehydrated with molecular sieve technology. The 99.7% ethanol is sent to fuel storage. The lignin residue is further dewatered in a solid-liquid separation step. The liquid stream is sent to wastewater treatment and the recycle loop.

(5) Ligneous Residue

The dewatered ligneous residue, containing mostly lignin and cellulose, is burned on-site to cogenerate steam and electricity that can be used by the process. The net electricity produced is sold to the grid.

In term of ethanol produced per unit mass of bagasse, the first biomass-to-ethanol conversion technology (enzyme-based process) is a more efficient technology (Kadam, 2000) and is selected for this research. The ethanol produced the biomass-to-ethanol conversion technologies can be further blended with gasoline or diesel and used as energy source for vehicles.

2.3 Life Cycle Assessment (LCA) and Life Cycle Impact Assessment (LCIA)

Life Cycle Assessment (LCA) is an environmental management tool that enables quantification of environmental burdens and their potential impacts over the whole life cycle of a product, process or activity from extraction to final disposal including manufacture, transport, use, reuse, recycle, maintenance and ultimate disposal (Figure 2-4).

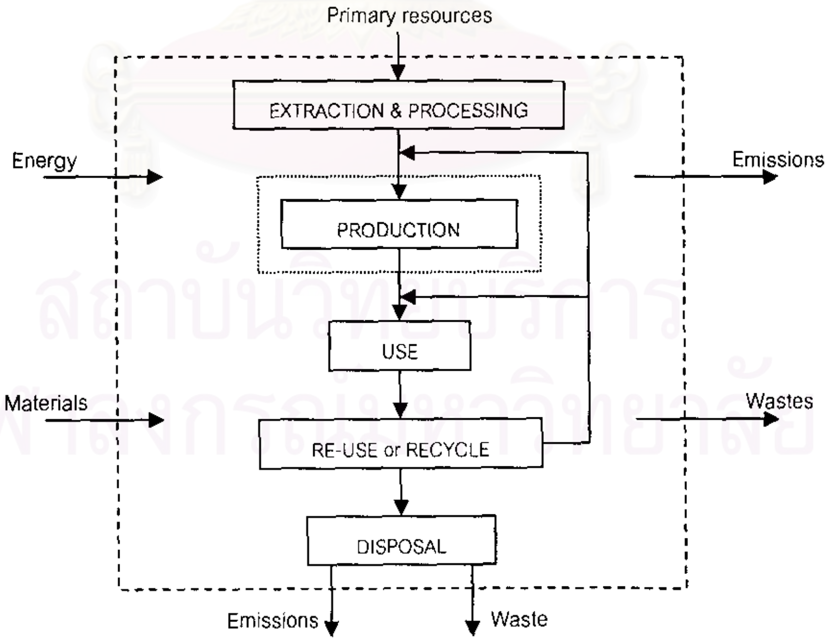


Figure 2-4 Stages in the life cycle of product (Azapagic, 1999)

LCA originated from "net energy analysis" studies in the 1970s. Some later studies included wastes and emissions. In 1990, the Society for Environmental Toxicology and Chemistry (SETAC) initiated activities to define LCA and develop a general methodology for conducting LCA studies. This methodology is widely accepted among LCA practitioners. The methodological framework for conducting LCA, as defined by SETAC, comprises 4 main interacting phases (Figure 2-5) which are:

(1) Goal definition and scooping,
(2) Inventory analysis,
(3) Impact assessment, and
(4) Improvement assessment.

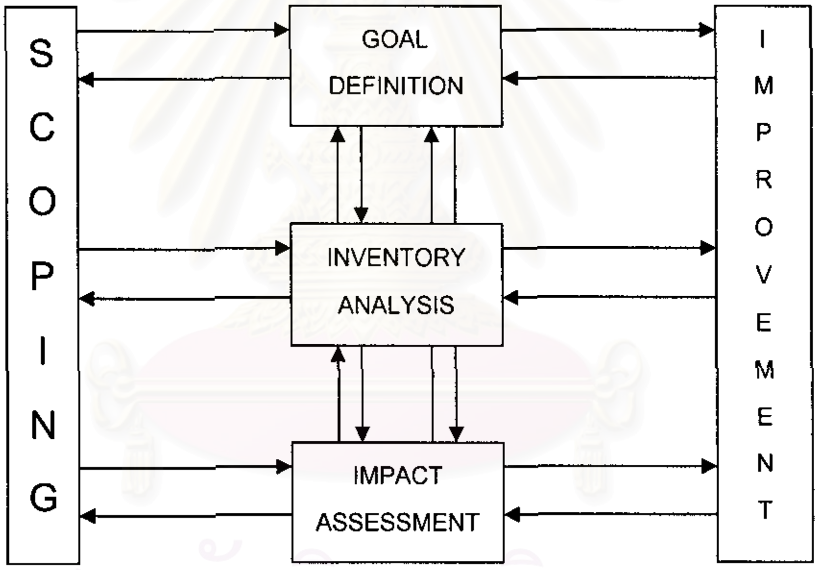


Figure 2-5 Interactions between LCA stages (Fava et al.,1991)

The life cycle impact assessment (LCIA) is the third among the four steps in LCA and is therefore the subset of LCA. To conduct the LCIA, a complete set of life cycle inventory (LCI) for the entire life cycle of a product, process and activity is required.

2.4 Multi-objective optimization (MO)

Optimization techniques have been available for over 50 years. Nowadays, optimization technology has become a key tool in making important business decisions that can increase competitive advantage. The optimization technique refers to the study of problems in which one seeks to minimize or maximize a real function by systematically choosing the values of real or integer variables from within an allowed set. Optimization begins with the development of a model that defines the problem and its parameters. Each parameter is represented as a "variable," while the relationships between business or process conditions are formulated as "constraints" and the desired "objective" (such as, to maximize profitability) is imposed. This is called model formulation process which is necessary for every optimization problem. For the complex problem, the model can be processed using "solver" which is a software that has at its core, highly sophisticated algorithms adept at intelligently sorting through huge amounts of data and analyzing possible approaches to come up with an optimized solution.

Traditionally, system optimization in engineering applications has focused on maximizing the economic objectives. Over the past 10 years, considerations for improving the environmental performance have been integrated into system optimization alongside economic criteria. More recently, life cycle thinking has been incorporated into the process design and optimization procedures (Azapagic and Clift, 1999). These developments are still underway and the published literature on this subject is quite limited. The optimization problem in the context of LCIA is beyond the conventional optimization model that in addition to an economic function, it involves environmental objectives and impacts. Thus, a single objective optimization problem is transformed into a multi-objective one. The system is optimized simultaneously on both economic and environmental performance, subject to certain constraints encompassing all activities from cradle to grave. This results in a number of optimum solutions for system improvements. By definition, none of the objectives can be improved without worsening the value of any other objective function. Therefore, some trade-offs between objective functions are necessary in order to reach a preferred optimum solution in a given situation.

In general, a multi-objective optimization (MO) problem of a system formulated in the LCIA context can take the following form.

$$
\begin{aligned}
\text{Minimize} \quad & f(x,y) = [f_1\ f_2 \ldots fp] \\
\text{Subject to:} \quad & h(x,y) = 0 \\
& g(x,y) \leq 0 \\
& x \in X \subseteq R^n \\
& y \in Y \subseteq Z^q
\end{aligned}
$$

where f is a vector of economic and environmental objective functions; $h(x,y) = 0$ and $g(x,y) \leq 0$ are equality and inequality constraints, and x and y are the vectors of continuous and integer variables, respectively.

An economic objective typically involves a cost or profit function as defined by:

$$\text{Minimize} \quad F = cy + f(x)$$

where c is a vector of cost or profit coefficients for integer variables (y and etc.) and f(x) is a linear or non-linear function related to continuous variables.

The environmental objectives in this context represent the impacts E_k.

$$\text{Minimize} \quad E_k = \sum_{n=1}^{N} ec_{k,j} B_j$$

where $ec_{k,j}$ represents the relative contribution of burden B_j to impact E_k (Azapagic and Clift, 1999).

CHAPTER III

MATERIALS AND METHODOLOGY

3.1 Life Cycle Impact Assessment Index: Global warming potential.

The Greenhouse potential refers to the ability of some atmospheric gases to retain heat that is radiating from the earth. Models have been developed to quantify the contribution made by emissions of various substances to the greenhouse potential. Generally these models provide an indication of the change in the heat radiation absorption of the atmosphere. Global warming potentials (GWPs) have been calculated to compare the emission of different greenhouse gases (IPCC 1994).

The overall result of emission of these gases on the Greenhouse Potential (E) is calculated as follows:

$$E = \sum GWP_i * m_i$$

where; for a greenhouse gas *i*,
m_i: the mass of the gas released (in kg),
GWP_i: its potential impact on global warming expressed in kg of CO_2 equivalent.

The following factors are used to calculate the greenhouse potential for various GHGs (Table 3-1).

Table 3-1 Greenhouse gas potential factors

Substance	unit	GWP_i
1,1,1-trichloroethane	kg	110
Carbon dioxide	kg	1
CFC-11	kg	4,000
CFC-113	kg	5,000
CFC-114	kg	9,300
CFC-115	kg	9,300
CFC-12	kg	8,500
CFC-13	kg	11,700
Dichloromethane	kg	9
Dinitrogen oxide	kg	310
HALON-1301	kg	5,600
HCFC-123	kg	93
HCFC-124	kg	480
HCFC-141b	kg	630
HCFC-142b	kg	2,000
HCFC-22	kg	1,700
HCFC-225ca	kg	170
HCFC-225cb	kg	530
HFC-125	kg	2,800
HFC-134	kg	1,000
HFC-134a	kg	1,300
HFC-143	kg	300
HFC-143a	kg	3,800
HFC-152a	kg	140
HFC-227ea	kg	2,900
HFC-23	kg	11,700
HFC-236fa	kg	6,300
HFC-245ca	kg	560
HFC-32	kg	650
HFC-41	kg	150

HFC-43-10mee	kg	1,300
Methane	kg	21
Perfluorobutane	kg	7,000
Perfluorocyclobutane	kg	8,700
Perfluoroethane	kg	9,200
Perfluorohexane	kg	7,400
Perfluoromethane	kg	6,500
Perfluoropentane	kg	7,500
Perfluoropropane	kg	7,000
Sulphur hexafluoride	kg	23,900
Tetrachloromethane	kg	1,400
Trichloromethane	kg	4

3.2 Functional Unit

The equivalency of both fuel types is calculated with their heating value. Data from calculation shown that 0.10125 L of ethanol mixed with 0.91125 L gasoline (1.0125 L of E10 blend) is equivalent to 1 L of current gasoline fuel (an octane rated 95 gasoline). The detail of the calculation of equivalency of E10 blend and current gasoline fuel is shown in Table 3-2.

Table 3-2 Equivalency between current gasoline fuel and E10 blend

Parameter	Unit	Current gasoline fuel	E10 blend
Heating value	MJ/L	33.86	33.45
Density	kg/L	0.737	0.742
Volume fraction of ethanol	%	0	10
Volume fraction of gasoline	%	100	90
Volume to achieve 33.86 MJ	L	1	1.0125

Equivalency: 1.0125 L of E10 equivalent to 1 L current gasoline fuel

3.3 Life Cycle Modeling

3.3.1 General Bagasse Data

Due to the lack on bagasse composition in Thailand, data taken from reliable sources are taken. The moisture of the bagasse is 50 %. The element analysis for bagasse is shown in Table 3-3 (Payne, 1991). Data on bagasse composition, both from the literature (Johnson et al. 1992) and NREL laboratory are provided in Table 3-4. Both sets of data agree quite well with each other. Johnson et al. (1992) also studied the changes in bagasse composition due to storage; their data does not predict significant sugar loss. Thus, in this analysis no change in bagasse composition upon storage is assumed.

Table 3-3 Elemental analysis for bagasse

Parameter	Value (dry basis)
Carbon	48.8 %
Hydrogen	6.2 %
Oxygen (by different)	45.0 %
Total	100 %

Table 3-4 Data on bagasse composition

Feedstock Component	Johnson et al. (1992) Dry wt %	NREL analysis Dry wt %
Glucan	41.0	40.6
Galactan	0.5	0.8
Mannan	0.4	0.2
Xylan	23.2	20.0
Arabinan	2.2	1.7
Lignin	24.3	25.5
Extractives	3.8	1.8
Ash	2.6	3.7
Uronic acids	2.3	5.7
Total	**100.3**	**100.0**

3.3.2 Data Summary for Bagasse-to-Ethanol Processes

The enzymatic based process is selected for ethanol production because it is considered a better technology over the two stage dilute–acid process. The estimates of inputs and outputs for the bagasse derived ethanol process simulated by NREL are performed based on 1 kg of dry bagasse (Kadam, 2000). The estimate of inputs and output adapted from NREL simulation for 1 ton of bagasse with 50 % moisture content are reported in Table 3-5. The CO_2 listed in Table 3-5 includes emission from burning ligneous residual.

Table 3-5 Data summary for bagasse-to-ethanol processes (Enzyme-based process)

Environmental flows	Value	Unit
Inputs		
Biomass	500.0	(kg/ton bagasse)
Lime	4.5	(kg/ton bagasse)
Water	983.0	(kg/ton bagasse)
NH3	14.0	(kg/ton bagasse)
Diesel	2.5	(L/ton bagasse)
H_2SO_4	22.0	(kg/ton bagasse)
Outputs		
Ethanol	150.8	(L /ton bagasse)
Gypsum	12.5	(kg/ton bagasse)
Ash	20.0	(kg/ton bagasse)
Ligneous residue	222.0	(kg/ton bagasse)
Biogas methane	7.5	(kg/ton bagasse)
Total CO_2	585.0	(kg/ton bagasse)
Net electricity	119.3	(kwh/ ton bagasse)

Adapted from Kadam, 2000

3.4 Life Cycle Impact Assessment Software

The software used for facilitating the life cycle impact assessment of global warming potential is SimaProV7.1 software developed by Pre Consultants, The Netherlands. This software is one of the most popular software. It has been widely used and accepted worldwide. It consists of the numbers of database. It is considered a user friendly software.

3.5 Optimization Software

The software chosen for solving the illustrative example is LINGO V4.0 developed by LINDO systems Inc, USA. This software is a simple tool for performing complex and powerful tasks. The software can solve both linear programming and non-linear programming. Moreover, there are several examples for modeling diversity of the cases e.g. linear programming, non-linear programming, quadratic programming, probabilistic programming and others.

3.6 Methodology

The general framework for this study is divided into 4 consecutive steps. This concept is called "Environmental System Optimization" (ESO) in this thesis. The details of each step are described as follows. Figure 3-1 represents the diagram of the overall study.

1. The analysis of the greenhouse gases (GHGs) emission and their impacts to global warming potential (GWP) generated from the existing operating conditions of the sugar mills in Thailand when the excess bagasse is used for onsite electricity onsite and the proposed operation condition when excess bagasse is processed for the offsite ethanol production. The ethanol is blended with the gasoline by a portion of 10% and 90% by volume respectively and the mixture is used as alternative fuel for gasoline vehicles in Thailand following the concept of life cycle impact assessment (LCIA).
2. The analysis of the cost and benefit associated of the existing operating conditions of the sugar mills in Thailand when the excess bagasse is used for onsite electricity onsite and the proposed operating condition when excess bagasse is processed for the offsite ethanol production. The ethanol is blended with the gasoline by a portion of 10% and 90% by volume respectively and the mixture is used as alternative fuel for gasoline vehicles in Thailand following the concept of life cycle cost analysis (LCC).

3. The development of the optimization model in context of life cycle impact assessment (LCIA) coupled with economic consideration for the utilization of excess bagasse left-over from sugar industry in Thailand.
4. The optimization and test the developed optimization model in order to determine the most appropriate option for utilization of the excess bagasse.

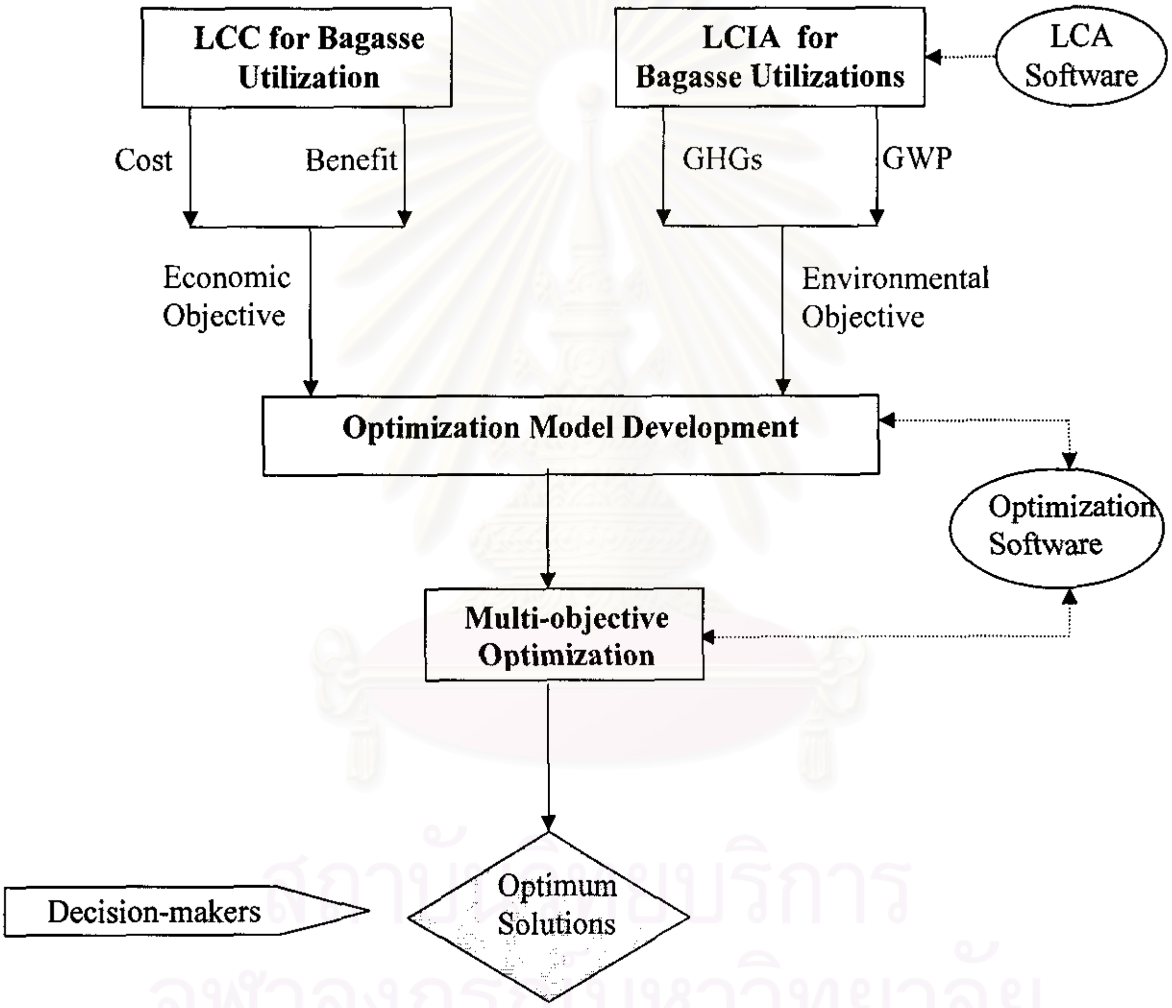


Figure 3-1 Study methodological framework

CHAPTER IV

RESULTS AND DISCUSSIONS

The structure of the studied model is categorized as shown in Figure 4-1 and the flow scheme for the excess bagasse utilization and management system is schematically shown in Figure 4-2. It is shown in the model that the excess bagasse coming from each sugar mill can be utilized in 3 schemes (Figure 4-1). First, the excess bagasse is 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 sugar 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 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 problem is rather complicated and the multi-objective optimization is chosen to assist in solving this problem. To achieve the goal of the study, the analysis of GWP of the two scenarios of bagasse utilization, the cost and benefit analysis of the first two schemes of bagasse utilization and the development and testing of a multi-objective optimization model which facilitate in finding out the optimal proportion of the excess bagasse to be utilized in each scenario have to be explored. The following sections discuss the details of all analyses.

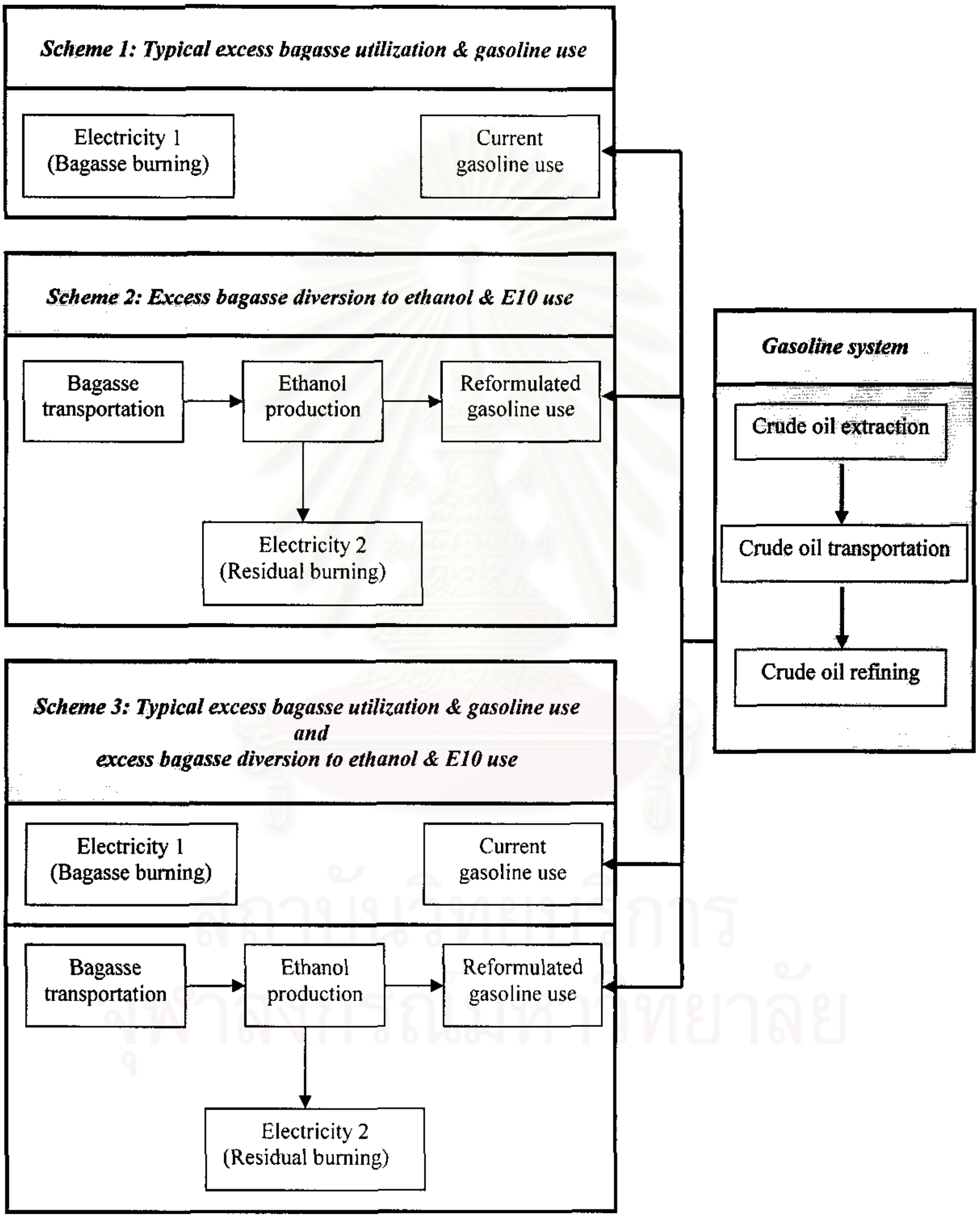


Fig. 4-1 Structure of the studied model (adapted from Kadam, 2000).

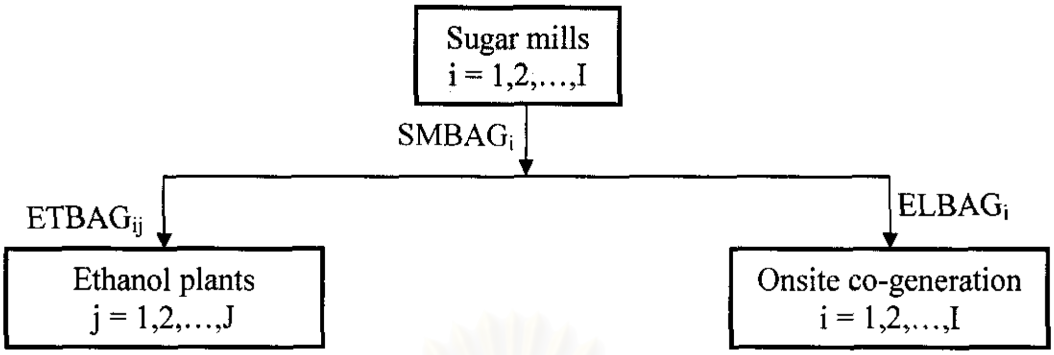


Fig. 4-2 Excess bagasse utilization and management system for sugar mills.

4.1 Life Cycle Impact Assessment of Global Warming Potential

The Greenhouse potential refers to the ability of some atmospheric gases to retain heat that is radiating from the earth. Models have been developed to quantify the contribution made by emissions of various substances to the greenhouse potential. Generally these models provide an indication of the change in the heat radiation absorption of the atmosphere. Global warming potential (GWP) has been calculated and 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.

The objective of the life cycle impact assessment (LCIA) is to quantify the GWP for the utilization of the excess bagasse generated from sugar industry by both scheme 1 and scheme 2 (Figure 4-1).

During the analysis, however, it should be concerned that the burning of bagasse to generate electricity deducts the chance to reduce the gasoline used in the transportation system. In analyzing the GWP of each bagasse utilization scheme, this factor is taken into consideration. The software chosen for facilitating in analysis and quantification of the emission factors of most processes is SIMA Pro V 7.1 developed by Pre Consultants. The results including the descriptions of each process in both two major bagasse utilization scenarios are discussed and explained in the next section.

4.1.1 Life Cycle Impact Assessment of Global Warming Potential for Bagasse Utilization in Scheme 1

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. There are 2 types of GWP involved. One is the GWP according to GHGs emitted in burning excess bagasse onsite in industrial boiler to generate electricity. The other is the offset GWP due to electricity production.

4.1.1.1 GHGs Emission from Bagasse Burning Process

By burning of excess bagasse in the industrial boiler to produce steam and subsequently produce electricity, CO_2 is emitted to atmosphere from this process. The moisture content in the excess bagasse is 50%. The carbon content in the dry excess bagasse is 48.8% (Payne, 1991). The formation of carbon dioxide between carbon contained in bagasse and oxygen containing in air during burning process is modeled according to the following reactions:

$$\begin{array}{lllllll} C & + & O_2 & \rightarrow & CO_2 & & \\ 12 & & 32 & & 44 & & \text{(kg/kmole)} \end{array}$$

From the above reaction, its calculation shows that 0.894 kg of CO_2 per kg of excess bagasse would be released to atmosphere as written below.

Carbon content in dry excess bagasse	48.8	%
Moisture content in the excess bagasse	50	%
1 kg of carbon result in	44/12 = 3.67 kg of CO_2	
1 kg of dry excess bagasse result in	3.67 x 0.488 = 1.788 kg of CO_2	
1 kg of excess bagasse result in	50% x 1.788 = 0.894 kg of CO_2	

4.1.1.2 Offset GWP due to electricity production

Presently the excess bagasse has been used for generating electricity onsite. The amount of electricity that can be generated from burning of bagasse based on data taken from Therdyothin, 1992 is shown below;

Specific steam production is	2.1	kg/kg of excess bagasse (Payne, 1991)
Specific steam consumption	10	kg/ kWh
Therefore, electricity production	0.21	kWh/kg of excess bagasse
Or	210	kWh/ton of excess bagasse

This amount of electricity produced would reduce the need of electricity generated from conventional technology practicing in Thailand. Therefore, reduction of GWP due to the equivalent amount of electricity generated from conventional technology practicing in Thailand called offset GWP is obtained.

In Thailand, the electricity is approximately generated by three types of conventional technologies. These technologies are hydro power plant, lignite power plant and combined power plant (gas and steam power plant). The fraction of electricity generated from each technology is summarized in Table 4-1.

Table 4-1 Fraction of electricity generated from conventional technology

Technology	Fraction
Hydro power plant	10%
Lignite power plant	53%
Combined power plant	37%
Total	100%

From EGAT, 2005

The GHGs emission due to the generation of electricity from each technology is described below.

(1.) Hydro power plant

Water storage power plants consist of a reservoir, a tunnel including a pressure line and a power house. Water storage power plants may produce intermittently according to the fluctuating demand (either within the day or the year). The inventory table indicates the GHGs per 1 TJ of electricity produced. The effect of construction of dams, tunnels, turbines and generators, the operation of the power plants and their dismantling are included in the analysis.

Table 4-2 GHGs emission inventory for production of 1 TJ of electricity by hydro power plant

Emissions to air	**kg**	**kg CO_2 eq.**
CFC-11	0.00000176	0.00704
CFC-114	0.0000464	0.43152
CFC-12	0.000000378	0.003213
CFC-13	0.000000237	0.0027729
CO_2	1114	1114
Dichloromethane	0.000000817	0.000007353
HALON-1301	0.0000272	0.15232
HCFC-22	0.000000416	0.0007072
HFC-134a	4.26E-17	5.538E-14
Methane	2.61645	54.94545
N_2O	0.01629	5.0499
Tetrachloromethane	0.00000158	0.002212
Trichloromethane	0.000000162	0.000000648
	TOTAL	**1,174.60**

(2.) Lignite power plant

The average lignite and hard coal power plant is calculated. For energy efficiency, the share of installed abatement technology, the amount of ashes, and the emission of airborne pollutants (including radionuclide), country-specific information or coal-specific composition information is used. Flue gas treatment is modeled per kg abated SO_X and NO_X, respectively. The construction of the power plant, land use, the operation of the cooling equipment and water-borne pollutants are included. The inventory table indicates the GHGs per 1 TJ of electricity produced.

Table 4-3 GHGs emission inventory for production of 1 TJ of electricity by lignite power plant

Emissions to air	kg	kg CO_2 eq.
CFC-11	0.00003	0.12
CFC-114	0.000793	7.3749
CFC-12	0.00000645	0.054825
CFC-13	0.00000405	0.047385
CO_2	370979	370979
Dichloromethane	0.00018	0.00162
HALON-1301	0.000186	1.0416
HCFC-22	0.00000706	0.012002
HFC-134a	4.21E-17	5.473E-14
Methane	31.49704	661.43784
N_2O	1.84632	572.3592
Tetrachloromethane	0.0000348	0.04872
Trichloromethane	0.000000562	0.000002248
	TOTAL	**372,221.50**

(3.) Combined power plant

Combined cycle plants have both a gas turbine fired by natural gas, and a steam boiler connected with steam turbine which use the exhaust gas from the gas turbine to produce electricity. High-pressure gas pipelines directly supply the fuel used. Working material requirements and waterborne emissions of the cooling circulation are included. Inventory of natural gas includes natural gas exploration, production, purification, long distance transportation, regional distribution and local supply. The construction of the power plant, land use, the operation of the cooling equipment and water-borne pollutants are included. The inventory table indicates the GHGs per 1 TJ of electricity produced.

Table 4-4 GHGs emission inventory for production of 1 TJ of electricity by combined power plant

Emissions to air	kg	kg CO_2 eq.
CFC-11	0.00000579	0.02316
CFC-114	0.000153	1.4229
CFC-12	0.00000125	0.010625
CFC-13	0.000000782	0.0091494
CO_2	245831	245831
Dichloromethane	0.0000815	0.0007335
HALON-1301	0.000488	2.7328
HCFC-22	0.00000138	0.002346
HFC-134a	-2.85E-15	-3.705E-12
Methane	373.7197	7848.1137
N_2O	1.49689	464.0359
Tetrachloromethane	0.0000213	0.02982
Trichloromethane	0.000000872	0.000003488
	TOTAL	**254,147.38**

Finally, the analysis of the offset GWP can be calculated and summarized in Table 4-5.

Table 4-5 Offset GWP due to electricity production

Technology	Fraction	GHGs emission		
	(I)	kg CO_2 eq. / TJ	kg CO_2 eq. / kWh (E)	I * E (kg CO_2 eq.)
Hydro power plant	10%	1,174.60	0.0042285	0.00
Lignite power plant	53%	372,221.50	1.3399974	0.71
Combined power plant	37%	254,147.38	0.9149306	0.34
AVG.(kg CO2 eq / kW-H)				**1.05**

4.1.2 Life Cycle Impact Assessment of Global Warming Potential for Bagasse Utilization in Scheme 2

Bagasse can be considered a valuable feedstock to ethanol production. Basically, the production of ethanol from biomass requires several steps Figure 4-3. The ethanol produced can be further blended with gasoline or diesel and used as energy source for vehicles (Kadam, 2002). This technology is pertinent to the Thailand scene because it can:

(1.) reduce the net emissions of carbon dioxide when used as an oxygenate additive to gasoline

(2.) spur rural economic development, and

(3.) improve the country.s energy security by reducing its reliance on foreign oil and associated risks.

This section analyses GWP due to bagasse-derived fuel ethanol technology in Thailand. There are several sub-processes included in the analysis. The explanation and analysis for each sub-process involved is discussed as follows.

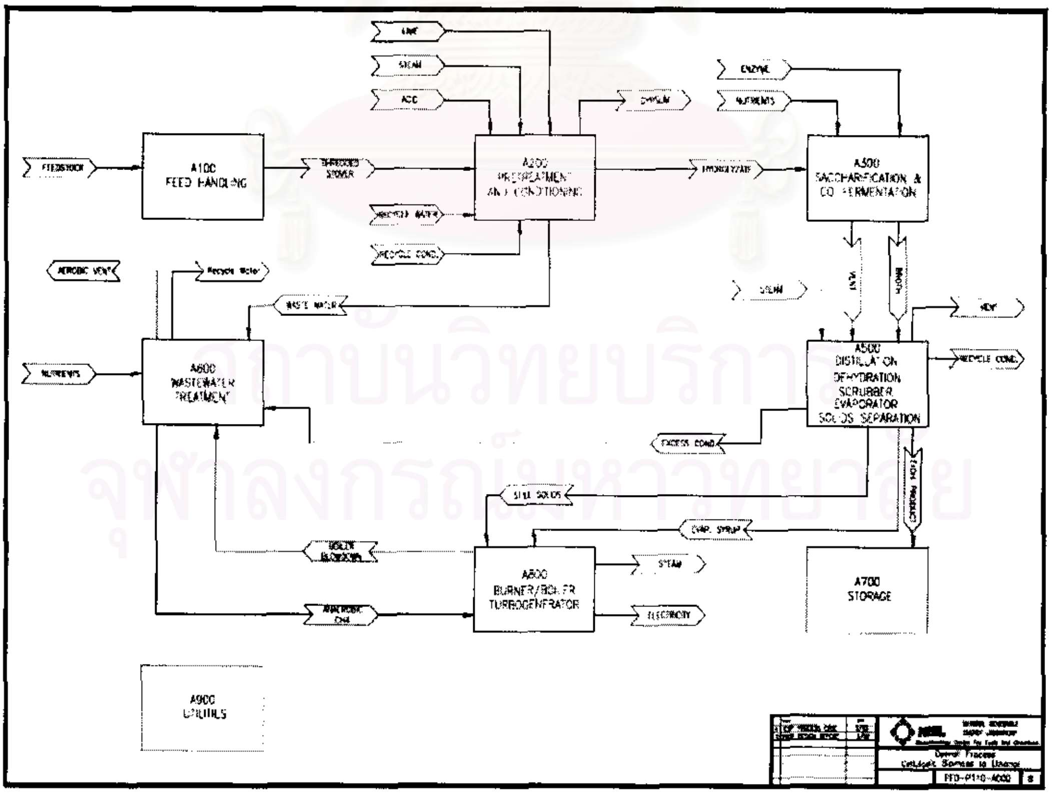


Figure 4-3 Ethanol production process (Aden et al., 2002)

4.1.2.1 Bagasse Transportation

The transportation of excess bagasse from sugar mills to the potential ethanol plant is performed by 10 wheels truck with trailer (dimension of each cabin 5.5(W) x 2.3(L) x 2.5(H) m^3). In the bagasse transportation, there are 2 factors included in the analysis. These factors are the tailpipe emission from the truck with trailer and the GHGs emission due to the production of diesel consumed during transportation.

4.1.2.1.1 Tailpipe emission

All trucks use diesel fuel as energy source. It is assume in the model that the average speed of truck of 60 km/hr. At this speed, the tailpipe GHGs emission is 0.075 kg CO_2 eq. per ton-km. (Japan Transport Cooperation Association, 2004).

4.1.2.1.2 Diesel Consumed

At the average speed of 60 km/hr, the diesel consumption of the truck is about 6 km./L (Japan Transport Cooperation Association, 2004). The quantification of GHGs emitted due to the production of diesel consumed in the bagasse transportation is relatively complex. There are 4 sub processes to be included. These are crude oil extraction, crude oil transportation, crude oil refining for producing diesel and diesel stock. It should be note that the crude oil refined in the petroleum refineries produce a number of different products. However, this section is only concerned with diesel. Therefore, the method of allocating total GHGs emissions to only the proportion of only diesel produced is considered. The allocation procedure used in this section is to allocate total GHGs releases among the products on a mass output basis. The data of a generic U.S refinery is used because it is consider being the most complete among other sources. It is reported that the mass fraction of diesel coming from all refineries is 22.17 % (Kadam et al., 1999). The description including the quantification for these 4 sub processes are summarized below.

(1.) Crude Oil Extraction

The analysis for GHGs emitted from crude oil extraction includes oil field exploration and crude oil production. For oil field exploration, the efforts needed for and the emissions caused by drilling activities are considered. For crude oil production, the variation in drilling efforts and energy consumption per mass of crude oil extracted between different region is modeled. Table 4-6 shows the GHGs emitted per 1 tons of crude oil extracted.

Table 4-6 GHGs emission inventory for extraction 1 ton of crude oil

Emissions to air	**Kg**	**kg CO_2 eq.**
CFC-11	5.37E-08	0.0002148
CFC-114	0.00000142	0.013206
CFC-12	1.15E-08	8500
CFC-13	7.25E-09	0.000084825
CO_2	236.08	236.08
Dichloromethane	1.56E-08	1.404E-07
HALON-1301	0.000412	2.3072
HCFC-22	0.000000013	0.0000221
HFC-134a	5.43E-19	7.059E-16
Methane	3.940819	82.757199
N_2O	0.00592	1.8352
Tetrachloromethane	0.000000165	0.000231
Trichloromethane	1.82E-08	7.28E-08
	TOTAL	**8,822.99**

(2.) Crude Oil Transportation

Transportation of crude oil from Middle Eastern oil producing countries to Thailand is considered. The mode of transportation is done by foreign tanker. Typically there are two types of engine technology used to drive the foreign tanker which are diesel fuel engines and steam turbine using bunker oil. The foreign tanker driven by steam turbine using bunker oil is modeled because this technology accounted for 90% of the total crude oil transportation. The GHGs emission from crude oil transportation per ton of crude oil is summarized in Table 4-7.

Table 4-7 GHGs emission inventory for transportation 1 ton of crude oil

Emissions to air	Kg	kg CO_2 eq.
CO_2	134	134
N_2O	0.00327	1.0137
Methane	0.00659	0.13839
	TOTAL	**135.15**

(3.) Crude Oil Refining (Diesel)

Oil refineries are complex facilities. Several processes, such as distillation, vacuum distillation, or steam reforming are required to produce a large variety of oil products such as diesel, gasoline and others. The analysis lead to product specific allocation factors for energy and pollutants. Furthermore working material consumption, additive requirements, production waste, and infrastructure are included. The summary of GHGs emission from refining 1 ton of diesel is shown in Table 4-8.

Table 4-8 GHGs emission inventory for diesel refining

Emissions to air	kg	kg CO_2 eq.
CFC-11	0.000000295	0.00118
CFC-114	0.00000779	0.072447
CFC-12	6.35E-08	0.00053975
CFC-13	3.98E-08	0.00046566
CO2	422.9	422.9
dichloromethane	8.43E-08	7.587E-07
HALON-1301	0.000416	2.3296
HCFC-22	7.01E-08	0.00011917
HFC-134a	1.36E-18	1.768E-15
methane	4.27354	89.74434
N2O	0.010811	3.35141
tetrachloromethane	0.00000036	0.000504
trichloromethane	3.88E-08	1.552E-07
	TOTAL	**518.40**

(4.) Diesel stock

Distribution includes storage in large stocks and the supply to the customer (households, companies and filling stations). The GHGs emissions during distribution are modeled on a product-specific basis. Vapor emission control is included in modeling. Besides the infrastructure and the energy consumption for the movement of goods, production waste (sludges from oil sumps and oil tanks), and hydrocarbon emissions (specified) are included on a product-specific basis. Table 4-9 reports GHGs release per 1 ton of diesel from this process.

Table 4-9 GHGs emission inventory for diesel stock

Emissions to air	kg	kg CO_2 eq.
CFC-11	0.000000401	0.001604
CFC-114	0.0000106	0.09858
CFC-12	8.62E-08	0.0007327
CFC-13	5.41E-08	0.00063297
CO2	505	505
dichloromethane	0.000000134	0.000001206
HALON-1301	0.000425	2.38
HCFC-22	9.57E-08	0.00016269
HFC-134a	1.82E-18	2.366E-15
methane	4.43101	93.05121
N2O	0.01682	5.2142
tetrachloromethane	0.000000738	0.0010332
trichloromethane	8.03E-08	3.212E-07
	TOTAL	**605.75**

Therefore, the GWP for the production of diesel consumed during transportation is calculated and summarized as shown in Table 4-10.

Table 4-10 GWP for the production of diesel

Processes	GWP		
	kg CO_2 eq. / kg of crude oil	**kg CO_2 eq./ kg of diesel**	**kg CO_2 eq. / L of diesel**
Crude oil extraction	8.82299	1.95655	
Crude oil transport	0.13515	0.02997	
Crude oil refining (diesel)		0.51840	
Diesel stock		0.60575	
TOTAL		**3.11**	**2.613**

The GWP due to the production of diesel consumed during transportation per load can be calculated as shown below.

Diesel consumption	6	km/L
GWP for the production of diesel	2.613	kg CO_2 eq./L
GWP due to the use of diesel	0.435	kg CO_2 eq./km
Loading capacity	2 x 5.5 x 2.3 x 2.5 x 100 = 6.2 tons	

Therefore, the GWP due to the production of diesel consumed during transportation is equal to 0.0704 kg CO_2 eq./ ton-km

4.1.2.2 Ethanol System

The ethanol production process as designed by NREL is briefly described in chapter 2. This process has been used for the development of model. The estimates of inputs and outputs for the bagasse derived ethanol process based on 1 ton of bagasse with 50 % moisture content are summarized in Table 4-11.

Table 4-11 Data summary for bagasse-to-ethanol processes

Environmental flows	Value	Unit
Inputs		
Biomass	500.0	(kg/ton bagasse)
Lime	4.5	(kg/ton bagasse)
Water	983.0	(kg/ton bagasse)
NH3	14.0	(kg/ton bagasse)
Diesel	2.5	(L/ton bagasse)
H_2SO_4	22.0	(kg/ton bagasse)
Outputs		
Ethanol	150.8	(L/ton bagasse)
Gypsum	12.5	(kg/ton bagasse)
Ash	20.0	(kg/ton bagasse)
Ligneous residue	222.0	(kg/ton bagasse)
Biogas methane	7.5	(kg/ton bagasse)
Total CO_2	585.0	(kg/ton bagasse)
Net electricity	119.3	(kwh/ ton bagasse)

Adapted from Kadam, 2000

It is found from Table 4-11 that 585 kg CO_2 eq./ton of excess bagasse. Following the LCIA method, there are also GHGs emissions due to the production of each input and the post processing of each output. These are explained as follows.

4.1.2.2.1 Production of lime

The process model for lime production includes limestone extraction, limestone crushing, and limestone calcinations. The production of lime was modeled according to the following reactions:

$$CaCO_3 \rightarrow CaO + CO_2$$

Table 4-12 GHGs emission from production 1 ton of lime

Emissions to air	**kg CO_2 eq.**
CO_2	880
TOTAL	**880**

4.1.2.2.2 Production of ammonia

Synthetic anhydrous ammonia production was modeled based on the natural gas-reforming process. Natural gas is used both as feedstock and fuel in this process. The process modeled assumes no CO_2 recovery and no emission to water or waste is specified.

Table 4-13 GHGs emission from production 1 ton of Ammonia

Emissions to air	**kg**	**kg CO_2 eq.**
Methane	7.14	149.94
CO_2	415.10	415.10
TOTAL		**565.04**

4.1.2.2.3 Production of diesel

The quantification of GHGs emitted due to the production of diesel consumed in the ethanol production process is similarly to the detail discussed in section 4.1.2.1.2. The GWP due to the production of diesel is 2.613 kg CO_2 eq./L.

4.1.2.2.4 Production of sulfuric acid

Sulfuric acid is produced from recovered sulfur or sulfur dioxide. The energy produced by the combustion of sulfur or the catalytic oxidation of SO_2 is used for production of sulfuric acid. The total process is therefore energetically self sufficient. It is found from the analysis the there is no GHGs emission coming from sulfuric acid production process (Sima Pro V7.1).

4.1.2.2.5 Processing of by-product methane

By product methane (7.5 kg/ ton of excess bagasse) coming from ethanol production is supposed to burn in an open field. Complete combustion is assumed for burning process. The processing of methane is modeled according to the following reactions:

$$\begin{array}{ccccccccc} CH_4 & + & 2\,O_2 & \rightarrow & 2\,H_2O & + & CO_2 & & \\ 16 & & 64 & & 36 & & 44 & & (kg/kmole) \end{array}$$

From the above reaction, it calculation shows that 40 kg of CO_2 per ton of excess bagasse would be release to atmosphere as written below.

By product methane	7.5 kg/ ton of excess bagasse)	
1 kg of CH_4 result in	44/16 = 2.75 kg of CO_2	
Therefore, 1 ton of excess bagasse result in	7.5 x 2.75	kg of CO_2
	20.625	kg of CO_2

4.1.2.2.6 Electricity Production1 (Residual burning)

Waste coming from ethanol production process (ligneous residual) is assumed to be burnt in onsite cogeneration. By doing that, Electricity of about 119.3 kWh / ton excess bagasse would be obtained. The amount of electricity produced would reduce the need of electricity generated from conventional technology practicing in Thailand. Therefore, reduction of GWP due to generation of electricity from conventional technology practicing in Thailand called offset GWP is obtained. CO_2 coming from ethanol production process shown in Table 4-11 is already include GHGs emission from burning of the ligneous residual.

The quantification of offset GWP due to production of electricity is similar to the detail discussed in section 4.1.1.2. The offset GWP due to the production of electricity in Thailand is 1.05 kg CO_2 eq./kWh.

4.1.2.3 E10 Blending and Use

The ethanol produced is blended with the gasoline by a portion of 10% and 90% by volume respectively and the mixture is used as alternative fuel for gasoline vehicles in Thailand. It is obvious that the amount gasoline consumed in the transportation system is reduced. The reduction of GWP due to production of gasoline in Thailand called offset GWP is obtained and is taken into consideration. Therefore, there are 3 types of GWP to be analyzed. First is the tailpipe emission coming from the vehicle using E10. Second is the offset GWP due to tailpipe emission from vehicle using current gasoline fuel. Third is the offset GWP due to the reduction of gasoline required.

4.1.2.3.1 The tailpipe emission

The GHGs emission factor for both vehicle using E10 as fuel and vehicle using current gasoline fuel are slightly different. Table 4-14 indicates GHGs emission factor for both types of vehicle.

Table 4-14 GHGs emission for vehicle using E10 blend and current gasoline fuel

Emissions	E10 (kg CO_2 eq./ L of fuel)	Current gasoline fuel (kg CO_2 eq./ L of fuel)
CH_4	0.004271675	0.003716912
CO_2	2.26	2.309
TOTAL	**2.26**	**2.31**

From Kadam et al., 1999

4.1.2.3.2 Gasoline System

It is obvious that ethanol produced from bagasse derived ethanol process reduce the amount gasoline consumed in the transportation system. Therefore, reduction of GWP due to production of gasoline in Thailand called offset GWP is obtained. In analysis the GWP, this factor is taken into consideration. The explanation and analysis for this factor are shown as followed.

The GHGs emission analysis in the gasoline system refers to GHGs emitted from the production of gasoline. There are 5 sub processes to be included in the gasoline system. These are crude oil extraction, crude oil transportation, crude oil refining for producing gasoline, gasoline stock and MTBE production. It should be note that the crude oil refined in the petroleum refineries produce a number of different products. However, this section is only concerned with gasoline. Therefore, the method of allocating total GHGs emissions to only the proportion of only gasoline produced is considered. The allocation procedure used in this section is to allocate total GHGs releases among the products on a mass output basis. The data of a generic U.S refinery is used because it is consider being the most completeness among other sources. It is reported that the mass fraction of gasoline coming from all refineries is 42.53 % (Kadam et al., 1999).

(1.) Crude Oil Extraction

The analysis for GHGs emitted from crude oil extraction includes oil field exploration and crude oil production. For oil field exploration, the efforts needed for and the emissions caused by drilling activities are considered. For crude oil production, the variation in drilling efforts and energy consumption per mass of crude oil extracted between different region is modeled. Table 4-15 shows the GHGs emitted per 1 tons of crude oil extracted.

Table 4-15 GHGs emission inventory for extraction 1 ton of crude oil

Emissions to air	**Kg**	**kg CO_2 eq.**
CFC-11	5.37E-08	0.0002148
CFC-114	0.00000142	0.013206
CFC-12	1.15E-08	8500
CFC-13	7.25E-09	0.000084825
CO_2	236.08	236.08
Dichloromethane	1.56E-08	1.404E-07
HALON-1301	0.000412	2.3072
HCFC-22	0.000000013	0.0000221
HFC-134a	5.43E-19	7.059E-16
Methane	3.940819	82.757199
N_2O	0.00592	1.8352
Tetrachloromethane	0.000000165	0.000231
Trichloromethane	1.82E-08	7.28E-08
	TOTAL	**8,822.99**

(2.) Crude Oil Transportation

Transportation of crude oil from Middle Eastern oil producing countries to Thailand is considered. The mode of transportation is done by foreign tanker. Typically there are two types of engine technology used to drive the foreign tanker which are diesel fuel engines and steam turbine using bunker oil. The foreign tanker driven by steam turbine using bunker oil is modeled because this technology accounted for 90% of the total crude oil transportation. The GHGs emission from crude oil transportation per ton of crude oil is summarized in Table 4-16.

Table 4-16 GHGs emission inventory for transportation 1 ton of crude oil

Emissions to air	**kg**	**kg CO_2 eq.**
CO_2	134	134
N_2O	0.00327	1.0137
Methane	0.00659	0.13839
TOTAL		**135.15**

(3.) Crude Oil Refining (Gasoline)

Oil refineries are complex facilities. Several processes, such as distillation, vacuum distillation, or steam reforming are required to produce a large variety of oil products such as gasoline, diesel and others. The analysis lead to product specific allocation factors for energy, and pollutants. Furthermore working material consumption, additive requirements, production waste, and infrastructure are included. The summary of GHGs emission per ton of gasoline produced is shown in Table 4-17.

Table 4-17 GHGs emission inventory for refining of gasoline

Emissions to air	kg	kg CO_2 eq.
CFC-11	0.00000047	0.00188
CFC-114	0.0000124	0.11532
CFC-12	0.000000101	0.0008585
CFC-13	6.35E-08	0.00074295
CO2	786.3	786.3
dichloromethane	0.000000352	0.000003168
HALON-1301	0.000448	2.5088
HCFC-22	0.000000111	0.0001887
methane	4.76219	100.00599
N2O	0.01269	3.9339
tetrachloromethane	0.00000053	0.000742
trichloromethane	5.29E-08	2.116E-07
TOTAL		**892.87**

(4.) Gasoline stock

Distribution includes storage in large stocks and the supply to the customer (households, companies and filling stations). The GHGs emissions during distribution are modeled on a product-specific basis. Vapor emission control is included in modeling. Besides the infrastructure and the energy consumption for the movement of goods, production waste (sludges from oil sumps and oil tanks), and hydrocarbon emissions (specified) are included on a product-specific basis. Table 4-18 concludes the GHGs emission from the gasoline stock process (1 ton of gasoline).

Table 4-18 GHGs emission inventory for gasoline stock

Emissions to air	kg	kg CO_2 eq.
CFC-11	0.000000718	0.002872
CFC-114	0.000019	0.1767
CFC-12	0.000000154	0.001309
CFC-13	9.69E-08	0.00113373
CO2	890.6	890.6
dichloromethane	0.00000044	0.00000396
HALON-1301	0.000459	2.5704
HCFC-22	0.000000177	0.0003009
HFC-134a	4.39E-19	5.707E-16
methane	4.97049	104.38029
N2O	0.01956	6.0636
tetrachloromethane	0.00000392	0.005488
trichloromethane	0.000000431	0.000001724
TOTAL		**1003.80**

Therefore, the GWP for the production of gasoline is calculated and summarized as shown in Table 4-19.

Table 4-19 GWP for the production of gasoline

Processes	**GWP**		
	kg CO_2 eq. / kg of crude oil	**kg CO_2 eq./ kg of gasoline**	**kg CO_2 eq. / L of gasoline**
Crude oil extraction	8.82299	3.75228	
Crude oil transport	0.13515	0.05748	
Crude oil refining (gasoline)		0.89287	
Gasoline stock		1.00380	
TOTAL		**5.71**	**4.2043**

(5.) MTBE production

MTBE (Methyl Tertiary Butyl Ether) is added to gasoline to produce a current gasoline fuel (lead free). MTBE is produced from methanol and isobutene in a strong acid environment in an ion exchanger as catalyst. After production various cleaning steps are required. For this process, it is assumed that isobutene is produced from naphtha and methanol is produced from natural gas. Table 4-20 shows GHGs emitted from the production of 1 ton MTBE.

Table 4-20 GHGs emission from MTBE production (1 ton)

Emissions to air	**kg**	**kg CO_2 eq.**
CFC-11	3.39E-10	0.001356
CFC-114	8.95E-09	0.083235
CFC-12	7.29E-11	0.00062
CFC-13	4.57E-11	0.000535
CO2	0.7784	778.4
dichloromethane	1.06E-09	9.54E-06
HALON-1301	3.27E-07	1.8312
HCFC-22	8.04E-11	0.000137
HFC-134a	-1.4E-20	-5.3E-14
methane	0.00457732	96.12372
N2O	9.877E-06	3.06187
tetrachloromethane	5.26E-10	0.000736
trichloromethane	3.94E-11	1.58E-07
TOTAL		**880**

4.2 Life Cycle Cost and Benefit Analysis

4.2.1 Life Cycle Cost and Benefit Analysis of Scheme1

Presently the excess bagasse has been used for generating electricity onsite. However, it is needed to take the value of the excess bagasse into account because the excess bagasse can be sold to ethanol producer. Therefore, the value of excess bagasse should be equal to the benefit gained from the electricity produced onsite.

Therefore, the sum of cost of excess bagasse used to generate electricity onsite and the benefit from the corresponding electricity that can be generated is zero.

4.2.2 Life Cycle Cost and Benefit Analysis of Scheme 2

In the economics analysis, several factors have been taken into consideration. The analysis of all factors follows the life cycle approach. The details of the analysis are explained below.

4.2.2.1 Cost of excess bagasse

Presently the excess bagasse has been used for generating electricity onsite. Therefore, the amount of excess bagasse needed to be sent to produce ethanol offsite should be bought at least at the price that equivalent to the benefit gained from the electricity produced onsite. The calculation based on data of boiler condition taken from Therdyothin, 1992 is shown below;

Specific steam production is	2.1	kg/kg of excess bagasse (Payne, 1991)
Specific steam consumption	10	kg/ kWh
Therefore, electricity production	0.21	kWh/kg of excess bagasse
Average price of electricity	4	฿ / kWh (PEA, 2005)
Therefore, Cost of excess bagasse	0.84	฿ / kg

4.2.2.2 Transportation cost of excess bagasse

The transportation of excess bagasse from sugar mills to the potential ethanol plant is performed by 10 wheels truck with trailer (dimension of each cabin 5.5(W) x 2.3(L) x 2.5(H) m^3). All trucks use diesel fuel as energy source. The transportation cost of excess bagasse to ethanol plant is the summation of two main divisions. One is the transportation cost based on the duration of the trip and the other is based on the distance traveled. For the first portion, there are two components governing its value which are maintenance and fuel costs. For the second portion, there are other two main components which are the vehicle cost and the crew cost. The calculation of the two components of transportation cost of excess bagasse is shown in Tables 4-21 and

4-22. Another set of data required for calculating the transportation are the distances between the sugar mills and ethanol plants which can be calculated from the map or optimization process. The duration of the trip will be calculated based upon average vehicle speed of 60 km per hour. for all routes. The life time of the vehicle is assumed to be 15 years.

Table 4-21 Transportation cost based on the distance traveled

Item	Cost	Fuel consumption*	Load (tons)	Cost per ton - km (฿)
Fuel cost	30 ฿/L	6 km./L	6.2	0.81
Maintenance Cost	3,500 ฿/ 5,000 km.		6.2	0.11
Total				**0.92**

* From Japan Transport Cooperation Association, 2004

Table 4-22 Transportation cost based on the duration of the trip

Item	Cost (฿)	Useful life	Load (tons)	Avg. speed (km/h)*	Cost per ton - km (฿)
Vehicle cost	2,000,000	15 years	6.2	60	0.12
Crew cost	8,000	1 month	6.2	60	0.09
Sub total					**0.21**

* From Japan Transport Cooperation Association, 2004

Therefore, the total transportation cost of excess bagasse is equal to 1.13 ฿ per ton – km (0.21 plus 0.92).

4.2.2.3 Cost of ethanol production

The ethanol production processes referenced in this paper was taken from NREL simulation. The simulation is performed based on the size of the ethanol plant of 2,000 tons of dry excess bagasse per day or 4,000 tons of excess bagasse per day (50% moisture content). This size is considered as the base case size. The cost components of the bagasse derived ethanol project are capital cost (total project investment costs), fixed operating costs (labor cost), and variable costs (including the cost of material, electricity and other utility). The life time of the ethanol plant is assumed to be 20 years. The cost components for the whole life time of the plant of the base case ethanol plant (for the exchange rate of 40 ฿ per US$) are summarized in table 4-23.

Table 4-23 Life time cost of ethanol production

Cost components	**Cost (฿)**
Capital cost	7,897,012,240
Fixed cost	3,978,240,000
Variable cost	30,225,241,120
Total	**42,100,493,360**

4.2.2.4 Benefit from ethanol produced

The benefits gaining from selling of ethanol produced is considered. According to the ethanol production processes as designed by NREL and briefly described in chapter 2, 1 ton of excess bagasse can produce 150.8 liters of ethanol. The price of the ethanol is 19 ฿ / liter (PTT, 2006). This relation has been used in the model.

4.2.2.5 Benefit from electricity produced

According to the ethanol production processes as designed by NREL and briefly described in chapter 2, the ligneous residual left from the ethanol production process can be burnt to produce electricity. The benefits gaining from selling of electricity generated is taken into accounted. The data shows that 1 ton of excess bagasse can produce electricity of 0.859 MJ or 119.3 kWh. The average price of the electricity used in the model is 4 ฿ / kWh. This relation has been used in the model.

4.3 Model formulation for environmental system optimization

This section discusses the development and testing of a multi-objective optimization model in order to assist the decision-making for the proper utilization scheme of excess bagasse generated in the sugar industry in Thailand. These selections are conducted by considering both the advantage and disadvantage on the GWP and economic basis.

The studied model is considered a multi-objective optimization, since it seeks an optimal solution between two objectives. In previous section, the life cycle impact assessment of the global warming potential (GWP) and the associated cost and benefit have been analyzed. The optimization model used for determining the optimal solution for deciding on the excess bagasse utilization has been developed. This model is developed to assist in 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 scheme 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.

4.3.1 Formulation of the Objectives Functions

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).

$$min\,U = W_{GWP}(EGWP + PGWP) + W_{economic}(EECON + PECON) \qquad (1)$$

W_{GWP} and $W_{economic}$ are weighting given to GWP objective and economic objective respectively. The sensitivity analysis of the model can be 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. Sum of both weighting given to GWP and economic is equal to 1.

4.3.1.1 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 of excess bagasse in onsite industrial boiler to generate electricity (BGWP). The other is the offset GWP due to electricity production (ELGWP1). The mathematical relation is formulated as shown in Eq. (2) and (3).

$$EGWP = BGWP - ELGWP1 \qquad (2)$$

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).

$$BGWP = \sum_{i=1}^{I} EFB \text{ x } ELBAG_i \qquad \forall i \qquad (3)$$

$$ELGWP1 = \sum_{i=1}^{I} EFEL \text{ x } ELBAG_i \qquad \forall i \qquad (4)$$

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).

$$PGWP = TGWP + ETGWP - E10GWP \tag{5}$$

The GWP due to the transportation of excess bagasse from each sugar mill to the corresponding ethanol plant consists of two terms. These are the GWP due to tailpipe emission from the truck with trailer used to transport the excess bagasse (TGWP1) and the GHGs emission due to the production of diesel consumed in by the truck with trailer used in excess transportation (TGWP2). The relations of these terms are formulated as shown in Eqs. (6) to (8).

$$TGWP = TGWP1 + TGWP2 \tag{6}$$

$$TGWP1 = \sum_{j=1}^{J}\sum_{i=1}^{I} EFT \ x \ D_{ij} \ x \ ETBAG_{ij} \ x \ y_{ij} \quad \forall i, \forall j \tag{7}$$

$$TGWP2 = \sum_{j=1}^{J}\sum_{i=1}^{I} EFT \ x \ D_{ij} \ x \ ETBAG_{ij} \ x \ y_{ij} \quad \forall i, \forall j \tag{8}$$

The GWP due to ethanol production comprises six terms. These are the GWP due to production of lime (LIMEGWP), the GWP due to production of ammonia (NH3GWP), the GWP due to production of diesel (DSGWP), the GWP due to CO_2 emitted from ethanol production process (CO2GWP), the GWP due to processing of by-product methane (CH4GWP) and offset GWP due to the generation of electricity from burning of ligneous residual (ELGWP2). The relations of these terms are formulated as shown in Eqs. (9) to (15).

$$ETGWP = LIMEGWP + NH3GWP + DSGWP + CO2GWP + CH4GWP - ELGWP2 \tag{9}$$

$$LIMEGWP = \sum_{j=1}^{J}\sum_{i=1}^{I} EFET \ x \ ETBAG_{ij} \ x \ y_{ij} \quad \forall i, \forall j \tag{10}$$

$$NH3GWP = \sum_{j=1}^{J}\sum_{i=1}^{I} EFET \ x \ ETBAG_{ij} \ x \ y_{ij} \quad \forall i, \forall j \tag{11}$$

$$DSGWP = \sum_{j=1}^{J}\sum_{i=1}^{I} EFET \ x \ ETBAG_{ij} \ x \ y_{ij} \quad \forall i, \forall j \tag{12}$$

$$CO2GWP = \sum_{j=1}^{J}\sum_{i=1}^{I} EFET \ x \ ETBAG_{ij} \ x \ y_{ij} \quad \forall i, \forall j \tag{13}$$

$$CH4GWP = \sum_{j=1}^{J}\sum_{i=1}^{I} EFET \ x \ ETBAG_{ij} \ x \ y_{ij} \quad \forall i, \forall j \tag{14}$$

$$ELGWP2 = \sum_{j=1}^{J}\sum_{i=1}^{I} EFET \; x \; ETBAG_{ij} \; x \; y_{ij} \quad \forall i, \forall j \tag{15}$$

The offset GWP due to the utilization of produced ethanol as E10 fuel considered mainly three terms. These are the GWP due to tailpipe emission from vehicle using E10 (E10USEGWP), the offset GWP due to tailpipe emission from vehicle using current gasoline fuel (GASGWP) and the offset GWP due to production of current gasoline fuel (GASPROWP). The relations of these terms are formulated as shown in Eqs. (16) to (19).

$$E10GWP = E10USEGWP - GASGWP - GASPROGWP \tag{16}$$

$$E10USEGWP = \sum_{j=1}^{J}\sum_{i=1}^{I} EFE10 \; x \; ETBAG_{ij} \; x \; y_{ij} \quad \forall i, \forall j \tag{17}$$

$$GASGWP = \sum_{j=1}^{J}\sum_{i=1}^{I} EFE10 \; x \; ETBAG_{ij} \; x \; y_{ij} \quad \forall i, \forall j \tag{18}$$

$$GASPROGWP = \sum_{j=1}^{J}\sum_{i=1}^{I} EFE10 \; x \; ETBAG_{ij} \; x \; y_{ij} \quad \forall i, \forall j \tag{19}$$

4.3.1.2 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. (20) to (22).

$$EECON = EBCOST - EELBFIT \tag{20}$$

$$EBCOST = \sum_{i=1}^{I} UPB \; x \; ELBAG_{i} \quad \forall i \tag{21}$$

$$EELBFIT = \sum_{i=1}^{I} ELP \; x \; ELPF \; x \; ELBAG_{i} \quad \forall i \tag{22}$$

For the excess bagasse utilization in scheme 2, the economic effects evaluated from the cost and benefits are formulated as shown in Eq.(23).

$$PECON = PCOST - PBFIT \tag{23}$$

The cost comprises the total cost of excess bagasse, cost of the excess bagasse transportation and cost of the ethanol production. 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). 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. (24) to (27).

$$PCOST = PBCOST + PTCOST + PEPCOST \tag{24}$$

$$PBCOST = \sum_{j=1}^{J}\sum_{i=1}^{I} UPB \times ETBAG_{ij} \times Y_{ij} \quad \forall i, \forall j \tag{25}$$

$$PTCOST = \sum_{j=1}^{J}\sum_{i=1}^{I} UCT \times D_{ij} \times ETBAG_{ij} \times Y_{ij} \quad \forall i, \forall j \tag{26}$$

$$PEPCOST = BCCOST \times \left(\left(\sum_{j=1}^{J}\sum_{i=1}^{I} ETBAG_{ij} \times Y_{ij}\right) / BCSIZE\right)^{exp} \quad \forall i, \forall j \tag{27}$$

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. (28) to (30).

$$PBFIT = PETBFIT + PELBFIT \tag{28}$$

$$PETBFIT = \sum_{j=1}^{J}\sum_{i=1}^{I} ETP \times ETPF \times ETBAG_{ij} \times Y_{ij} \quad \forall i, \forall j \tag{29}$$

$$PELBFIT = \sum_{j=1}^{J}\sum_{i=1}^{I} ELP \times XELPF \times ETBAG_{ij} \times Y_{ij} \quad \forall i, \forall j \tag{30}$$

4.3.2 Formulation of constraints

Based on ESO, the next step is to formulate the constraints. All of the mathematical models presented in Eqs. (1) to (30) are subjected to performed under the following constraints.

$$\sum_{j=1}^{J} ETBAG_{ij} \ x \ Y_{ij} + ELBAG_{i} = SMBAG_{i} \quad \forall i \tag{31}$$

$$y_{ij} = \begin{cases} 1 \ if \ sugar \ mill \ i \ has \ to \ send \ its \ excess \ bagasse \ to \ ethanol \ plant \ j \\ 0 \ otherwise \end{cases} \quad \forall i, \forall j \tag{32}$$

$$\sum_{j=1}^{J} y_{ij} \leq 1 \qquad \forall i \tag{33}$$

$$z_{j} = \begin{cases} 1 \ if \ ethanol \ plant \ j \ is \ open \\ 0 \ otherwise \end{cases} \qquad \forall j \tag{34}$$

$$y_{ij} <= z_{j} \qquad \forall i \tag{35}$$

$$\sum_{j=1}^{J} z_{j} \leq N \tag{36}$$

The first constraint (Eq. 31) is derived from the mass balance of the excess bagasse. Eqs. (32) and (33) indicate the 0-1 variable representing the presence or absent of excess bagasse transported from sugar mill i to ethanol plant j. Eq. (34) indicates the 0-1 variable representing the presence or absence of ethanol plant j. Eq. (35) forces the excess bagasse from a sugar mill sent to an ethanol plant one by one. Finally, Eq. (36) is developed to set the maximum number of ethanol plant. This number is set by taken the availability of excess bagasse into consideration.

4.4 Application of ESO

The case chosen for illustration of the ESO approach is an existing sugar industry in the Northeastern 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.

4.4.1 Description of the Case

The case selected covers the whole area of Northeastern Thailand where 13 sugar mills are located. Based on the production year 2002-2003, the excess bagasse from each sugar mill has been calculated and tabulated in Table 4-24 (Product Development Department, 2003).

Table 4-24 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**

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. With the application of ArcView GIS V3.2, the locations of all sugar mills of the study area can be defined and are shown in Fig. 4-4. The potential locations of the ethanol plants can be computed by the center of gravity method (Krajewski et al., 2006). The computation starts with clustering the sugar mills. The potential locations of the ethanol plants can be then calculated using the following formulae shown in Eqs. (37) and (38).

$$CXET = \sum_{i=1}^{I}(CXSM_i x SMBAG_i)/\sum_{i=1}^{I} SMBAG_i \tag{37}$$

$$CYET = \sum_{i=1}^{I}(CYSM_i x SMBAG_i)/\sum_{i=1}^{I} SMBAG_i \tag{38}$$

The clustering process has been performed 3 times (first for 1 ethanol plant, second for 2 ethanol plants and third for 3 ethanol plants). The total of 6 potential ethanol plants can be calculated. The potential locations of all 6 ethanol plants are also presented in Figure 4-4.

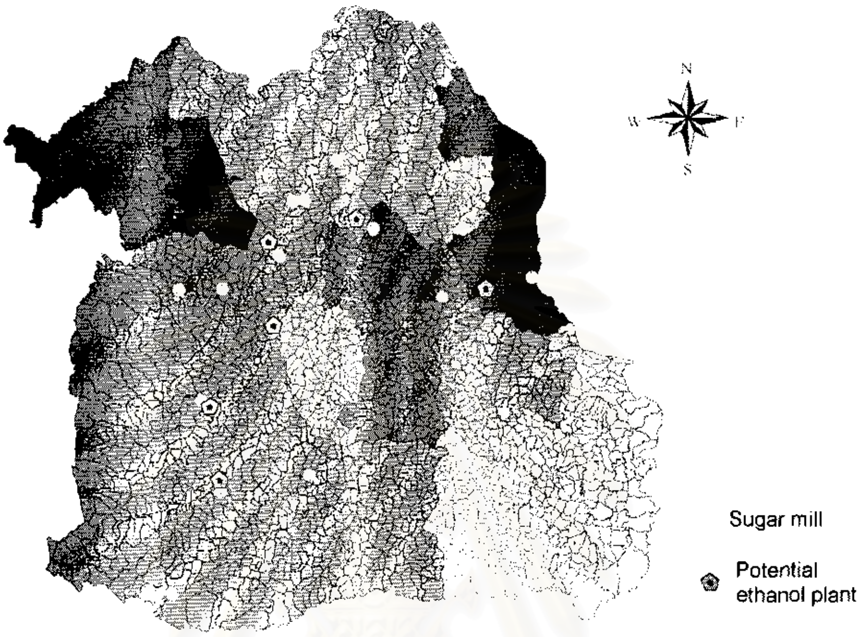


Figure 4-4 Locations of all sugar mills and potential locations of the ethanol plants

Figure 4-5 presents the simplified locations of sugar mills and the potential locations of ethanol plants. This figure is converted from the map in Figure 4-4 to provide the better image and fit the network analysis in this study. It consists of 19 nodes. 13 nodes represent the locations of sugar mills and 6 nodes represent the potential locations of ethanol plants. The node information obtained from ArcView GIS V3.2 is given in Table 4-25.

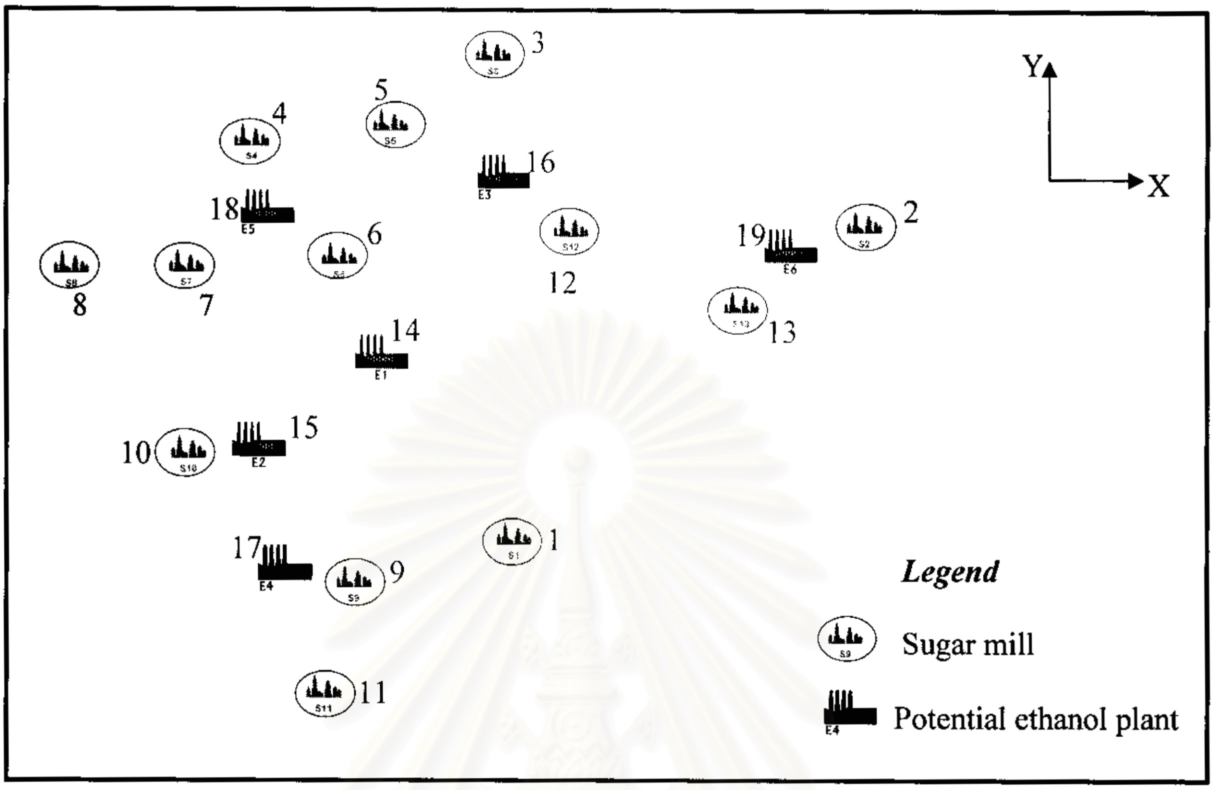


Figure 4-5 Simplified locations of all sugar mills and potential locations of the ethanol plants.

Table 4-25 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

4.4.2 Model Formulation

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 analysis of all factors follows the life cycle approach. The details of the analysis of the GWP related data and the analysis of the economics related data are as already discussed in section 4.1 and 4.2 respectively. The mathematical formulations and models developed for optimization process are shown as follows.

4.4.2.1 Formulation of the mathematical model for GWP

4.4.2.1.1 Formulation of the mathematical model for GWP of scheme 1

There are 2 types of GWP involved. One is the GWP according to GHGs emitted in burning excess bagasse in onsite industrial boiler to generate electricity. The other is the offset GWP due to electricity production.

According the calculation discussed in section 4.1.1.1, the GHGs emission from bagasse burning process is 894 kg of CO_2 eq. per ton of excess bagasse.

And according the calculation discussed in section 4.1.1.2, the offset GWP due to electricity production is 1.05 kg of CO_2 eq. per kWh. The electricity production from burning of excess bagasse in cogeneration is equal to 210 kWh per ton of excess bagasse. Therefore, the offset GWP due to electricity production is 220.5 kg of CO_2 eq. per ton of excess bagasse.

Totally, CO_2 Emission factor for scheme 1 = 894 - 220.5 = 673.5 kg of CO_2 eq. per ton of excess bagasse. Therefore, the mathematical expressions of the GWP due to burning excess bagasse in all sugar mills, the offset GWP due to electricity production from burning excess bagasse and the GWP due to the utilization of excess bagasse in scheme 1 can be written as shown in Eqs. 39 to 41.

$$BGWP = \sum_{i=1}^{I} 894 \ x \ ELBAG_i \qquad \forall i \tag{39}$$

$$ELGWP1 = \sum_{i=1}^{I} 220.5 \ x \ ELBAG_i \qquad \forall i \tag{40}$$

$$EGWP = BGWP - ELGWP1 = \sum_{i=1}^{I} 673.5 \ x \ ELBAG_i \qquad \forall i \tag{41}$$

4.4.2.1.2 Formulation of the mathematical model for GWP of scheme 2

(1) Bagasse Transportation

The analysis is accounted for GWP due to the transportation of excess bagasse from each sugar mill to corresponding ethanol plant. There are two types of GWP to be included in bagasse transportation process. These are the tailpipe emission from the truck with trailer and the GHGs emission due to the production of diesel consumed in by the truck with trailer.

According the explanation shown in section 4.1.2.1.1, the tailpipe emission from the truck with trailer is 0.075 kg CO_2 eq. per ton-km. And according the calculation discussed in section 4.1.2.1.2, the GHGs emission due to the production of diesel consumed in by the truck with trailer is 0.0704 kg of CO_2 eq. per ton-km. Therefore, the mathematical expressions of the tailpipe emission from the truck with trailer and the GHGs emission due to the production of diesel consumed in by the truck with trailer can be formulated (Eqs. 42 to 44).

$$TGWP1 = \sum_{j=1}^{J}\sum_{i=1}^{I} 0.075x2 \ x \ D_{ij} \ x \ ETBAG_{ij} \ x \ y_{ij} \quad \forall i, \forall j \tag{42}$$

$$TGWP2 = \sum_{j=1}^{J}\sum_{i=1}^{I} 0.0704x2 \ x \ D_{ij} \ x \ ETBAG_{ij} \ x \ y_{ij} \quad \forall i, \forall j \tag{43}$$

$$TGWP = TGWP1 + TGWP2 = \sum_{j=1}^{J}\sum_{i=1}^{I} 0.1454x2 \ x \ D_{ij} \ x \ ETBAG_{ij} \ x \ y_{ij} \quad \forall i, \forall j \tag{44}$$

(2) Ethanol System

There are several processes/factors taken into consideration during analysis of ethanol system. These processes/factors are already discussed in section 4.1.2.2. The mathematical expression of each process/factor is discussed here.

The CO_2 emitted from ethanol production process itself is equal to 585 kg of CO_2 eq. per ton of the excess bagasse used in the ethanol production process. The mathematical expressions of the CO_2 emitted from the ethanol production process is shown in Eq. 45.

$$CO2GWP = \sum_{j=1}^{J}\sum_{i=1}^{I} 585 \ x \ ETBAG_{ij} \ x \ y_{ij} \quad \forall i, \forall j \tag{45}$$

The production of lime results in GHGs emission of 880 kg CO_2 eq. per ton of lime produced. 1 tons of the excess bagasse used in the ethanol production process require 4.5 kg of lime. Therefore, the GHGs emission due to the production of lime is equal to 3.96 kg CO_2 eq. per ton of excess bagasse used. The mathematical expressions of the GHGs emission from the production of lime used in ethanol production system can be formulated as indicated in Eq. 46.

$$LIMEGWP = \sum_{j=1}^{J}\sum_{i=1}^{I} 3.96 \ x \ ETBAG_{ij} \ x \ y_{ij} \quad \forall i, \forall j \tag{46}$$

The production of ammonia results in GHGs emission of 565.04 kg CO_2 eq. per ton of ammonia produced. 1 tons of the excess bagasse used in the ethanol production process require 14 kg of ammonia. Therefore, the GHGs emission due to the production of ammonia is equal to 7.91 kg CO_2 eq. per ton of excess bagasse used. The mathematical expressions of the GHGs emission from the production of ammonia used in ethanol production system can be formulated as follow.

$$NH3GWP = \sum_{j=1}^{J}\sum_{i=1}^{I} 7.91 \ x \ ETBAG_{ij} \ x \ y_{ij} \quad \forall i, \forall j \tag{47}$$

The production of diesel results in GHGs emission of 2.613 kg CO_2 eq. per liter of diesel produced. 1 tons of the excess bagasse used in the ethanol production process require 2.5 liters of diesel. Therefore, the GHGs emission due to the production of diesel is equal to 6.53 kg CO_2 eq. per ton of excess bagasse used. The mathematical expression of the GHGs emission from the production of diesel used in ethanol production system is formulated in Eq. 48.

$$DSGWP = \sum_{j=1}^{J}\sum_{i=1}^{I} 6.53 \ x \ ETBAG_{ij} \ x \ y_{ij} \quad \forall i, \forall j \tag{48}$$

As explained in section 4.1.2.2.4, there are no GHGs emitted from sulfuric acid production process.

By product methane (7.5 kg of methane / ton of excess) coming from ethanol production is supposed to burn in an open field. Complete combustion is assumed for burning process. CO_2 coming from burning process is 2.75 kg per kg of methane. Therefore, the CO_2 release from burning of by-product methane is equal to 20.625 kg CO_2 eq. per ton of excess bagasse used. The mathematical expression of the CO_2 emitted from the ethanol production process is expressed in Eq. 49.

$$CH4GWP = \sum_{j=1}^{J}\sum_{i=1}^{I} 20.625 \ x \ ETBAG_{ij} \ x \ y_{ij} \quad \forall i, \forall j \tag{49}$$

Waste coming from ethanol production process (ligneous residual) is assumed to burn in onsite cogeneration. By doing that, Electricity of about 119.3 kWh per ton of excess bagasse would be obtained. This amount of electricity produced would reduce the need of electricity generated from conventional technology practicing in Thailand. Therefore, reduction of GWP due to generation of electricity from conventional technology practicing in Thailand called offset GWP is obtained. According the calculation discussed in section 4.1.2.2.7, the offset GWP due to electricity production is 1.05 kg of CO_2 eq. per kWh. The electricity production from burning of ligneous residual is equal to 119.3 kWh per ton of excess bagasse used in ethanol production process. Therefore, the offset GWP due to electricity production from ethanol production process is 125.27 kg of CO_2 eq. per ton of excess bagasse. The mathematical expressions of the offset GWP due to electricity production from burning of ligneous residual can be written as shown in Eq. 50.

$$ELGWP2 = \sum_{i=1}^{I} 125.75 \ x \ ELBAG_{i} \qquad \forall i \tag{50}$$

Therefore, the total GWP of the ethanol system is equal to 498.76 kg of CO_2 eq. per ton of excess bagasse (585 plus 7.91 plus 6.53 plus 20.625 minus 125.75). The mathematical expressions of the GWP due to the ethanol production can be written as in Eqs. 51 to 52.

$$ETGWP = CO2GWP + LIMEGWP + NH3GWP + DSGWP + H4GWP - ELGWP2 \quad (51)$$

$$ETGWP = \sum_{i=1}^{I} 498.76 \; x \; ELBAG_i \qquad \forall i \quad (52)$$

(3) E10 Blending and use

There are two factors taken into consideration during analysis of E10 blending and use. The first factor is the reduction of GHGs tailpipe emission for the vehicle used E10 as fuel compare to the vehicle used current gasoline fuel (an octane rating 95 gasoline). For the second factor, it is obvious that the amount gasoline consumed in the transportation system is reduced due to the replacement of ethanol for current gasoline fuel. Therefore, the reduction of GWP due to production of equivalent gasoline replaced in Thailand could be obtained. This is called the offset GWP due to production of current gasoline fuel.

Table 4-26 summarizes the amount of E10 that can be produced per ton of bagasse. The amount of current gasoline fuel that equivalent the E10 in term of heating value is also taken into consideration and included in the same table.

Table 4-26 E10 production per ton of excess bagasse and the amount of current gasoline fuel equivalent

Ethanol produced (L)	E10 (L)	Current gasoline fuel equivalent (L)
150.8	1508.2	1489.6

According to the data reported in section 4.1.2.3.1, the tailpipe GHGs emission from vehicle use each types of fuel per ton of excess bagasse can be calculated. The tailpipe GHGs emission from the E10 vehicle is equal to 3408.62 kg CO_2 eq. per ton of excess bagasse (2.26 multiplied by 1508.2). The tailpipe GHGs emission from the vehicle use current gasoline fuel is equal to 3441.05 kg CO_2 eq. per ton of excess bagasse (2.31 multiplied by 1489.6). The mathematical expressions of these two terms are formulated in Eqs 53 and 54.

$$E10USEGWP = \sum_{j=1}^{J}\sum_{i=1}^{I} 3408.62 \ x \ ETBAG_{ij} \ x \ y_{ij} \quad \forall i, \forall j \tag{53}$$

$$GASGWP = \sum_{j=1}^{J}\sum_{i=1}^{I} 3441.05 \ x \ ETBAG_{ij} \ x \ y_{ij} \quad \forall i, \forall j \tag{54}$$

1 liter of a current gasoline fuel contains 0.89 liter of gasoline and 0.11 liter of MTBE or 0.081 kg of MTBE (Kadam et al., 1999). According to the data reported in section 4.1.2.3.2, the production of gasoline results in GHGs emission of 4.20 kg CO_2 eq. per liter of gasoline produced or 3.74 kg CO_2 eq. per liter of current gasoline fuel. The production of MTBE results in GHGs emission of 0.88 kg CO_2 eq. per kg of MTBE produced or 0.071 kg CO_2 eq. per liter of current gasoline fuel. Therefore the offset GWP due to production of current gasoline fuel is equal to 3.816 kg CO_2 eq. per liter of current gasoline fuel produced or 568.42 kg CO_2 eq. per ton of excess bagasse (3.816 multiplied by 0.1multiplied by 1489.6). The mathematical expressions of the offset GWP due to production of current gasoline fuel can be then formulated as indicated in Eq. 55.

$$GASPROGWP = \sum_{j=1}^{J}\sum_{i=1}^{I} 586.42 \ x \ ETBAG_{ij} \ x \ y_{ij} \quad \forall i, \forall j \tag{55}$$

Therefore, the total GWP due to the E10 blending and used is equal to -600.855 kg of CO_2 eq. per ton of excess bagasse (plus 3408.62 minus 3441.05 minus 586.42). The mathematical expressions of the GWP due to the E10 blending and use can be written and shown in Eqs. 56 and 57.

$$E10GWP = E10USEGWP - GASGWP - GASPROGWP \tag{56}$$

$$E10GWP = \sum_{j=1}^{J}\sum_{i=1}^{I} -600.855 \ x \ ETBAG_{ij} \ x \ y_{ij} \quad \forall i, \forall j \tag{57}$$

4.4.2.2 Formulation of the mathematical model for economics

4.4.2.2.1 Formulation of the mathematical model for economics of scheme 1

Presently the excess bagasse has been used for generating electricity onsite. However, it is needed to take the value of the excess bagasse into account because the excess bagasse can be sold to ethanol producer. Therefore, the value of excess bagasse should be equal to the benefit gained from the electricity produced onsite. Based on the calculation discussion in section 4.2.1.1, the sum of cost of excess bagasse used to generate electricity onsite and the benefit from the corresponding electricity that can be generated is zero. The expression is modeled in Eqs. 58 to 60.

$$EBCOST = \sum_{i=1}^{I} UPB \ x \ ELBAG_i \quad \forall i \tag{58}$$

$$EELBFIT = \sum_{i=1}^{I} ELP \ x \ ELPF \ x \ ELBAG_i \quad \forall i \tag{59}$$

$$EECON = EBCOST - EELBFIT = 0 \tag{60}$$

4.4.2.2.2 Formulation of the mathematical model for economics of scheme 2

For the excess bagasse utilization in scheme 2, the economic effects are evaluated from the cost and benefits as formulated below. The explanation of this equation is discussed in section 4.2.2. The cost consists of three terms which are cost of excess bagasse, transportation cost of excess bagasse and cost of ethanol production. The benefit comprises two terms which are benefit from ethanol produced and from by-product electricity. The mathematical expressions are already shown in Eqs. 23 to 30. The detail of each term (both cost and benefit) is explained below.

(1.) Cost of excess bagasse

According to the calculation discussed in section 4.2.2.1, it is found that the cost of excess bagasse should be 0.84 ฿ per kg or 840 ฿ per ton. Therefore, the mathematical expressions for the cost of excess bagasse can be formulated as follow.

$$PBCOST = \sum_{j=1}^{J}\sum_{i=1}^{I} 840 \text{ x } ETBAG_{ij} \text{ x } Y_{ij} \quad \forall i, \forall j \tag{61}$$

(2.) Transportation cost of excess bagasse

According to the calculation discussed in section 4.2.2.2, it is found that the transportation cost of excess bagasse is equal to 1.13 ฿ per ton-km. Therefore, the mathematical expressions for the transportation cost of excess bagasse can be formulated as shown in Eq. 62.

$$PTCOST = \sum_{j=1}^{J}\sum_{i=1}^{I} 1.13 \text{x} 2 \text{ x } D_{ij} \text{ x } ETBAG_{ij} \text{ x } Y_{ij} \quad \forall i, \forall j \tag{62}$$

(3.) Cost of ethanol production

According to the calculation discussed in section 4.2.2.2, the ethanol production cost for the base case ethanol plant (the size of base case ethanol plant of 4,000 tons of excess bagasse per day) for the life time (assumed to be 20 years) is 42,100,493,360 ฿. Therefore the ethanol production cost for 1 year is equal to 2,124,915,868 ฿. However, 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 of about 0.7 (Wooley et al. 1999). The mathematical expressions for the ethanol production cost can be defined as indicated in Eq. 63.

$$PEPCOST = 2{,}124{,}915{,}868 \text{ x } \left(\left(\sum_{j=1}^{J}\sum_{i=1}^{I} ETBAG_{ij} \text{ x } Y_{ij}\right) / 4{,}000 \text{x} 365\right)^{exp} \quad \forall i, \forall j \tag{63}$$

(4.) Benefit from ethanol produced

The benefits gaining from selling of ethanol produced is considered. According to the ethanol production processes as designed by NREL and briefly described in chapter 2, 1 ton of excess bagasse can produce 150.8 liters of ethanol. The price of the ethanol is 19 ฿ / liter. This relation has been used in the model as shown in Eq. 64.

$$PETBFIT = \sum_{j=1}^{J}\sum_{i=1}^{I} 19\ x 150.8\ x\ ETBAG_{ij}\ x\ Y_{ij} \quad \forall i, \forall j \tag{64}$$

(5.) Benefit from by-product electricity

The ligneous residual left from the ethanol production process can be burnt to produce electricity. The benefits gaining from selling of electricity generated is taken into accounted. The data shows that 1 ton of excess bagasse can produce electricity of 119.3 kWh. The average price of the electricity used in the model is 4 ฿ / kWh. This relation has been used in the model as shown in Eq. 65.

$$PELBFIT = \sum_{j=1}^{J}\sum_{i=1}^{I} 4\ x\ 119.3\ x\ ETBAG_{ij}\ x\ Y_{ij} \quad \forall i, \forall j \tag{65}$$

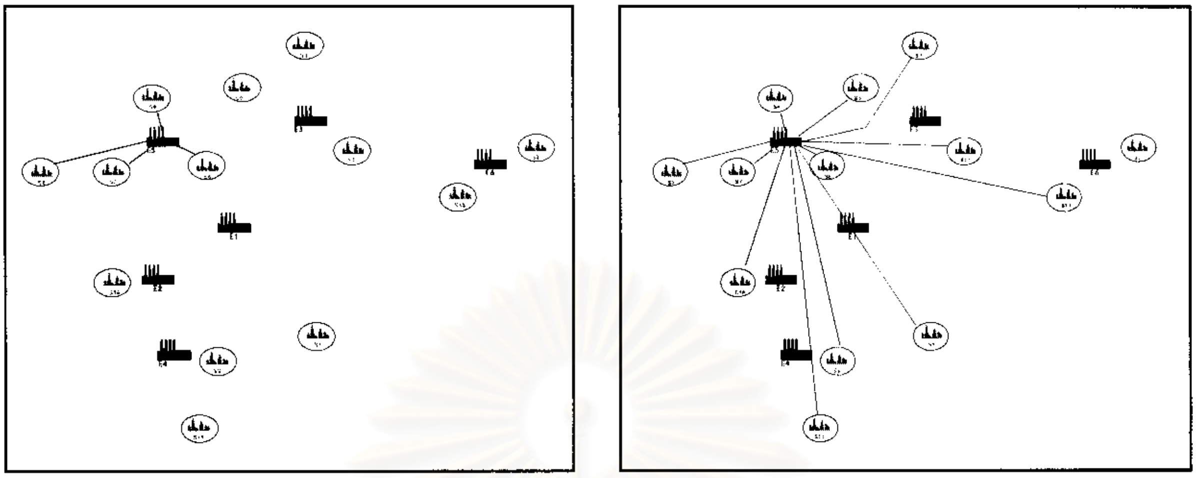
The total benefit which is the benefit gained from selling of both ethanol and electricity can be developed and shown in Eq. 66.

$$PBFIT = \sum_{j=1}^{J}\sum_{i=1}^{I} 3346.2\ x\ ETBAG_{ij}\ x\ Y_{ij} \quad \forall i, \forall j \tag{66}$$

Therefore, the economic factor of scheme 2 is formulated by sum of all terms of cost minus all terms of benefit.

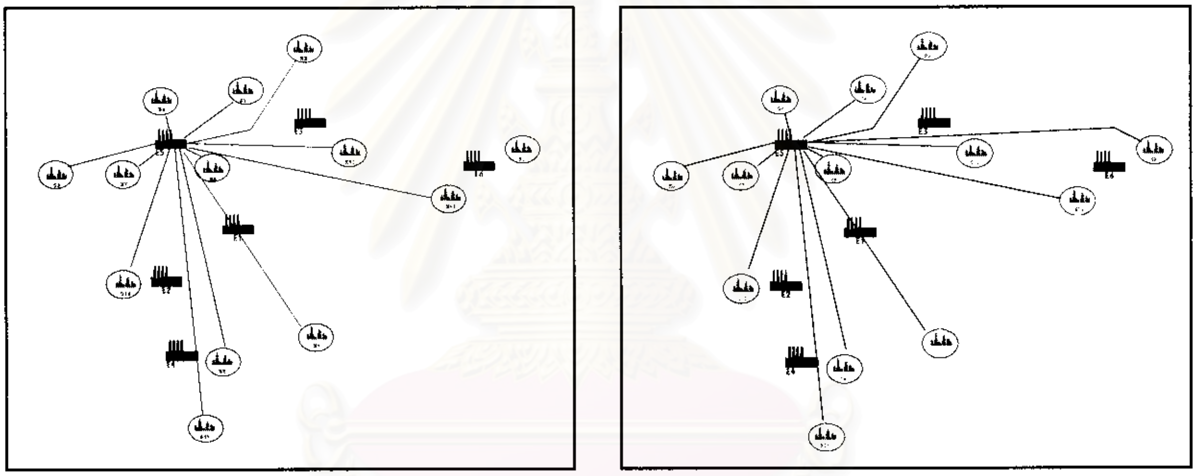
4.4.3 Results

The illustration case chosen for demonstrate the application of ESO 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. Figure 4-6 (a-d) 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 4-27. A compromise solution can be obtained by judiciously choosing the weightings to GWP and economics.



(a) W_{GWP}: 0.0 and $W_{economic}$: 1.0

(b) W_{GWP}: 0.3 and $W_{economic}$: 0.7



(c) W_{GWP}: 0.7 and $W_{economic}$: 0.3

(d) W_{GWP}: 1.0 and $W_{economic}$: 0.0

Figure 4-6 Effects of variation on weightings to economics and GWP.

Table 4-27 Results from optimization of the illustrative case

Case	W_{GWP}	$W_{economic}$	Total GWP (tons of CO_2 equivalent / year)			Total economics (million ฿ / 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	-45.6	917.65	138,566
b	0.3	0.7	-59,015	23,000	-36,015	-448.4	2,274.67	343,476
c	0.7	0.3	-59,015	23,000	-36,015	-448.4	2,274.67	343,476
d	1.0	0.0	-60,423	0	-60,423	-476.8	2,368.24	357,604

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 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 no. 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 liters 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 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 45.6 million ฿ per year. In case (b) and (c): the results are similar. All of the excess 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 2,274.67 tons of bagasse per day. The ethanol plants can produce 343,476 liters 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 448.4 million ฿ 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 2,368.24 tons of bagasse per day. 357,604 liters 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 476.8 million ฿ 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 current gasoline fuel used in vehicles, hence reducing the GHGs emission due to the production of current gasoline fuel. Moreover, the tailpipe GHGs emission from the vehicles using E10 is lower than the tailpipe GHGs emission from the vehicles using current gasoline fuel. 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-over in sugar mills and the unit cost of several parameters (e.g. gasoline, excess bagasse, electricity and etc.). The optimization results shown in Table 4-27 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.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The main conclusions from this work are summarized below.

- In global perspective, the excess bagasse left-over from sugar industry is the valuable resource of biomass for renewable energy technology.
- Sugar industry in Thailand plays an important role in global perspective in term of sugarcane growing, sugar production and excess bagasse utilization.
- Presently, the utilization of excess bagasse has been focused on onsite cogeneration.
- The utilization of excess bagasse for ethanol production has attracted more interest and been promoted. The excess bagasse derived ethanol technology results in GWP reduction. The bagasse derived ethanol technology would be focused in the near future.
- 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.
- With the current climate change and oil crisis, the analysis of GWP for the excess bagasse utilization options can help the decision makers compare and choose the better option. The analysis of GWP should follow the life cycle impact assessment approach since it provides the whole cycle (cradle to grave) for the analysis and the approach has been more accepted by the environmentalists.
- The economics analysis which accounted for both cost and benefit for the excess bagasse utilization should be included in order to make more attractive for the private investors.

- The application of ESO which consist of analysis of GWP coupled with the associated cost followed by the multi-objective optimization could facilitate in finding out the appropriate option for the utilization of excess bagasse generated in Thailand. This method could assist in deciding for 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. It 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.
- The application of ESO applied to the illustrative case has been successfully performed to satisfy both environmental and economic objectives. 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 current gasoline fuel used in vehicles, hence reducing the GHGs emission due to the production of current gasoline fuel. Moreover, the tailpipe GHGs emission from the vehicles using E10 is lower than the tailpipe GHGs emission from the vehicles using current gasoline fuel. 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 is also noticed from the results that the weighting given to each objective affect the selection of size of the ethanol plant. The selection of the location of the ethanol plant tends to be located close to the big sugar mills where plenty of excess bagasse exists. However, the distances between sugar mills and ethanol plant also affect the selection of location of ethanol plant.

It can also be summarized that the total GWP and the total economics of the system for the illustrative case 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.).

5.2 Recommendations and Future Works

This research was successful in determination for the optimal solutions for the utilization of excess bagasse generated in Thailand. However, there are still some recommendations for further study.

- The model developed in the research can be tested by include all sugar mills located in Thailand. As the more amount of excess bagasse is involved, the result from the optimization might be changed. This is because of the economy of scale and the change of other attributes.
- The model can also be modified and applied to higher portion of ethanol blending e.g. E20 (20 % of ethanol by volume), E85 (85 % of ethanol by volume) and E100 (pure ethanol) which have been attracted more interest and promoted in developed countries.
- The "ESO" approach can be modified and applied to other similar cases especially for other types of biomass available in Thailand (e.g. rice straw, corn and corn stover, and others).
- More environmental impacts should be included in the model development e.g. resource depletion potential, ozone depletion potential, air acidification potential, eutrophication potential, photochemical smog, human toxicity and other impacts. These impacts might play an important role in some circumstances. However, the model would become more complex and the more powerful software or solver might be necessary.

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APPENDICES

APPENDIX A

THE LINGO CODES FOR ILLUSTRATIVE CASE AND THE RESULS

The illustrative case 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. The LINGO code and the results for each are indicated below.

(a) Weighting to GWP: 0.0 and weighting to economics: 1.0

(1.) LINGO CODE

```
MODEL:
SETS:
     SUGAR / 1..13 /                    : SMBAG, ELBAG;
     ETHANOL / 1..6 /                   : Z;
     LINKSMET( SUGAR, ETHANOL)          : ETBAG, D, Y;

ENDSETS

    DATA:

      SMBAG = 36407.796, 34149.851, 68128.772, 52630.688, 52303.471,
87091.836, 90239.012,         104982.903, 89329.901, 89591.893,
61628.003, 36663.296, 61258.657;

          D =     122,  98,   194,  73,   185,  196,
                  206,  271,  146,  295,  209,  46,
                  133,  209,  53,   263,  82,   145,
                  96,   168,  50,   225,  38,   157,
                  97,   171,  42,   227,  43,   149,
                  53,   125,  59,   182,  14,   155,
                  49,   89,   110,  150,  49,   197,
                  78,   91,   141,  152,  77,   231,
                  134,  69,   224,  8,    195,  252,
                  81,   6,    175,  64,   132,  230,
                  222,  150,  312,  92,   280,  333,
                  108,  186,  18,   232,  84,   92,
                  134,  200,  88,   228,  143,  26;

    ENDDATA
!/////////////////OBJECTIVE FUNCTION ///////////////////////;

   [COST] MIN =   @SUM(LINKSMET(I,J):1*1.13*2*D(I,J)*ETBAG(I,J)*Y(I,J)) +
                   @SUM(LINKSMET(I,J):1*840*ETBAG(I,J)*Y(I,J)) +
                  1*2124915868*(@SUM(LINKSMET(I,J):ETBAG(I,J)*Y(I,J))/1460000)^0.7 -
                  @SUM(LINKSMET(I,J):1*3346.2*ETBAG(I,J)*Y(I,J)) +
                  @SUM(LINKSMET(I,J):0*498.7559567*ETBAG(I,J)*Y(I,J)) +
                  @SUM(LINKSMET(I,J):0*0.075*2*D(I,J)*ETBAG(I,J)*Y(I,J)) +
                  @SUM(LINKSMET(I,J):0*0.070370166*2*D(I,J)*ETBAG(I,J)*Y(I,J)) -
                  @SUM(LINKSMET(I,J):0*600.855253*ETBAG(I,J)*Y(I,J)) +
                  @SUM(SUGAR(I):0*673.5*ELBAG(I));
```

```
!///////////////////CONSTRAINTS ////////////////////////;

!SUBJECT TO;
@FOR(SUGAR(I):
      @SUM(ETHANOL(J): ETBAG(I,J))+ ELBAG(I)  = SMBAG(I));

@FOR( SUGAR( I):
      @SUM( ETHANOL( J): Y( I, J)) <= 1);

@FOR(SUGAR(I):
      @FOR(ETHANOL(J):ETBAG(I,J)  = ETBAG(I,J)*Y(I,J)));


@SUM(ETHANOL(J):Z(J))=1;

@FOR(SUGAR(I):
      @FOR(ETHANOL(J): Y(I,J)<=Z(J)));

!Y BINARY;
      @FOR(LINKSMET(I,J):
        @BIN(Y(I,J)));

!Z BINARY;
      @FOR(ETHANOL(J): @BIN(Z(J)));
END
```

(2.) THE RESULT

```
Rows=     184 Vars=     175 No. integer vars=      84
 Nonlinear rows=      79 Nonlinear vars=     156 Nonlinear constraints=
78
 Nonzeros=     670 Constraint nonz=    487 Density=0.021
 No. < :   91 No. =:   92 No. > :    0, Obj=MIN Single cols=   13

 Optimal solution found at step:         6
 Objective value:                 -0.4571420E+08
 Branch count:                           0


                       Variable           Value        Reduced Cost
                      SMBAG( 1)        36407.80           0.0000000
                      SMBAG( 2)        34149.85           0.0000000
                      SMBAG( 3)        68128.77           0.0000000
                      SMBAG( 4)        52630.69           0.0000000
                      SMBAG( 5)        52303.47           0.0000000
                      SMBAG( 6)        87091.84           0.0000000
                      SMBAG( 7)        90239.01           0.0000000
                      SMBAG( 8)        104982.9           0.0000000
                      SMBAG( 9)        89329.90           0.0000000
                     SMBAG( 10)        89591.89           0.0000000
                     SMBAG( 11)        61628.00           0.0000000
                     SMBAG( 12)        36663.30           0.0000000
                     SMBAG( 13)        61258.66           0.0000000
                      ELBAG( 1)        36407.80           0.0000000
                      ELBAG( 2)        34149.85           0.0000000
                      ELBAG( 3)        68128.77           0.0000000
                      ELBAG( 4)       0.0000000           0.0000000
                      ELBAG( 5)        52303.47           0.0000000
                      ELBAG( 6)       0.0000000           0.0000000
                      ELBAG( 7)       0.0000000           0.0000000
                      ELBAG( 8)       0.0000000           0.0000000
                      ELBAG( 9)        89329.90           0.0000000
                     ELBAG( 10)        89591.89           0.0000000
                     ELBAG( 11)        61628.00           0.0000000
                     ELBAG( 12)        36663.30           0.0000000
                     ELBAG( 13)        61258.66           0.0000000
                          Z( 1)       0.0000000           0.0000000
                          Z( 2)       0.0000000           0.0000000
                          Z( 3)       0.0000000           0.0000000
                          Z( 4)       0.0000000           0.0000000
                          Z( 5)        1.000000           0.0000000
                          Z( 6)       0.0000000           0.0000000
                   ETBAG( 1, 1)       0.0000000           0.0000000
                   ETBAG( 1, 2)       0.4345089E-13       0.0000000
                   ETBAG( 1, 3)       0.0000000           0.0000000
                   ETBAG( 1, 4)       0.0000000           0.0000000
                   ETBAG( 1, 5)       0.0000000           0.0000000
                   ETBAG( 1, 6)       0.0000000           0.0000000
                   ETBAG( 2, 1)       0.0000000           0.0000000
                   ETBAG( 2, 2)       0.0000000           0.0000000
                   ETBAG( 2, 3)       0.0000000           0.0000000
                   ETBAG( 2, 4)       0.0000000           0.0000000
                   ETBAG( 2, 5)       0.0000000           0.0000000
                   ETBAG( 2, 6)       0.0000000           0.0000000
                   ETBAG( 3, 1)       0.0000000           0.0000000
```

```
 ETBAG( 3, 2)        0.0000000           0.0000000
 ETBAG( 3, 3)        0.0000000           0.0000000
 ETBAG( 3, 4)        0.0000000           0.0000000
 ETBAG( 3, 5)        0.0000000           0.0000000
 ETBAG( 3, 6)        0.0000000           0.0000000
 ETBAG( 4, 1)        0.0000000           0.0000000
 ETBAG( 4, 2)        0.0000000           0.0000000
 ETBAG( 4, 3)        0.0000000           0.0000000
 ETBAG( 4, 4)        0.0000000           0.0000000
 ETBAG( 4, 5)         52630.69           0.0000000
 ETBAG( 4, 6)        0.0000000           0.0000000
 ETBAG( 5, 1)        0.0000000           0.0000000
 ETBAG( 5, 2)        0.0000000           0.0000000
 ETBAG( 5, 3)        0.0000000           0.0000000
 ETBAG( 5, 4)        0.0000000           0.0000000
 ETBAG( 5, 5)        0.0000000           0.0000000
 ETBAG( 5, 6)        0.0000000           0.0000000
 ETBAG( 6, 1)        0.0000000           0.0000000
 ETBAG( 6, 2)        0.0000000           0.0000000
 ETBAG( 6, 3)        0.0000000           0.0000000
 ETBAG( 6, 4)        0.0000000           0.0000000
 ETBAG( 6, 5)         87091.84           0.0000000
 ETBAG( 6, 6)        0.0000000           0.0000000
 ETBAG( 7, 1)        0.0000000           0.0000000
 ETBAG( 7, 2)        0.0000000           0.0000000
 ETBAG( 7, 3)        0.0000000           0.0000000
 ETBAG( 7, 4)        0.0000000           0.0000000
 ETBAG( 7, 5)         90239.02           0.0000000
 ETBAG( 7, 6)        0.0000000           0.0000000
 ETBAG( 8, 1)        0.0000000           0.0000000
 ETBAG( 8, 2)        0.0000000           0.0000000
 ETBAG( 8, 3)        0.0000000           0.0000000
 ETBAG( 8, 4)        0.0000000           0.0000000
 ETBAG( 8, 5)         104982.9           0.0000000
 ETBAG( 8, 6)        0.0000000           0.0000000
 ETBAG( 9, 1)        0.0000000           0.0000000
 ETBAG( 9, 2)        0.0000000           0.0000000
 ETBAG( 9, 3)        0.0000000           0.0000000
 ETBAG( 9, 4)        0.0000000           0.0000000
 ETBAG( 9, 5)        0.0000000           0.0000000
 ETBAG( 9, 6)        0.0000000           0.0000000
ETBAG( 10, 1)        0.0000000           0.0000000
ETBAG( 10, 2)        0.0000000           0.0000000
ETBAG( 10, 3)        0.0000000           0.0000000
ETBAG( 10, 4)        0.0000000           0.0000000
ETBAG( 10, 5)        0.0000000           0.0000000
ETBAG( 10, 6)        0.0000000           0.0000000
ETBAG( 11, 1)        0.0000000           0.0000000
ETBAG( 11, 2)        0.0000000           0.0000000
ETBAG( 11, 3)        0.0000000           0.0000000
ETBAG( 11, 4)        0.5874020E-13       0.0000000
ETBAG( 11, 5)        0.0000000           0.0000000
ETBAG( 11, 6)        0.0000000           0.0000000
ETBAG( 12, 1)        0.0000000           0.0000000
ETBAG( 12, 2)        0.0000000           0.0000000
ETBAG( 12, 3)        0.2558292E-13       0.0000000
ETBAG( 12, 4)        0.0000000           0.0000000
ETBAG( 12, 5)        0.0000000           0.0000000
ETBAG( 12, 6)        0.0000000           0.0000000
ETBAG( 13, 1)        0.0000000           0.0000000
```

```
           ETBAG( 13, 2)        0.0000000            0.0000000
           ETBAG( 13, 3)        0.0000000            0.0000000
           ETBAG( 13, 4)        0.0000000            0.0000000
           ETBAG( 13, 5)        0.0000000            0.0000000
           ETBAG( 13, 6)        0.0000000            0.0000000
                D( 1, 1)         122.0000            0.0000000
                D( 1, 2)         98.00000            0.0000000
                D( 1, 3)         194.0000            0.0000000
                D( 1, 4)         73.00000            0.0000000
                D( 1, 5)         185.0000            0.0000000
                D( 1, 6)         196.0000            0.0000000
                D( 2, 1)         206.0000            0.0000000
                D( 2, 2)         271.0000            0.0000000
                D( 2, 3)         146.0000            0.0000000
                D( 2, 4)         295.0000            0.0000000
                D( 2, 5)         209.0000            0.0000000
                D( 2, 6)         46.00000            0.0000000
                D( 3, 1)         133.0000            0.0000000
                D( 3, 2)         209.0000            0.0000000
                D( 3, 3)         53.00000            0.0000000
                D( 3, 4)         263.0000            0.0000000
                D( 3, 5)         82.00000            0.0000000
                D( 3, 6)         145.0000            0.0000000
                D( 4, 1)         96.00000            0.0000000
                D( 4, 2)         168.0000            0.0000000
                D( 4, 3)         50.00000            0.0000000
                D( 4, 4)         225.0000            0.0000000
                D( 4, 5)         38.00000            0.0000000
                D( 4, 6)         157.0000            0.0000000
                D( 5, 1)         97.00000            0.0000000
                D( 5, 2)         171.0000            0.0000000
                D( 5, 3)         42.00000            0.0000000
                D( 5, 4)         227.0000            0.0000000
                D( 5, 5)         43.00000            0.0000000
                D( 5, 6)         149.0000            0.0000000
                D( 6, 1)         53.00000            0.0000000
                D( 6, 2)         125.0000            0.0000000
                D( 6, 3)         59.00000            0.0000000
                D( 6, 4)         182.0000            0.0000000
                D( 6, 5)         14.00000            0.0000000
                D( 6, 6)         155.0000            0.0000000
                D( 7, 1)         49.00000            0.0000000
                D( 7, 2)         89.00000            0.0000000
                D( 7, 3)         110.0000            0.0000000
                D( 7, 4)         150.0000            0.0000000
                D( 7, 5)         49.00000            0.0000000
                D( 7, 6)         197.0000            0.0000000
                D( 8, 1)         78.00000            0.0000000
                D( 8, 2)         91.00000            0.0000000
                D( 8, 3)         141.0000            0.0000000
                D( 8, 4)         152.0000            0.0000000
                D( 8, 5)         77.00000            0.0000000
                D( 8, 6)         231.0000            0.0000000
                D( 9, 1)         134.0000            0.0000000
                D( 9, 2)         69.00000            0.0000000
                D( 9, 3)         224.0000            0.0000000
                D( 9, 4)         8.000000            0.0000000
                D( 9, 5)         195.0000            0.0000000
                D( 9, 6)         252.0000            0.0000000
               D( 10, 1)         81.00000            0.0000000
```

```
D( 10, 2)         6.000000          0.0000000
D( 10, 3)         175.0000          0.0000000
D( 10, 4)         64.00000          0.0000000
D( 10, 5)         132.0000          0.0000000
D( 10, 6)         230.0000          0.0000000
D( 11, 1)         222.0000          0.0000000
D( 11, 2)         150.0000          0.0000000
D( 11, 3)         312.0000          0.0000000
D( 11, 4)         92.00000          0.0000000
D( 11, 5)         280.0000          0.0000000
D( 11, 6)         333.0000          0.0000000
D( 12, 1)         108.0000          0.0000000
D( 12, 2)         186.0000          0.0000000
D( 12, 3)         18.00000          0.0000000
D( 12, 4)         232.0000          0.0000000
D( 12, 5)         84.00000          0.0000000
D( 12, 6)         92.00000          0.0000000
D( 13, 1)         134.0000          0.0000000
D( 13, 2)         200.0000          0.0000000
D( 13, 3)         88.00000          0.0000000
D( 13, 4)         228.0000          0.0000000
D( 13, 5)         143.0000          0.0000000
D( 13, 6)         26.00000          0.0000000
  Y( 1, 1)       0.0000000          0.0000000
  Y( 1, 2)       0.0000000          0.0000000
  Y( 1, 3)       0.0000000          0.0000000
  Y( 1, 4)       0.0000000          0.0000000
  Y( 1, 5)       0.0000000          0.0000000
  Y( 1, 6)       0.0000000          0.0000000
  Y( 2, 1)       0.0000000          0.0000000
  Y( 2, 2)       0.0000000          0.0000000
  Y( 2, 3)       0.0000000          0.0000000
  Y( 2, 4)       0.0000000          0.0000000
  Y( 2, 5)       0.0000000          0.0000000
  Y( 2, 6)       0.0000000          0.0000000
  Y( 3, 1)       0.0000000          0.0000000
  Y( 3, 2)       0.0000000          0.0000000
  Y( 3, 3)       0.0000000          0.0000000
  Y( 3, 4)       0.0000000          0.0000000
  Y( 3, 5)       0.0000000          0.0000000
  Y( 3, 6)       0.0000000          0.0000000
  Y( 4, 1)       0.0000000          0.0000000
  Y( 4, 2)       0.0000000          0.0000000
  Y( 4, 3)       0.0000000          0.0000000
  Y( 4, 4)       0.0000000          0.0000000
  Y( 4, 5)        1.000000          0.0000000
  Y( 4, 6)       0.0000000          0.0000000
  Y( 5, 1)       0.0000000          0.0000000
  Y( 5, 2)       0.0000000          0.0000000
  Y( 5, 3)       0.0000000          0.0000000
  Y( 5, 4)       0.0000000          0.0000000
  Y( 5, 5)       0.0000000          0.0000000
  Y( 5, 6)       0.0000000          0.0000000
  Y( 6, 1)       0.0000000          0.0000000
  Y( 6, 2)       0.0000000          0.0000000
  Y( 6, 3)       0.0000000          0.0000000
  Y( 6, 4)       0.0000000          0.0000000
  Y( 6, 5)        1.000000          0.0000000
  Y( 6, 6)       0.0000000          0.0000000
  Y( 7, 1)       0.0000000          0.0000000
```

```
  Y( 7, 2)        0.0000000             0.0000000
  Y( 7, 3)        0.0000000             0.0000000
  Y( 7, 4)        0.0000000             0.0000000
  Y( 7, 5)         1.000000             0.0000000
  Y( 7, 6)        0.0000000             0.0000000
  Y( 8, 1)        0.0000000             0.0000000
  Y( 8, 2)        0.0000000             0.0000000
  Y( 8, 3)        0.0000000             0.0000000
  Y( 8, 4)        0.0000000             0.0000000
  Y( 8, 5)         1.000000             0.0000000
  Y( 8, 6)        0.0000000             0.0000000
  Y( 9, 1)        0.0000000             0.0000000
  Y( 9, 2)        0.0000000             0.0000000
  Y( 9, 3)        0.0000000             0.0000000
  Y( 9, 4)        0.0000000             0.0000000
  Y( 9, 5)        0.0000000             0.0000000
  Y( 9, 6)        0.0000000             0.0000000
 Y( 10, 1)        0.0000000             0.0000000
 Y( 10, 2)        0.0000000             0.0000000
 Y( 10, 3)        0.0000000             0.0000000
 Y( 10, 4)        0.0000000             0.0000000
 Y( 10, 5)        0.0000000             0.0000000
 Y( 10, 6)        0.0000000             0.0000000
 Y( 11, 1)        0.0000000             0.0000000
 Y( 11, 2)        0.0000000             0.0000000
 Y( 11, 3)        0.0000000             0.0000000
 Y( 11, 4)        0.0000000             0.0000000
 Y( 11, 5)        0.0000000             0.0000000
 Y( 11, 6)        0.0000000             0.0000000
 Y( 12, 1)        0.0000000             0.0000000
 Y( 12, 2)        0.0000000             0.0000000
 Y( 12, 3)        0.0000000             0.0000000
 Y( 12, 4)        0.0000000             0.0000000
 Y( 12, 5)        0.0000000             0.0000000
 Y( 12, 6)        0.0000000             0.0000000
 Y( 13, 1)        0.0000000             0.0000000
 Y( 13, 2)        0.0000000             0.0000000
 Y( 13, 3)        0.0000000             0.0000000
 Y( 13, 4)        0.0000000             0.0000000
 Y( 13, 5)        0.0000000             0.0000000
 Y( 13, 6)        0.0000000             0.0000000

      Row    Slack or Surplus      Dual Price
     COST      -0.4571420E+08       0.0000000
        2      -0.8750000E-03       0.0000000
        3      -0.5625000E-03       0.0000000
        4      -0.1437500E-02       0.0000000
        5      -0.5000000E-03       0.0000000
        6      -0.1656250E-02       0.0000000
        7      -0.6250000E-04       0.0000000
        8      -0.3625000E-02       0.0000000
        9      -0.3250000E-02       0.0000000
       10      -0.2562500E-02       0.0000000
       11      -0.2375000E-02       0.0000000
       12      -0.9062500E-03       0.0000000
       13      -0.8750000E-03       0.0000000
       14      -0.7500000E-03       0.0000000
       15        1.000000           0.0000000
       16        1.000000           0.0000000
       17        1.000000           0.0000000
```

```
 18        0.0000000           0.0000000
 19         1.000000           0.0000000
 20        0.0000000           0.0000000
 21        0.0000000           0.0000000
 22        0.0000000           0.0000000
 23         1.000000           0.0000000
 24         1.000000           0.0000000
 25         1.000000           0.0000000
 26         1.000000           0.0000000
 27         1.000000           0.0000000
 28        0.0000000           0.0000000
 29        0.0000000           0.0000000
 30        0.0000000           0.0000000
 31        0.0000000           0.0000000
 32        0.0000000           0.0000000
 33        0.0000000           0.0000000
 34        0.0000000           0.0000000
 35        0.0000000           0.0000000
 36        0.0000000           0.0000000
 37        0.0000000           0.0000000
 38        0.0000000           0.0000000
 39        0.0000000           0.0000000
 40        0.0000000           0.0000000
 41        0.0000000           0.0000000
 42        0.0000000           0.0000000
 43        0.0000000           0.0000000
 44        0.0000000           0.0000000
 45        0.0000000           0.0000000
 46        0.0000000           0.0000000
 47        0.0000000           0.0000000
 48        0.0000000           0.0000000
 49        0.0000000           0.0000000
 50        0.0000000           0.0000000
 51        0.0000000           0.0000000
 52        0.0000000           0.0000000
 53        0.0000000           0.0000000
 54        0.0000000           0.0000000
 55        0.0000000           0.0000000
 56        0.0000000           0.0000000
 57        0.0000000           0.0000000
 58        0.0000000           0.0000000
 59        0.0000000           0.0000000
 60        0.0000000           0.0000000
 61        0.0000000           0.0000000
 62        0.0000000           0.0000000
 63        0.0000000           0.0000000
 64        0.0000000           0.0000000
 65        0.0000000           0.0000000
 66        0.0000000           0.0000000
 67        0.0000000           0.0000000
 68        0.0000000           0.0000000
 69        0.0000000           0.0000000
 70        0.0000000           0.0000000
 71        0.0000000           0.0000000
 72        0.0000000           0.0000000
 73        0.0000000           0.0000000
 74        0.0000000           0.0000000
 75        0.0000000           0.0000000
 76        0.0000000           0.0000000
 77        0.0000000           0.0000000
```

```
 78        0.0000000              0.0000000
 79        0.0000000              0.0000000
 80        0.0000000              0.0000000
 81        0.0000000              0.0000000
 82        0.0000000              0.0000000
 83        0.0000000              0.0000000
 84        0.0000000              0.0000000
 85        0.0000000              0.0000000
 86        0.0000000              0.0000000
 87        0.0000000              0.0000000
 88        0.0000000              0.0000000
 89        0.0000000              0.0000000
 90        0.0000000              0.0000000
 91        0.0000000              0.0000000
 92        0.0000000              0.0000000
 93        0.0000000              0.0000000
 94        0.0000000              0.0000000
 95        0.0000000              0.0000000
 96        0.0000000              0.0000000
 97        0.0000000              0.0000000
 98        0.0000000              0.0000000
 99        0.0000000              0.0000000
100        0.0000000              0.0000000
101        0.0000000              0.0000000
102        0.0000000              0.0000000
103        0.0000000              0.0000000
104        0.0000000              0.0000000
105        0.0000000              0.0000000
106        0.0000000              0.0000000
107        0.0000000              0.0000000
108        0.0000000              0.0000000
109        0.0000000              0.0000000
110        0.0000000              0.0000000
111         1.000000              0.0000000
112        0.0000000              0.0000000
113        0.0000000              0.0000000
114        0.0000000              0.0000000
115        0.0000000              0.0000000
116        0.0000000              0.0000000
117         1.000000              0.0000000
118        0.0000000              0.0000000
119        0.0000000              0.0000000
120        0.0000000              0.0000000
121        0.0000000              0.0000000
122        0.0000000              0.0000000
123         1.000000              0.0000000
124        0.0000000              0.0000000
125        0.0000000              0.0000000
126        0.0000000              0.0000000
127        0.0000000              0.0000000
128        0.0000000              0.0000000
129        0.0000000              0.0000000
130        0.0000000              0.0000000
131        0.0000000              0.0000000
132        0.0000000              0.0000000
133        0.0000000              0.0000000
134        0.0000000              0.0000000
135         1.000000              0.0000000
136        0.0000000              0.0000000
137        0.0000000              0.0000000
```

```
 138      0.0000000           0.0000000
 139      0.0000000           0.0000000
 140      0.0000000           0.0000000
 141      0.0000000           0.0000000
 142      0.0000000           0.0000000
 143      0.0000000           0.0000000
 144      0.0000000           0.0000000
 145      0.0000000           0.0000000
 146      0.0000000           0.0000000
 147      0.0000000           0.0000000
 148      0.0000000           0.0000000
 149      0.0000000           0.0000000
 150      0.0000000           0.0000000
 151      0.0000000           0.0000000
 152      0.0000000           0.0000000
 153      0.0000000           0.0000000
 154      0.0000000           0.0000000
 155      0.0000000           0.0000000
 156      0.0000000           0.0000000
 157      0.0000000           0.0000000
 158      0.0000000           0.0000000
 159       1.000000           0.0000000
 160      0.0000000           0.0000000
 161      0.0000000           0.0000000
 162      0.0000000           0.0000000
 163      0.0000000           0.0000000
 164      0.0000000           0.0000000
 165       1.000000           0.0000000
 166      0.0000000           0.0000000
 167      0.0000000           0.0000000
 168      0.0000000           0.0000000
 169      0.0000000           0.0000000
 170      0.0000000           0.0000000
 171       1.000000           0.0000000
 172      0.0000000           0.0000000
 173      0.0000000           0.0000000
 174      0.0000000           0.0000000
 175      0.0000000           0.0000000
 176      0.0000000           0.0000000
 177       1.000000           0.0000000
 178      0.0000000           0.0000000
 179      0.0000000           0.0000000
 180      0.0000000           0.0000000
 181      0.0000000           0.0000000
 182      0.0000000           0.0000000
 183       1.000000           0.0000000
 184      0.0000000           0.0000000
```

(b) Weighting to GWP: 0.3 and weighting to economics: 0.7

(1.) LINGCODE

```
MODEL:

SETS:
     SUGAR / 1..13 /                  : SMBAG, ELBAG;
     ETHANOL / 1..6 /                 : Z;
     LINKSMET( SUGAR, ETHANOL)        : ETBAG, D, Y;

ENDSETS

    DATA:

      SMBAG = 36407.796, 34149.851, 68128.772, 52630.688, 52303.471,
87091.836, 90239.012,           104982.903, 89329.901, 89591.893,
61628.003, 36663.296, 61258.657;

          D =     122,  98,   194,  73,   185,  196,
                  206,  271,  146,  295,  209,  46,
                  133,  209,  53,   263,  82,   145,
                  96,   168,  50,   225,  38,   157,
                  97,   171,  42,   227,  43,   149,
                  53,   125,  59,   182,  14,   155,
                  49,   89,   110,  150,  49,   197,
                  78,   91,   141,  152,  77,   231,
                  134,  69,   224,  8,    195,  252,
                  81,   6,    175,  64,   132,  230,
                  222,  150,  312,  92,   280,  333,
                  108,  186,  18,   232,  84,   92,
                  134,  200,  88,   228,  143,  26;


ENDDATA

!/////////////////OBJECTIVE FUNCTION //////////////////////;

   [COST] MIN =     @SUM(LINKSMET(I,J):0.7*1.13*2*D(I,J)*ETBAG(I,J)*Y(I,J)) +
                     @SUM(LINKSMET(I,J):0.7*840*ETBAG(I,J)*Y(I,J)) +
                 0.7*2124915868*(@SUM(LINKSMET(I,J):ETBAG(I,J)*Y(I,J))/1460000)^0.7 -
                    @SUM(LINKSMET(I,J):0.7*3346.2*ETBAG(I,J)*Y(I,J)) +
                    @SUM(LINKSMET(I,J):0.3*498.7559567*ETBAG(I,J)*Y(I,J)) +
                    @SUM(LINKSMET(I,J):0.3*0.075*2*D(I,J)*ETBAG(I,J)*Y(I,J)) +
                    @SUM(LINKSMET(I,J):0.3*0.070370166*2*D(I,J)*ETBAG(I,J)*Y(I,J)) -
                    @SUM(LINKSMET(I,J):0.3*600.855253*ETBAG(I,J)*Y(I,J)) +
                    @SUM(SUGAR(I):0.3*673.5*ELBAG(I));
```

```
!//////////////////CONSTRAINTS ////////////////////////;

!SUBJECT TO;
@FOR(SUGAR(I):
      @SUM(ETHANOL(J): ETBAG(I,J))+ ELBAG(I) = SMBAG(I));

@FOR( SUGAR( I):
      @SUM( ETHANOL( J): Y( I, J)) <= 1);

@FOR(SUGAR(I):
      @FOR(ETHANOL(J):ETBAG(I,J) = ETBAG(I,J)*Y(I,J)));


@SUM(ETHANOL(J):Z(J))=1;

@FOR(SUGAR(I):
      @FOR(ETHANOL(J): Y(I,J)<=Z(J)));

!Y BINARY;
      @FOR(LINKSMET(I,J):
        @BIN(Y(I,J)));

!Z BINARY;
      @FOR(ETHANOL(J): @BIN(Z(J)));
END
```

(2.) RESULT

```
Rows=    184 Vars=    175 No. integer vars=     84
 Nonlinear rows=     79 Nonlinear vars=    156 Nonlinear constraints=
78
 Nonzeros=    683 Constraint nonz=   487 Density=0.021
 No. < :  91 No. =:  92 No. > :    0, Obj=MIN Single cols=    0

 Optimal solution found at step:         65
 Objective value:                -0.3251890E+09
 Branch count:                            2

                       Variable           Value        Reduced Cost
                      SMBAG( 1)        36407.80           0.0000000
                      SMBAG( 2)        34149.85           0.0000000
                      SMBAG( 3)        68128.77           0.0000000
                      SMBAG( 4)        52630.69           0.0000000
                      SMBAG( 5)        52303.47           0.0000000
                      SMBAG( 6)        87091.84           0.0000000
                      SMBAG( 7)        90239.01           0.0000000
                      SMBAG( 8)        104982.9           0.0000000
                      SMBAG( 9)        89329.90           0.0000000
                     SMBAG( 10)        89591.89           0.0000000
                     SMBAG( 11)        61628.00           0.0000000
                     SMBAG( 12)        36663.30           0.0000000
                     SMBAG( 13)        61258.66           0.0000000
                      ELBAG( 1)       0.0000000           0.0000000
                      ELBAG( 2)        34149.85           0.0000000
                      ELBAG( 3)       0.0000000           0.0000000
                      ELBAG( 4)       0.0000000           0.0000000
                      ELBAG( 5)       0.0000000           0.0000000
                      ELBAG( 6)       0.0000000           0.0000000
                      ELBAG( 7)       0.0000000           0.0000000
                      ELBAG( 8)       0.0000000           0.0000000
                      ELBAG( 9)       0.0000000           0.0000000
                     ELBAG( 10)       0.0000000           0.0000000
                     ELBAG( 11)       0.0000000           0.0000000
                     ELBAG( 12)       0.0000000           0.0000000
                     ELBAG( 13)       0.0000000           0.0000000
                          Z( 1)       0.0000000           0.0000000
                          Z( 2)       0.0000000           0.0000000
                          Z( 3)       0.0000000           0.0000000
                          Z( 4)       0.0000000           0.0000000
                          Z( 5)        1.000000           0.0000000
                          Z( 6)       0.0000000           0.0000000
                   ETBAG( 1, 1)       0.0000000           0.0000000
                   ETBAG( 1, 2)       0.0000000           0.0000000
                   ETBAG( 1, 3)       0.0000000           0.0000000
                   ETBAG( 1, 4)       0.0000000           0.0000000
                   ETBAG( 1, 5)        36407.80           0.0000000
                   ETBAG( 1, 6)       0.0000000           0.0000000
                   ETBAG( 2, 1)       0.0000000           0.0000000
                   ETBAG( 2, 2)       0.0000000           0.0000000
                   ETBAG( 2, 3)       0.0000000           0.0000000
                   ETBAG( 2, 4)       0.0000000           0.0000000
                   ETBAG( 2, 5)       0.0000000           0.0000000
                   ETBAG( 2, 6)       0.0000000           0.0000000
                   ETBAG( 3, 1)       0.0000000           0.0000000
```

```
 ETBAG( 3, 2)        0.0000000          0.0000000
 ETBAG( 3, 3)        0.3590005E-05      0.0000000
 ETBAG( 3, 4)        0.0000000          0.0000000
 ETBAG( 3, 5)         68128.77          0.0000000
 ETBAG( 3, 6)        0.0000000          0.0000000
 ETBAG( 4, 1)        0.0000000          0.0000000
 ETBAG( 4, 2)        0.5169428E-05      0.0000000
 ETBAG( 4, 3)        0.0000000          0.0000000
 ETBAG( 4, 4)        0.0000000          0.0000000
 ETBAG( 4, 5)         52630.69          0.0000000
 ETBAG( 4, 6)        0.0000000          0.0000000
 ETBAG( 5, 1)        0.0000000          0.0000000
 ETBAG( 5, 2)        0.0000000          0.0000000
 ETBAG( 5, 3)        0.0000000          0.0000000
 ETBAG( 5, 4)        0.0000000          0.0000000
 ETBAG( 5, 5)         52303.47          0.0000000
 ETBAG( 5, 6)        0.0000000          0.0000000
 ETBAG( 6, 1)        0.0000000          0.0000000
 ETBAG( 6, 2)        0.0000000          0.0000000
 ETBAG( 6, 3)        0.0000000          0.0000000
 ETBAG( 6, 4)        0.0000000          0.0000000
 ETBAG( 6, 5)         87091.84          0.0000000
 ETBAG( 6, 6)        0.0000000          0.0000000
 ETBAG( 7, 1)        0.0000000          0.0000000
 ETBAG( 7, 2)        0.0000000          0.0000000
 ETBAG( 7, 3)        0.0000000          0.0000000
 ETBAG( 7, 4)        0.0000000          0.0000000
 ETBAG( 7, 5)         90239.02          0.0000000
 ETBAG( 7, 6)        0.0000000          0.0000000
 ETBAG( 8, 1)        0.0000000          0.0000000
 ETBAG( 8, 2)        0.0000000          0.0000000
 ETBAG( 8, 3)        0.0000000          0.0000000
 ETBAG( 8, 4)        0.0000000          0.0000000
 ETBAG( 8, 5)         104982.9          0.0000000
 ETBAG( 8, 6)        0.0000000          0.0000000
 ETBAG( 9, 1)        0.0000000          0.0000000
 ETBAG( 9, 2)        0.0000000          0.0000000
 ETBAG( 9, 3)        0.0000000          0.0000000
 ETBAG( 9, 4)        0.0000000          0.0000000
 ETBAG( 9, 5)         89329.90          0.0000000
 ETBAG( 9, 6)        0.0000000          0.0000000
ETBAG( 10, 1)        0.0000000          0.0000000
ETBAG( 10, 2)        0.0000000          0.0000000
ETBAG( 10, 3)        0.0000000          0.0000000
ETBAG( 10, 4)        0.0000000          0.0000000
ETBAG( 10, 5)         89591.89          0.0000000
ETBAG( 10, 6)        0.0000000          0.0000000
ETBAG( 11, 1)        0.0000000          0.0000000
ETBAG( 11, 2)        0.0000000          0.0000000
ETBAG( 11, 3)        0.0000000          0.0000000
ETBAG( 11, 4)        0.0000000          0.0000000
ETBAG( 11, 5)         61628.00          0.0000000
ETBAG( 11, 6)        0.0000000          0.0000000
ETBAG( 12, 1)        0.0000000          0.0000000
ETBAG( 12, 2)        0.0000000          0.0000000
ETBAG( 12, 3)        0.0000000          0.0000000
ETBAG( 12, 4)        0.0000000          0.0000000
ETBAG( 12, 5)         36663.30          0.0000000
ETBAG( 12, 6)        0.0000000          0.0000000
ETBAG( 13, 1)        0.0000000          0.0000000
```

```
      ETBAG( 13, 2)        0.0000000          0.0000000
      ETBAG( 13, 3)        0.0000000          0.0000000
      ETBAG( 13, 4)        0.0000000          0.0000000
      ETBAG( 13, 5)         61258.66          0.0000000
      ETBAG( 13, 6)        0.0000000          0.0000000
           D( 1, 1)         122.0000          0.0000000
           D( 1, 2)         98.00000          0.0000000
           D( 1, 3)         194.0000          0.0000000
           D( 1, 4)         73.00000          0.0000000
           D( 1, 5)         185.0000          0.0000000
           D( 1, 6)         196.0000          0.0000000
           D( 2, 1)         206.0000          0.0000000
           D( 2, 2)         271.0000          0.0000000
           D( 2, 3)         146.0000          0.0000000
           D( 2, 4)         295.0000          0.0000000
           D( 2, 5)         209.0000          0.0000000
           D( 2, 6)         46.00000          0.0000000
           D( 3, 1)         133.0000          0.0000000
           D( 3, 2)         209.0000          0.0000000
           D( 3, 3)         53.00000          0.0000000
           D( 3, 4)         263.0000          0.0000000
           D( 3, 5)         82.00000          0.0000000
           D( 3, 6)         145.0000          0.0000000
           D( 4, 1)         96.00000          0.0000000
           D( 4, 2)         168.0000          0.0000000
           D( 4, 3)         50.00000          0.0000000
           D( 4, 4)         225.0000          0.0000000
           D( 4, 5)         38.00000          0.0000000
           D( 4, 6)         157.0000          0.0000000
           D( 5, 1)         97.00000          0.0000000
           D( 5, 2)         171.0000          0.0000000
           D( 5, 3)         42.00000          0.0000000
           D( 5, 4)         227.0000          0.0000000
           D( 5, 5)         43.00000          0.0000000
           D( 5, 6)         149.0000          0.0000000
           D( 6, 1)         53.00000          0.0000000
           D( 6, 2)         125.0000          0.0000000
           D( 6, 3)         59.00000          0.0000000
           D( 6, 4)         182.0000          0.0000000
           D( 6, 5)         14.00000          0.0000000
           D( 6, 6)         155.0000          0.0000000
           D( 7, 1)         49.00000          0.0000000
           D( 7, 2)         89.00000          0.0000000
           D( 7, 3)         110.0000          0.0000000
           D( 7, 4)         150.0000          0.0000000
           D( 7, 5)         49.00000          0.0000000
           D( 7, 6)         197.0000          0.0000000
           D( 8, 1)         78.00000          0.0000000
           D( 8, 2)         91.00000          0.0000000
           D( 8, 3)         141.0000          0.0000000
           D( 8, 4)         152.0000          0.0000000
           D( 8, 5)         77.00000          0.0000000
           D( 8, 6)         231.0000          0.0000000
           D( 9, 1)         134.0000          0.0000000
           D( 9, 2)         69.00000          0.0000000
           D( 9, 3)         224.0000          0.0000000
           D( 9, 4)         8.000000          0.0000000
           D( 9, 5)         195.0000          0.0000000
           D( 9, 6)         252.0000          0.0000000
          D( 10, 1)         81.00000          0.0000000
```

```
D( 10, 2)        6.000000             0.0000000
D( 10, 3)        175.0000             0.0000000
D( 10, 4)        64.00000             0.0000000
D( 10, 5)        132.0000             0.0000000
D( 10, 6)        230.0000             0.0000000
D( 11, 1)        222.0000             0.0000000
D( 11, 2)        150.0000             0.0000000
D( 11, 3)        312.0000             0.0000000
D( 11, 4)        92.00000             0.0000000
D( 11, 5)        280.0000             0.0000000
D( 11, 6)        333.0000             0.0000000
D( 12, 1)        108.0000             0.0000000
D( 12, 2)        186.0000             0.0000000
D( 12, 3)        18.00000             0.0000000
D( 12, 4)        232.0000             0.0000000
D( 12, 5)        84.00000             0.0000000
D( 12, 6)        92.00000             0.0000000
D( 13, 1)        134.0000             0.0000000
D( 13, 2)        200.0000             0.0000000
D( 13, 3)        88.00000             0.0000000
D( 13, 4)        228.0000             0.0000000
D( 13, 5)        143.0000             0.0000000
D( 13, 6)        26.00000             0.0000000
  Y( 1, 1)      0.0000000             0.0000000
  Y( 1, 2)      0.0000000             0.0000000
  Y( 1, 3)      0.0000000             0.0000000
  Y( 1, 4)      0.0000000             0.0000000
  Y( 1, 5)       1.000000             0.0000000
  Y( 1, 6)      0.0000000             0.0000000
  Y( 2, 1)      0.0000000             0.0000000
  Y( 2, 2)      0.0000000             0.0000000
  Y( 2, 3)      0.0000000             0.0000000
  Y( 2, 4)      0.0000000             0.0000000
  Y( 2, 5)      0.0000000             0.0000000
  Y( 2, 6)      0.0000000             0.0000000
  Y( 3, 1)      0.0000000             0.0000000
  Y( 3, 2)      0.0000000             0.0000000
  Y( 3, 3)      0.0000000             0.0000000
  Y( 3, 4)      0.0000000             0.0000000
  Y( 3, 5)       1.000000             0.0000000
  Y( 3, 6)      0.0000000             0.0000000
  Y( 4, 1)      0.0000000             0.0000000
  Y( 4, 2)      0.0000000             0.0000000
  Y( 4, 3)      0.0000000             0.0000000
  Y( 4, 4)      0.0000000             0.0000000
  Y( 4, 5)       1.000000             0.0000000
  Y( 4, 6)      0.0000000             0.0000000
  Y( 5, 1)      0.0000000             0.0000000
  Y( 5, 2)      0.0000000             0.0000000
  Y( 5, 3)      0.0000000             0.0000000
  Y( 5, 4)      0.0000000             0.0000000
  Y( 5, 5)       1.000000             0.0000000
  Y( 5, 6)      0.0000000             0.0000000
  Y( 6, 1)      0.0000000             0.0000000
  Y( 6, 2)      0.0000000             0.0000000
  Y( 6, 3)      0.0000000             0.0000000
  Y( 6, 4)      0.0000000             0.0000000
  Y( 6, 5)       1.000000             0.0000000
  Y( 6, 6)      0.0000000             0.0000000
  Y( 7, 1)      0.0000000             0.0000000
```

```
                 Y( 7, 2)        0.0000000            0.0000000
                 Y( 7, 3)        0.0000000            0.0000000
                 Y( 7, 4)        0.0000000            0.0000000
                 Y( 7, 5)         1.000000            0.0000000
                 Y( 7, 6)        0.0000000            0.0000000
                 Y( 8, 1)        0.0000000            0.0000000
                 Y( 8, 2)        0.0000000            0.0000000
                 Y( 8, 3)        0.0000000            0.0000000
                 Y( 8, 4)        0.0000000            0.0000000
                 Y( 8, 5)         1.000000            0.0000000
                 Y( 8, 6)        0.0000000            0.0000000
                 Y( 9, 1)        0.0000000            0.0000000
                 Y( 9, 2)        0.0000000            0.0000000
                 Y( 9, 3)        0.0000000            0.0000000
                 Y( 9, 4)        0.0000000            0.0000000
                 Y( 9, 5)         1.000000            0.0000000
                 Y( 9, 6)        0.0000000            0.0000000
                Y( 10, 1)        0.0000000            0.0000000
                Y( 10, 2)        0.0000000            0.0000000
                Y( 10, 3)        0.0000000            0.0000000
                Y( 10, 4)        0.0000000            0.0000000
                Y( 10, 5)         1.000000            0.0000000
                Y( 10, 6)        0.0000000            0.0000000
                Y( 11, 1)        0.0000000            0.0000000
                Y( 11, 2)        0.0000000            0.0000000
                Y( 11, 3)        0.0000000            0.0000000
                Y( 11, 4)        0.0000000            0.0000000
                Y( 11, 5)         1.000000            0.0000000
                Y( 11, 6)        0.0000000            0.0000000
                Y( 12, 1)        0.0000000            0.0000000
                Y( 12, 2)        0.0000000            0.0000000
                Y( 12, 3)        0.0000000            0.0000000
                Y( 12, 4)        0.0000000            0.0000000
                Y( 12, 5)         1.000000            0.0000000
                Y( 12, 6)        0.0000000            0.0000000
                Y( 13, 1)        0.0000000            0.0000000
                Y( 13, 2)        0.0000000            0.0000000
                Y( 13, 3)        0.0000000            0.0000000
                Y( 13, 4)        0.0000000            0.0000000
                Y( 13, 5)         1.000000            0.0000000
                Y( 13, 6)        0.0000000            0.0000000

                      Row    Slack or Surplus      Dual Price
                     COST       -0.3251890E+09       -202.0500
                        2       -0.8750000E-03       0.0000000
                        3       -0.5625000E-03       0.0000000
                        4       -0.1437500E-02       0.0000000
                        5       -0.5000000E-03       0.0000000
                        6       -0.1656250E-02       0.0000000
                        7       -0.6250000E-04       0.0000000
                        8       -0.3625000E-02       0.0000000
                        9       -0.3250000E-02       0.0000000
                       10       -0.2562500E-02       0.0000000
                       11       -0.2375000E-02       0.0000000
                       12       -0.9062500E-03       0.0000000
                       13       -0.8750000E-03       0.0000000
                       14       -0.7500000E-03       0.0000000
                       15       -0.1250000E-07       0.0000000
                       16         1.000000           0.0000000
                       17       -0.1250000E-07       0.0000000
```

```
18         0.0000000                0.0000000
19         0.0000000                0.0000000
20        -0.1250000E-07            0.0000000
21        -0.1250000E-07            0.0000000
22         0.0000000                0.0000000
23        -0.1250000E-07            0.0000000
24        -0.1250000E-07            0.0000000
25        -0.1250000E-07            0.0000000
26        -0.1250000E-07            0.0000000
27         0.0000000                0.0000000
28         0.0000000                0.0000000
29         0.0000000                0.0000000
30         0.0000000                0.0000000
31         0.0000000                0.0000000
32         0.0000000                0.0000000
33         0.0000000                0.0000000
34         0.0000000                0.0000000
35         0.0000000                0.0000000
36         0.0000000                0.0000000
37         0.0000000                0.0000000
38         0.0000000                0.0000000
39         0.0000000                0.0000000
40         0.0000000                0.0000000
41         0.0000000                0.0000000
42        -0.3590005E-05            0.0000000
43         0.0000000                0.0000000
44         0.0000000                0.0000000
45         0.0000000                0.0000000
46         0.0000000                0.0000000
47        -0.5169428E-05            0.0000000
48         0.0000000                0.0000000
49         0.0000000                0.0000000
50         0.0000000                0.0000000
51         0.0000000                0.0000000
52         0.0000000                0.0000000
53         0.0000000                0.0000000
54         0.0000000                0.0000000
55         0.0000000                0.0000000
56         0.0000000                0.0000000
57         0.0000000                0.0000000
58         0.0000000                0.0000000
59         0.0000000                0.0000000
60         0.0000000                0.0000000
61         0.0000000                0.0000000
62         0.0000000                0.0000000
63         0.0000000                0.0000000
64         0.0000000                0.0000000
65         0.0000000                0.0000000
66         0.0000000                0.0000000
67         0.0000000                0.0000000
68         0.0000000                0.0000000
69         0.0000000                0.0000000
70         0.0000000                0.0000000
71         0.0000000                0.0000000
72         0.0000000                0.0000000
73         0.0000000                0.0000000
74         0.0000000                0.0000000
75         0.0000000                0.0000000
76         0.0000000                0.0000000
77         0.0000000                0.0000000
```

```
  78         0.0000000              0.0000000
  79         0.0000000              0.0000000
  80         0.0000000              0.0000000
  81         0.0000000              0.0000000
  82         0.0000000              0.0000000
  83         0.0000000              0.0000000
  84         0.0000000              0.0000000
  85         0.0000000              0.0000000
  86         0.0000000              0.0000000
  87         0.0000000              0.0000000
  88         0.0000000              0.0000000
  89         0.0000000              0.0000000
  90         0.0000000              0.0000000
  91         0.0000000              0.0000000
  92         0.0000000              0.0000000
  93         0.0000000              0.0000000
  94         0.0000000              0.0000000
  95         0.0000000              0.0000000
  96         0.0000000              0.0000000
  97         0.0000000              0.0000000
  98         0.0000000              0.0000000
  99         0.0000000              0.0000000
 100         0.0000000              0.0000000
 101         0.0000000              0.0000000
 102         0.0000000              0.0000000
 103         0.0000000              0.0000000
 104         0.0000000              0.0000000
 105         0.0000000              0.0000000
 106       -0.1250000E-07           0.0000000
 107         0.0000000              0.0000000
 108         0.0000000              0.0000000
 109         0.0000000              0.0000000
 110         0.0000000              0.0000000
 111         0.0000000              0.0000000
 112         0.0000000              0.0000000
 113         0.0000000              0.0000000
 114         0.0000000              0.0000000
 115         0.0000000              0.0000000
 116         0.0000000              0.0000000
 117          1.000000              0.0000000
 118         0.0000000              0.0000000
 119         0.0000000              0.0000000
 120         0.0000000              0.0000000
 121         0.0000000              0.0000000
 122         0.0000000              0.0000000
 123         0.0000000              0.0000000
 124         0.0000000              0.0000000
 125         0.0000000              0.0000000
 126         0.0000000              0.0000000
 127         0.0000000              0.0000000
 128         0.0000000              0.0000000
 129         0.0000000              0.0000000
 130         0.0000000              0.0000000
 131         0.0000000              0.0000000
 132         0.0000000              0.0000000
 133         0.0000000              0.0000000
 134         0.0000000              0.0000000
 135         0.0000000              0.0000000
 136         0.0000000              0.0000000
 137         0.0000000              0.0000000
```

```
138        0.0000000            0.0000000
139        0.0000000            0.0000000
140        0.0000000            0.0000000
141        0.0000000            0.0000000
142        0.0000000            0.0000000
143        0.0000000            0.0000000
144        0.0000000            0.0000000
145        0.0000000            0.0000000
146        0.0000000            0.0000000
147        0.0000000            0.0000000
148        0.0000000            0.0000000
149        0.0000000            0.0000000
150        0.0000000            0.0000000
151        0.0000000            0.0000000
152        0.0000000            0.0000000
153        0.0000000            0.0000000
154        0.0000000            0.0000000
155        0.0000000            0.0000000
156        0.0000000            0.0000000
157        0.0000000            0.0000000
158        0.0000000            0.0000000
159        0.0000000            0.0000000
160        0.0000000            0.0000000
161        0.0000000            0.0000000
162        0.0000000            0.0000000
163        0.0000000            0.0000000
164        0.0000000            0.0000000
165        0.0000000            0.0000000
166        0.0000000            0.0000000
167        0.0000000            0.0000000
168        0.0000000            0.0000000
169        0.0000000            0.0000000
170        0.0000000            0.0000000
171        0.0000000            0.0000000
172        0.0000000            0.0000000
173        0.0000000            0.0000000
174        0.0000000            0.0000000
175        0.0000000            0.0000000
176        0.0000000            0.0000000
177        0.0000000            0.0000000
178        0.0000000            0.0000000
179        0.0000000            0.0000000
180        0.0000000            0.0000000
181        0.0000000            0.0000000
182        0.0000000            0.0000000
183        0.0000000            0.0000000
184        0.0000000            0.0000000
```

(c) Weighting to GWP: 0.7 and weighting to economics: 0.3

(1.) LINGO CODE

```
MODEL:

SETS:
     SUGAR / 1..13 /                    : SMBAG, ELBAG;
     ETHANOL / 1..6 /                   : Z;
     LINKSMET( SUGAR, ETHANOL)          : ETBAG, D, Y;

ENDSETS

    DATA:

      SMBAG = 36407.796, 34149.851, 68128.772, 52630.688, 52303.471,
87091.836, 90239.012,           104982.903, 89329.901, 89591.893,
61628.003, 36663.296, 61258.657;

          D =      122,  98,   194,  73,   185,  196,
                   206,  271,  146,  295,  209,  46,
                   133,  209,  53,   263,  82,   145,
                   96,   168,  50,   225,  38,   157,
                   97,   171,  42,   227,  43,   149,
                   53,   125,  59,   182,  14,   155,
                   49,   89,   110,  150,  49,   197,
                   78,   91,   141,  152,  77,   231,
                   134,  69,   224,  8,    195,  252,
                   81,   6,    175,  64,   132,  230,
                   222,  150,  312,  92,   280,  333,
                   108,  186,  18,   232,  84,   92,
                   134,  200,  88,   228,  143,  26;


ENDDATA

!//////////////////OBJECTIVE FUNCTION ////////////////////////;

   [COST] MIN  =       @SUM(LINKSMET(I,J):0.3*1.13*2*D(I,J)*ETBAG(I,J)*Y(I,J)) +
                        @SUM(LINKSMET(I,J):0.3*840*ETBAG(I,J)*Y(I,J)) +
                  0.3*2124915868*(@SUM(LINKSMET(I,J):ETBAG(I,J)*Y(I,J))/1460000)^0.7 -
                       @SUM(LINKSMET(I,J):0.3*3346.2*ETBAG(I,J)*Y(I,J)) +
                       @SUM(LINKSMET(I,J):0.7*498.7559567*ETBAG(I,J)*Y(I,J)) +
                       @SUM(LINKSMET(I,J):0.7*0.075*2*D(I,J)*ETBAG(I,J)*Y(I,J)) +
                       @SUM(LINKSMET(I,J):0.7*0.070370166*2*D(I,J)*ETBAG(I,J)*Y(I,J)) -
                       @SUM(LINKSMET(I,J):0.7*600.855253*ETBAG(I,J)*Y(I,J)) +
                       @SUM(SUGAR(I):0.7*673.5*ELBAG(I));
```

```
!///////////////////CONSTRAINTS ////////////////////////;

!SUBJECT TO;
@FOR(SUGAR(I):
      @SUM(ETHANOL(J): ETBAG(I,J))+ ELBAG(I) = SMBAG(I));

@FOR( SUGAR( I):
      @SUM( ETHANOL( J): Y( I, J)) <= 1);

@FOR(SUGAR(I):
      @FOR(ETHANOL(J):ETBAG(I,J) = ETBAG(I,J)*Y(I,J)));


@SUM(ETHANOL(J):Z(J))=1;

@FOR(SUGAR(I):
      @FOR(ETHANOL(J): Y(I,J)<=Z(J)));

!Y BINARY;
      @FOR(LINKSMET(I,J):
        @BIN(Y(I,J)));

!Z BINARY;
      @FOR(ETHANOL(J): @BIN(Z(J)));
END
```

(2.) RESULT

```
Rows=     184 Vars=     175 No. integer vars=      84
 Nonlinear rows=      79 Nonlinear vars=     156 Nonlinear constraints=
78
 Nonzeros=     683 Constraint nonz=    487 Density=0.021
 No. < :   91 No. =:   92 No. > :    0, Obj=MIN Single cols=     0

 Optimal solution found at step:         11
 Objective value:               -0.1599372E+09
 Branch count:                           0

                      Variable           Value        Reduced Cost
                     SMBAG( 1)        36407.80           0.0000000
                     SMBAG( 2)        34149.85           0.0000000
                     SMBAG( 3)        68128.77           0.0000000
                     SMBAG( 4)        52630.69           0.0000000
                     SMBAG( 5)        52303.47           0.0000000
                     SMBAG( 6)        87091.84           0.0000000
                     SMBAG( 7)        90239.01           0.0000000
                     SMBAG( 8)        104982.9           0.0000000
                     SMBAG( 9)        89329.90           0.0000000
                    SMBAG( 10)        89591.89           0.0000000
                    SMBAG( 11)        61628.00           0.0000000
                    SMBAG( 12)        36663.30           0.0000000
                    SMBAG( 13)        61258.66           0.0000000
                     ELBAG( 1)       0.0000000           0.0000000
                     ELBAG( 2)        34149.85           0.0000000
                     ELBAG( 3)       0.0000000           0.0000000
                     ELBAG( 4)       0.0000000           0.0000000
                     ELBAG( 5)       0.0000000           0.0000000
                     ELBAG( 6)       0.0000000           0.0000000
                     ELBAG( 7)       0.0000000           0.0000000
                     ELBAG( 8)       0.0000000           0.0000000
                     ELBAG( 9)       0.0000000           0.0000000
                    ELBAG( 10)       0.0000000           0.0000000
                    ELBAG( 11)       0.0000000           0.0000000
                    ELBAG( 12)       0.0000000           0.0000000
                    ELBAG( 13)       0.0000000           0.0000000
                         Z( 1)       0.0000000           0.0000000
                         Z( 2)       0.0000000           0.0000000
                         Z( 3)       0.0000000           0.0000000
                         Z( 4)       0.0000000           0.0000000
                         Z( 5)        1.000000           0.0000000
                         Z( 6)       0.0000000           0.0000000
                  ETBAG( 1, 1)       0.0000000           0.0000000
                  ETBAG( 1, 2)       0.0000000           0.0000000
                  ETBAG( 1, 3)       0.0000000           0.0000000
                  ETBAG( 1, 4)       0.2838020E-13       0.0000000
                  ETBAG( 1, 5)        36407.80           0.0000000
                  ETBAG( 1, 6)       0.0000000           0.0000000
                  ETBAG( 2, 1)       0.0000000           0.0000000
                  ETBAG( 2, 2)       0.0000000           0.0000000
                  ETBAG( 2, 3)       0.0000000           0.0000000
                  ETBAG( 2, 4)       0.0000000           0.0000000
                  ETBAG( 2, 5)       0.0000000           0.0000000
                  ETBAG( 2, 6)       0.1053212E-13       0.0000000
                  ETBAG( 3, 1)       0.0000000           0.0000000
```

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  ETBAG( 3, 2)      0.0000000            0.0000000
  ETBAG( 3, 3)      0.0000000            0.0000000
  ETBAG( 3, 4)      0.0000000            0.0000000
  ETBAG( 3, 5)       68128.77            0.0000000
  ETBAG( 3, 6)      0.0000000            0.0000000
  ETBAG( 4, 1)      0.0000000            0.0000000
  ETBAG( 4, 2)      0.0000000            0.0000000
  ETBAG( 4, 3)      0.0000000            0.0000000
  ETBAG( 4, 4)      0.0000000            0.0000000
  ETBAG( 4, 5)       52630.69            0.0000000
  ETBAG( 4, 6)      0.0000000            0.0000000
  ETBAG( 5, 1)      0.0000000            0.0000000
  ETBAG( 5, 2)      0.0000000            0.0000000
  ETBAG( 5, 3)      0.0000000            0.0000000
  ETBAG( 5, 4)      0.0000000            0.0000000
  ETBAG( 5, 5)       52303.47            0.0000000
  ETBAG( 5, 6)      0.0000000            0.0000000
  ETBAG( 6, 1)      0.0000000            0.0000000
  ETBAG( 6, 2)      0.0000000            0.0000000
  ETBAG( 6, 3)      0.0000000            0.0000000
  ETBAG( 6, 4)      0.0000000            0.0000000
  ETBAG( 6, 5)       87091.84            0.0000000
  ETBAG( 6, 6)      0.0000000            0.0000000
  ETBAG( 7, 1)      0.0000000            0.0000000
  ETBAG( 7, 2)      0.0000000            0.0000000
  ETBAG( 7, 3)      0.0000000            0.0000000
  ETBAG( 7, 4)      0.8939205E-22        0.0000000
  ETBAG( 7, 5)       90239.02            0.0000000
  ETBAG( 7, 6)      0.0000000            0.0000000
  ETBAG( 8, 1)      0.0000000            0.0000000
  ETBAG( 8, 2)      0.0000000            0.0000000
  ETBAG( 8, 3)      0.0000000            0.0000000
  ETBAG( 8, 4)      0.0000000            0.0000000
  ETBAG( 8, 5)       104982.9            0.0000000
  ETBAG( 8, 6)      0.0000000            0.0000000
  ETBAG( 9, 1)      0.0000000            0.0000000
  ETBAG( 9, 2)      0.0000000            0.0000000
  ETBAG( 9, 3)      0.0000000            0.0000000
  ETBAG( 9, 4)      0.0000000            0.0000000
  ETBAG( 9, 5)       89329.90            0.0000000
  ETBAG( 9, 6)      0.0000000            0.0000000
 ETBAG( 10, 1)      0.0000000            0.0000000
 ETBAG( 10, 2)      0.2603881E-13        0.0000000
 ETBAG( 10, 3)      0.0000000            0.0000000
 ETBAG( 10, 4)      0.0000000            0.0000000
 ETBAG( 10, 5)       89591.89            0.0000000
 ETBAG( 10, 6)      0.0000000            0.0000000
 ETBAG( 11, 1)      0.0000000            0.0000000
 ETBAG( 11, 2)      0.0000000            0.0000000
 ETBAG( 11, 3)      0.0000000            0.0000000
 ETBAG( 11, 4)      0.0000000            0.0000000
 ETBAG( 11, 5)       61628.00            0.0000000
 ETBAG( 11, 6)      0.0000000            0.0000000
 ETBAG( 12, 1)      0.0000000            0.0000000
 ETBAG( 12, 2)      0.0000000            0.0000000
 ETBAG( 12, 3)      0.0000000            0.0000000
 ETBAG( 12, 4)      0.0000000            0.0000000
 ETBAG( 12, 5)       36663.30            0.0000000
 ETBAG( 12, 6)      0.0000000            0.0000000
 ETBAG( 13, 1)      0.0000000            0.0000000
```

```
ETBAG( 13, 2)      0.0000000          0.0000000
ETBAG( 13, 3)      0.0000000          0.0000000
ETBAG( 13, 4)      0.0000000          0.0000000
ETBAG( 13, 5)       61258.66          0.0000000
ETBAG( 13, 6)      0.2028638E-13      0.0000000
     D( 1, 1)       122.0000          0.0000000
     D( 1, 2)       98.00000          0.0000000
     D( 1, 3)       194.0000          0.0000000
     D( 1, 4)       73.00000          0.0000000
     D( 1, 5)       185.0000          0.0000000
     D( 1, 6)       196.0000          0.0000000
     D( 2, 1)       206.0000          0.0000000
     D( 2, 2)       271.0000          0.0000000
     D( 2, 3)       146.0000          0.0000000
     D( 2, 4)       295.0000          0.0000000
     D( 2, 5)       209.0000          0.0000000
     D( 2, 6)       46.00000          0.0000000
     D( 3, 1)       133.0000          0.0000000
     D( 3, 2)       209.0000          0.0000000
     D( 3, 3)       53.00000          0.0000000
     D( 3, 4)       263.0000          0.0000000
     D( 3, 5)       82.00000          0.0000000
     D( 3, 6)       145.0000          0.0000000
     D( 4, 1)       96.00000          0.0000000
     D( 4, 2)       168.0000          0.0000000
     D( 4, 3)       50.00000          0.0000000
     D( 4, 4)       225.0000          0.0000000
     D( 4, 5)       38.00000          0.0000000
     D( 4, 6)       157.0000          0.0000000
     D( 5, 1)       97.00000          0.0000000
     D( 5, 2)       171.0000          0.0000000
     D( 5, 3)       42.00000          0.0000000
     D( 5, 4)       227.0000          0.0000000
     D( 5, 5)       43.00000          0.0000000
     D( 5, 6)       149.0000          0.0000000
     D( 6, 1)       53.00000          0.0000000
     D( 6, 2)       125.0000          0.0000000
     D( 6, 3)       59.00000          0.0000000
     D( 6, 4)       182.0000          0.0000000
     D( 6, 5)       14.00000          0.0000000
     D( 6, 6)       155.0000          0.0000000
     D( 7, 1)       49.00000          0.0000000
     D( 7, 2)       89.00000          0.0000000
     D( 7, 3)       110.0000          0.0000000
     D( 7, 4)       150.0000          0.0000000
     D( 7, 5)       49.00000          0.0000000
     D( 7, 6)       197.0000          0.0000000
     D( 8, 1)       78.00000          0.0000000
     D( 8, 2)       91.00000          0.0000000
     D( 8, 3)       141.0000          0.0000000
     D( 8, 4)       152.0000          0.0000000
     D( 8, 5)       77.00000          0.0000000
     D( 8, 6)       231.0000          0.0000000
     D( 9, 1)       134.0000          0.0000000
     D( 9, 2)       69.00000          0.0000000
     D( 9, 3)       224.0000          0.0000000
     D( 9, 4)       8.000000          0.0000000
     D( 9, 5)       195.0000          0.0000000
     D( 9, 6)       252.0000          0.0000000
    D( 10, 1)       81.00000          0.0000000
```

```
D( 10, 2)        6.000000             0.0000000
D( 10, 3)        175.0000             0.0000000
D( 10, 4)        64.00000             0.0000000
D( 10, 5)        132.0000             0.0000000
D( 10, 6)        230.0000             0.0000000
D( 11, 1)        222.0000             0.0000000
D( 11, 2)        150.0000             0.0000000
D( 11, 3)        312.0000             0.0000000
D( 11, 4)        92.00000             0.0000000
D( 11, 5)        280.0000             0.0000000
D( 11, 6)        333.0000             0.0000000
D( 12, 1)        108.0000             0.0000000
D( 12, 2)        186.0000             0.0000000
D( 12, 3)        18.00000             0.0000000
D( 12, 4)        232.0000             0.0000000
D( 12, 5)        84.00000             0.0000000
D( 12, 6)        92.00000             0.0000000
D( 13, 1)        134.0000             0.0000000
D( 13, 2)        200.0000             0.0000000
D( 13, 3)        88.00000             0.0000000
D( 13, 4)        228.0000             0.0000000
D( 13, 5)        143.0000             0.0000000
D( 13, 6)        26.00000             0.0000000
  Y( 1, 1)      0.0000000             0.0000000
  Y( 1, 2)      0.0000000             0.0000000
  Y( 1, 3)      0.0000000             0.0000000
  Y( 1, 4)      0.0000000             0.0000000
  Y( 1, 5)       1.000000             0.0000000
  Y( 1, 6)      0.0000000             0.0000000
  Y( 2, 1)      0.0000000             0.0000000
  Y( 2, 2)      0.0000000             0.0000000
  Y( 2, 3)      0.0000000             0.0000000
  Y( 2, 4)      0.0000000             0.0000000
  Y( 2, 5)      0.0000000             0.0000000
  Y( 2, 6)      0.0000000             0.0000000
  Y( 3, 1)      0.0000000             0.0000000
  Y( 3, 2)      0.0000000             0.0000000
  Y( 3, 3)      0.0000000             0.0000000
  Y( 3, 4)      0.0000000             0.0000000
  Y( 3, 5)       1.000000             0.0000000
  Y( 3, 6)      0.0000000             0.0000000
  Y( 4, 1)      0.0000000             0.0000000
  Y( 4, 2)      0.0000000             0.0000000
  Y( 4, 3)      0.0000000             0.0000000
  Y( 4, 4)      0.0000000             0.0000000
  Y( 4, 5)       1.000000             0.0000000
  Y( 4, 6)      0.0000000             0.0000000
  Y( 5, 1)      0.0000000             0.0000000
  Y( 5, 2)      0.0000000             0.0000000
  Y( 5, 3)      0.0000000             0.0000000
  Y( 5, 4)      0.0000000             0.0000000
  Y( 5, 5)       1.000000             0.0000000
  Y( 5, 6)      0.0000000             0.0000000
  Y( 6, 1)      0.0000000             0.0000000
  Y( 6, 2)      0.0000000             0.0000000
  Y( 6, 3)      0.0000000             0.0000000
  Y( 6, 4)      0.0000000             0.0000000
  Y( 6, 5)       1.000000             0.0000000
  Y( 6, 6)      0.0000000             0.0000000
  Y( 7, 1)      0.0000000             0.0000000
```

```
          Y( 7, 2)        0.0000000            0.0000000
          Y( 7, 3)        0.0000000            0.0000000
          Y( 7, 4)        0.0000000            0.0000000
          Y( 7, 5)         1.000000            0.0000000
          Y( 7, 6)        0.0000000            0.0000000
          Y( 8, 1)        0.0000000            0.0000000
          Y( 8, 2)        0.0000000            0.0000000
          Y( 8, 3)        0.0000000            0.0000000
          Y( 8, 4)        0.0000000            0.0000000
          Y( 8, 5)         1.000000            0.0000000
          Y( 8, 6)        0.0000000            0.0000000
          Y( 9, 1)        0.0000000            0.0000000
          Y( 9, 2)        0.0000000            0.0000000
          Y( 9, 3)        0.0000000            0.0000000
          Y( 9, 4)        0.0000000            0.0000000
          Y( 9, 5)         1.000000            0.0000000
          Y( 9, 6)        0.0000000            0.0000000
         Y( 10, 1)        0.0000000            0.0000000
         Y( 10, 2)        0.0000000            0.0000000
         Y( 10, 3)        0.0000000            0.0000000
         Y( 10, 4)        0.0000000            0.0000000
         Y( 10, 5)         1.000000            0.0000000
         Y( 10, 6)        0.0000000            0.0000000
         Y( 11, 1)        0.0000000            0.0000000
         Y( 11, 2)        0.0000000            0.0000000
         Y( 11, 3)        0.0000000            0.0000000
         Y( 11, 4)        0.0000000            0.0000000
         Y( 11, 5)         1.000000            0.0000000
         Y( 11, 6)        0.0000000            0.0000000
         Y( 12, 1)        0.0000000            0.0000000
         Y( 12, 2)        0.0000000            0.0000000
         Y( 12, 3)        0.0000000            0.0000000
         Y( 12, 4)        0.0000000            0.0000000
         Y( 12, 5)         1.000000            0.0000000
         Y( 12, 6)        0.0000000            0.0000000
         Y( 13, 1)        0.0000000            0.0000000
         Y( 13, 2)        0.0000000            0.0000000
         Y( 13, 3)        0.0000000            0.0000000
         Y( 13, 4)        0.0000000            0.0000000
         Y( 13, 5)         1.000000            0.0000000
         Y( 13, 6)        0.0000000            0.0000000

               Row   Slack or Surplus      Dual Price
              COST     -0.1599372E+09       0.0000000
                 2     -0.8750000E-03       0.0000000
                 3     -0.5625000E-03       0.0000000
                 4     -0.1437500E-02       0.0000000
                 5     -0.5000000E-03       0.0000000
                 6     -0.1656250E-02       0.0000000
                 7     -0.6250000E-04       0.0000000
                 8     -0.3625000E-02       0.0000000
                 9     -0.3250000E-02       0.0000000
                10     -0.2562500E-02       0.0000000
                11     -0.2375000E-02       0.0000000
                12     -0.9062500E-03       0.0000000
                13     -0.8750000E-03       0.0000000
                14     -0.7500000E-03       0.0000000
                15      0.0000000           0.0000000
                16       1.000000           0.0000000
                17      0.0000000           0.0000000
```

```
 18        0.0000000              0.0000000
 19        0.0000000              0.0000000
 20        0.0000000              0.0000000
 21        0.0000000              0.0000000
 22        0.0000000              0.0000000
 23        0.0000000              0.0000000
 24        0.0000000              0.0000000
 25        0.0000000              0.0000000
 26        0.0000000              0.0000000
 27        0.0000000              0.0000000
 28        0.0000000              0.0000000
 29        0.0000000              0.0000000
 30        0.0000000              0.0000000
 31        0.0000000              0.0000000
 32        0.0000000              0.0000000
 33        0.0000000              0.0000000
 34        0.0000000              0.0000000
 35        0.0000000              0.0000000
 36        0.0000000              0.0000000
 37        0.0000000              0.0000000
 38        0.0000000              0.0000000
 39        0.0000000              0.0000000
 40        0.0000000              0.0000000
 41        0.0000000              0.0000000
 42        0.0000000              0.0000000
 43        0.0000000              0.0000000
 44        0.0000000              0.0000000
 45        0.0000000              0.0000000
 46        0.0000000              0.0000000
 47        0.0000000              0.0000000
 48        0.0000000              0.0000000
 49        0.0000000              0.0000000
 50        0.0000000              0.0000000
 51        0.0000000              0.0000000
 52        0.0000000              0.0000000
 53        0.0000000              0.0000000
 54        0.0000000              0.0000000
 55        0.0000000              0.0000000
 56        0.0000000              0.0000000
 57        0.0000000              0.0000000
 58        0.0000000              0.0000000
 59        0.0000000              0.0000000
 60        0.0000000              0.0000000
 61        0.0000000              0.0000000
 62        0.0000000              0.0000000
 63        0.0000000              0.0000000
 64        0.0000000              0.0000000
 65        0.0000000              0.0000000
 66        0.0000000              0.0000000
 67        0.0000000              0.0000000
 68        0.0000000              0.0000000
 69        0.0000000              0.0000000
 70        0.0000000              0.0000000
 71        0.0000000              0.0000000
 72        0.0000000              0.0000000
 73        0.0000000              0.0000000
 74        0.0000000              0.0000000
 75        0.0000000              0.0000000
 76        0.0000000              0.0000000
 77        0.0000000              0.0000000
```

```
  78         0.0000000                0.0000000
  79         0.0000000                0.0000000
  80         0.0000000                0.0000000
  81         0.0000000                0.0000000
  82         0.0000000                0.0000000
  83         0.0000000                0.0000000
  84         0.0000000                0.0000000
  85         0.0000000                0.0000000
  86         0.0000000                0.0000000
  87         0.0000000                0.0000000
  88         0.0000000                0.0000000
  89         0.0000000                0.0000000
  90         0.0000000                0.0000000
  91         0.0000000                0.0000000
  92         0.0000000                0.0000000
  93         0.0000000                0.0000000
  94         0.0000000                0.0000000
  95         0.0000000                0.0000000
  96         0.0000000                0.0000000
  97         0.0000000                0.0000000
  98         0.0000000                0.0000000
  99         0.0000000                0.0000000
 100         0.0000000                0.0000000
 101         0.0000000                0.0000000
 102         0.0000000                0.0000000
 103         0.0000000                0.0000000
 104         0.0000000                0.0000000
 105         0.0000000                0.0000000
 106         0.0000000                0.0000000
 107         0.0000000                0.0000000
 108         0.0000000                0.0000000
 109         0.0000000                0.0000000
 110         0.0000000                0.0000000
 111         0.0000000                0.0000000
 112         0.0000000                0.0000000
 113         0.0000000                0.0000000
 114         0.0000000                0.0000000
 115         0.0000000                0.0000000
 116         0.0000000                0.0000000
 117          1.000000                0.0000000
 118         0.0000000                0.0000000
 119         0.0000000                0.0000000
 120         0.0000000                0.0000000
 121         0.0000000                0.0000000
 122         0.0000000                0.0000000
 123         0.0000000                0.0000000
 124         0.0000000                0.0000000
 125         0.0000000                0.0000000
 126         0.0000000                0.0000000
 127         0.0000000                0.0000000
 128         0.0000000                0.0000000
 129         0.0000000                0.0000000
 130         0.0000000                0.0000000
 131         0.0000000                0.0000000
 132         0.0000000                0.0000000
 133         0.0000000                0.0000000
 134         0.0000000                0.0000000
 135         0.0000000                0.0000000
 136         0.0000000                0.0000000
 137         0.0000000                0.0000000
```

138	0.0000000	0.0000000
139	0.0000000	0.0000000
140	0.0000000	0.0000000
141	0.0000000	0.0000000
142	0.0000000	0.0000000
143	0.0000000	0.0000000
144	0.0000000	0.0000000
145	0.0000000	0.0000000
146	0.0000000	0.0000000
147	0.0000000	0.0000000
148	0.0000000	0.0000000
149	0.0000000	0.0000000
150	0.0000000	0.0000000
151	0.0000000	0.0000000
152	0.0000000	0.0000000
153	0.0000000	0.0000000
154	0.0000000	0.0000000
155	0.0000000	0.0000000
156	0.0000000	0.0000000
157	0.0000000	0.0000000
158	0.0000000	0.0000000
159	0.0000000	0.0000000
160	0.0000000	0.0000000
161	0.0000000	0.0000000
162	0.0000000	0.0000000
163	0.0000000	0.0000000
164	0.0000000	0.0000000
165	0.0000000	0.0000000
166	0.0000000	0.0000000
167	0.0000000	0.0000000
168	0.0000000	0.0000000
169	0.0000000	0.0000000
170	0.0000000	0.0000000
171	0.0000000	0.0000000
172	0.0000000	0.0000000
173	0.0000000	0.0000000
174	0.0000000	0.0000000
175	0.0000000	0.0000000
176	0.0000000	0.0000000
177	0.0000000	0.0000000
178	0.0000000	0.0000000
179	0.0000000	0.0000000
180	0.0000000	0.0000000
181	0.0000000	0.0000000
182	0.0000000	0.0000000
183	0.0000000	0.0000000
184	0.0000000	0.0000000

(d) Weighting to GWP: 1.0 and weighting to economics: 0.0

(1.)LINGO CODE

```
MODEL:

SETS:
     SUGAR / 1..13 /                    : SMBAG, ELBAG;
     ETHANOL / 1..6 /                   : Z;
     LINKSMET( SUGAR, ETHANOL)          : ETBAG, D, Y;

ENDSETS

    DATA:

      SMBAG = 36407.796, 34149.851, 68128.772, 52630.688, 52303.471,
87091.836, 90239.012,           104982.903, 89329.901, 89591.893,
61628.003, 36663.296, 61258.657;

          D =      122,  98,   194,  73,   185,  196,
                   206,  271,  146,  295,  209,  46,
                   133,  209,  53,   263,  82,   145,
                   96,   168,  50,   225,  38,   157,
                   97,   171,  42,   227,  43,   149,
                   53,   125,  59,   182,  14,   155,
                   49,   89,   110,  150,  49,   197,
                   78,   91,   141,  152,  77,   231,
                   134,  69,   224,  8,    195,  252,
                   81,   6,    175,  64,   132,  230,
                   222,  150,  312,  92,   280,  333,
                   108,  186,  18,   232,  84,   92,
                   134,  200,  88,   228,  143,  26;


ENDDATA

!/////////////////OBJECTIVE FUNCTION ///////////////////////;

  [COST] MIN =      @SUM(LINKSMET(I,J):0*1.13*2*D(I,J)*ETBAG(I,J)*Y(I,J)) +
                     @SUM(LINKSMET(I,J):0*840*ETBAG(I,J)*Y(I,J)) +
                    0*2124915868*(@SUM(LINKSMET(I,J):ETBAG(I,J)*Y(I,J))/1460000)^0.7 -
                    @SUM(LINKSMET(I,J):0*3346.2*ETBAG(I,J)*Y(I,J)) +
                    @SUM(LINKSMET(I,J):1*498.7559567*ETBAG(I,J)*Y(I,J)) +
                    @SUM(LINKSMET(I,J):1*0.075*2*D(I,J)*ETBAG(I,J)*Y(I,J)) +
                    @SUM(LINKSMET(I,J):1*0.070370166*2*D(I,J)*ETBAG(I,J)*Y(I,J)) -
                    @SUM(LINKSMET(I,J):1*600.855253*ETBAG(I,J)*Y(I,J)) +
                    @SUM(SUGAR(I):1*673.5*ELBAG(I));
```

```
!/////////////////CONSTRAINTS ///////////////////////;

!SUBJECT TO;
@FOR(SUGAR(I):
      @SUM(ETHANOL(J): ETBAG(I,J))+ ELBAG(I) = SMBAG(I));

@FOR( SUGAR( I):
      @SUM( ETHANOL( J): Y( I, J)) <= 1);

@FOR(SUGAR(I):
      @FOR(ETHANOL(J):ETBAG(I,J) = ETBAG(I,J)*Y(I,J)));


@SUM(ETHANOL(J):Z(J))=1;

@FOR(SUGAR(I):
      @FOR(ETHANOL(J): Y(I,J)<=Z(J)));

!Y BINARY;
      @FOR(LINKSMET(I,J):
        @BIN(Y(I,J)));

!Z BINARY;
      @FOR(ETHANOL(J): @BIN(Z(J)));
END
```

(2.) RESULT

```
Rows=     184 Vars=     175 No. integer vars=      84
 Nonlinear rows=      79 Nonlinear vars=     156 Nonlinear constraints=
78
 Nonzeros=     683 Constraint nonz=    487 Density=0.021
 No. < :   91 No. =:   92 No. > :    0, Obj=MIN Single cols=     0

 Optimal solution found at step:         6
 Objective value:                -0.6040988E+08
 Branch count:                           0


                       Variable           Value        Reduced Cost
                      SMBAG( 1)        36407.80           0.0000000
                      SMBAG( 2)        34149.85           0.0000000
                      SMBAG( 3)        68128.77           0.0000000
                      SMBAG( 4)        52630.69           0.0000000
                      SMBAG( 5)        52303.47           0.0000000
                      SMBAG( 6)        87091.84           0.0000000
                      SMBAG( 7)        90239.01           0.0000000
                      SMBAG( 8)        104982.9           0.0000000
                      SMBAG( 9)        89329.90           0.0000000
                     SMBAG( 10)        89591.89           0.0000000
                     SMBAG( 11)        61628.00           0.0000000
                     SMBAG( 12)        36663.30           0.0000000
                     SMBAG( 13)        61258.66           0.0000000
                      ELBAG( 1)       0.0000000           0.0000000
                      ELBAG( 2)       0.0000000           0.0000000
                      ELBAG( 3)       0.0000000           0.0000000
                      ELBAG( 4)       0.0000000           0.0000000
                      ELBAG( 5)       0.0000000           0.0000000
                      ELBAG( 6)       0.0000000           0.0000000
                      ELBAG( 7)       0.0000000           0.0000000
                      ELBAG( 8)       0.0000000           0.0000000
                      ELBAG( 9)       0.0000000           0.0000000
                     ELBAG( 10)       0.0000000           0.0000000
                     ELBAG( 11)       0.0000000           0.0000000
                     ELBAG( 12)       0.0000000           0.0000000
                     ELBAG( 13)       0.0000000           0.0000000
                          Z( 1)       0.0000000           0.0000000
                          Z( 2)       0.0000000           0.0000000
                          Z( 3)       0.0000000           0.0000000
                          Z( 4)       0.0000000           0.0000000
                          Z( 5)        1.000000           0.0000000
                          Z( 6)       0.0000000           0.0000000
                   ETBAG( 1, 1)       0.0000000           0.0000000
                   ETBAG( 1, 2)       0.0000000           0.0000000
                   ETBAG( 1, 3)       0.0000000           0.0000000
                   ETBAG( 1, 4)       0.0000000           0.0000000
                   ETBAG( 1, 5)        36407.80           0.0000000
                   ETBAG( 1, 6)       0.0000000           0.0000000
                   ETBAG( 2, 1)       0.0000000           0.0000000
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APPENDIX B
MANUSCRIPT SUBMITTED TO
JOURNAL OF ENVIRONMENTAL IMPACT ASSESSMENTAL REVIEW

Ms. Ref. No.: EIR-D-07-00075R3
Title: The Development of Multi-Objective Optimization Model For Excess Bagasse Utilization: A Case Study for Thailand
Environmental Impact Assessment Review

Dear Bancha Buddadee,

I am pleased to inform you that your REVISED paper "The Development of Multi-Objective Optimization Model For Excess Bagasse Utilization: A Case Study for Thailand" has been accepted for publication in Environmental Impact Assessment Review.

Below are comments from the editor and reviewers.

Thank you for submitting your work to Environmental Impact Assessment Review.

Yours sincerely,

Eric Johnson
Editor-in-Chief
Environmental Impact Assessment Review

Comments from the editors and reviewers:

****

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Manuscript Draft

Manuscript Number: EIR-D-07-00075R3

Title: The Development of Multi-Objective Optimization Model For Excess Bagasse Utilization: A Case Study for Thailand

Article Type: Full Length Article

Section/Category:

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

Corresponding Author: Bancha Buddadee, M.Eng.

Corresponding Author's Institution: Chulalongkorn University

First Author: Bancha Buddadee, M.Eng.

Order of Authors: Bancha Buddadee, M.Eng.; Wanpen Wirojanakud, PhD; Daniel Watts, PhD; Rapeepan Pitakaso, PhD

Manuscript Region of Origin:

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 facilitate 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.

July 24, 2007

Dear Editor: Dr. Eric Johnson

We would like to thanks for your consideration on our paper. We would like to submit the revised version of the manuscript (Ms. Ref. No.: EIR-D-07-00075). The manuscript was revised according to the suggestions and comment of the reviewer(s). The changes / revisions made on the manuscript are explained in the following table.

Revisions	Reviewer(s) comments	Point of revision
1.	Table 5 is very important! They simply must point out the range of global warmer emissions under the different scenarios. It goes from 582 thousand tonnes positive to 60 thousand tonnes negative! This is interesting. They also must mention this in the abstract!	The abstract was rewritten. The second and third paragraphs of section 3.2 were rewritten.
2.	There are still a number of language mistakes. The authors need to find a good speaker of English to edit the draft carefully.	All files were checked and corrected.

We do hope that the revised manuscript conforms to all suggestions and comment. Please accept our sincerest thanks for your consideration.

Sincerely yours

Asst.Prof. Bancha Buddadee
Department of Mechanical Engineering
Faculty of Engineering, Ubon Ratchathani University
Ubon Ratchathani 34190, Thailand
Tel:+66-4535-3381
Fax:+66-4535-3333
E-mail: bancha_eng@yahoo.com

Cover Page

Article's title: The Development of Multi-Objective Optimization Model For Excess Bagasse Utilization: A Case Study for Thailand

Authors:
1.) Bancha Buddadee
National Research Center for Environmental and Hazardous Waste Management,
Chulalongkorn University, Bangkok 10330, Thailand
E-mail: bancha_eng@yahoo.com

2.) Wanpen Wirojanakud
Research Center of Environmental and Hazardous Substance Management,
Department of Environmental Engineering, Faculty of Engineering, Khon Kaen University,
Khon Kaen 40002, Thailand
E-mail: wanpen@kku.ac.th

3.) Daniel J. Watts
Center for Environmental Engineering and Science, New Jersey Institute of Technology,
Newark, New Jersey 07102, USA
E-mail: daniel.watts@njit.edu

4.) Rapeepan Pitakaso
Department of Industrial Engineering, Faculty of Engineering, Ubonratchathani University,
Ubonratchathani 34190, Thailand
E-mail: enrapepi@ubu.ac.th

Corresponding author:
Asst.Prof. Bancha Buddadee
Department of Mechanical Engineering, Faculty of Engineering,
Ubonratchathani University, Ubonratchathani 34190, Thailand
Tel.: +66-4535-3381
Fax: +66-4535-3333
E-mail: bancha_eng@yahoo.com

1.) Bancha Buddadee
National Research Center for Environmental and Hazardous Waste Management,
Chulalongkorn University, Bangkok 10330, Thailand

Biography:

Asst. Prof. Bancha Buddadee holds a M.Eng. from IHE, The Netherlands. He has joint the Department of Mechanical Engineering, Ubonratchathani University, Thailand as lecturer since 1996. His interested research areas are optimization system, renewable energy, public sector management, waste exchange management. He has involved in several projects such as design of municipality wastewater system (Jakarat Nakornratchasima, Thailand), provincial strategic planning on energy (Nakornphanom, Mukdaharn, and Kalasin, Thailand), demonstration and promotion of biodiesel for used vegetable oil, and etc.

2.) Wanpen Wirojanakud
Research Center of Environmental and Hazardous Substance Management,
Department of Environmental Engineering, Faculty of Engineering, Khon Kaen University,
Khon Kaen 40002, Thailand

Biography:

Assoc. Prof. Dr. Wanpen Wirojanakud holds a PhD in Environmental Engineering. She has served as Head of the Department of Environmental Engineering, Khon Kaen University, Thailand. She also established Research Center of Environmental and Hazardous Substance Management, Khon Kaen University and has served as executive director of the center. Her research areas cover waste exchange and management, wastewater management, and hazardous waste management.

3.) Daniel J. Watts
Center for Environmental Engineering and Science, New Jersey Institute of Technology,
Newark, New Jersey 07102, USA

Biography:

Dr. Daniel J. Watts holds a PhD in organic chemistry (1969) from Indiana University in Bloomington, Indiana. He has served as executive director of the Otto H. York Center for Environmental Engineering and Science, NJIT. Through interaction with New Jersey Department of Environmental Protection and the United States Environmental Protection Agency, he developed the concept and support for the New Jersey Technical Assistance Program for Industrial Pollution Prevention. In addition, he developed a research partnership with the U.S. Army Industrial Ecology Center, leading to the funding of the Sustainable Green Manufacturing Initiative.

4.) Rapeepan Pitakaso
Department of Industrial Engineering, Faculty of Engineering, Ubonratchathani University,
Ubonratchathani 34190, Thailand

Biography:

Dr. Rapeepan Pitakaso holds a PhD in "Business Administration: Production, Operation and Logistical Management" (2005) from University of Vienna, Austria. He has worked for the Department of Industrial Engineering, Ubonratchathani University, Thailand as lecturer since 1998. His research areas cover optimization, operation and production management, logistical management, software development, database management. He was awarded several scholarships such as Royal Thai government scholarship (2001-2003), Tim Kendal Price for the most outstanding student in academic performance, AIT (2003), and Austrian government scholarship (2003-2005).

Title Page

Article's title: The Development of Multi-Objective Optimization Model For Excess Bagasse Utilization: A Case Study for Thailand

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

Detailed Response to Reviewers

July 24, 2007

Dear Reviewer(s),

We would like to thanks for your consideration on our paper. We would like to submit the revised version of the manuscript (Ms. Ref. No.: EIR-D-07-00075). The manuscript was revised according to the suggestions and comment of the reviewer(s). The changes / revisions made on the manuscript are explained in the following table.

Revisions	Reviewer(s) comments	Point of revision
1.	Table 5 is very important! They simply must point out the range of global warmer emissions under the different scenarios. It goes from 582 thousand tonnes positive to 60 thousand tonnes negative! This is interesting. They also must mention this in the abstract!	The abstract was rewritten. The second and third paragraphs of section 3.2 were rewritten.
2.	There are still a number of language mistakes. The authors need to find a good speaker of English to edit the draft carefully.	All files were checked and corrected.

We do hope that the revised manuscript conforms to all suggestions and comment. Please accept our sincerest thanks for your consideration.

Sincerely yours

Asst.Prof. Bancha Buddadee
Department of Mechanical Engineering
Faculty of Engineering, Ubon Ratchathani University
Ubon Ratchathani 34190, Thailand
Tel:+66-4535-3381
Fax:+66-4535-3333
E-mail: bancha_eng@yahoo.com

The Development of Multi-Objective Optimization Model For Excess Bagasse Utilization: A Case Study for Thailand

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 facilitate 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) 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 lignocellolusic 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 have 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 the corn and linocellulosic 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 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 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 scheme 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,……,I ; j = 1,……,J)
E10GWP	offset GWP due to the utilization of produced ethanol as E10 fuel
EBCOST	cost of excess bagasse burnt in all sugar mills
EECON	economic effects from the utilization of excess bagasse in scheme 1
EELBFIT	benefit from selling electricity generated from burning of excess bagasse in all sugar mills
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 produced in 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,……,I)
ELGWP	offset GWP due to the generation of electricity by burning of excess bagasse in all sugar mills
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).

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

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).

$$EGWP = BGWP + ELGWP \tag{2}$$

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).

$$BGWP = \sum_{i=1}^{I} EFB \; x \; ELBAG_i \qquad \forall i \tag{3}$$

$$ELGWP = \sum_{i=1}^{I} EFEL \; x \; ELBAG_i \qquad \forall i \tag{4}$$

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).

$$PGWP = TGWP + ETGWP + E10GWP \tag{5}$$

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) to (8).

$$TGWP = \sum_{j=1}^{J}\sum_{i=1}^{I} EFT \ x \ D_{ij} \ x \ ETBAG_{ij} \ x \ y_{ij} \quad \forall i, \forall j \tag{6}$$

$$ETGWP = \sum_{j=1}^{J}\sum_{i=1}^{I} EFET \ x \ ETBAG_{ij} \ x \ y_{ij} \quad \forall i, \forall j \tag{7}$$

$$E10GWP = \sum_{j=1}^{J}\sum_{i=1}^{I} EFE10 \ x \ ETBAG_{ij} \ x \ y_{ij} \quad \forall i, \forall j \tag{8}$$

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) to (11).

$$EECON = EBCOST - EELBFIT \tag{9}$$

$$EBCOST = \sum_{i=1}^{I} UPB \ x \ ELBAG_{i} \quad \forall i \tag{10}$$

$$EELBFIT = \sum_{i=1}^{I} ELP \ x \ ELPF \ x \ ELBAG_{i} \quad \forall i \tag{11}$$

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

$$PECON = PCOST - PBFIT \qquad (12)$$

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) to (16).

$$PCOST = PBCOST + PTCOST + PEPCOST \qquad (13)$$

$$PBCOST = \sum_{j=1}^{J}\sum_{i=1}^{I} UPB \; x \; ETBAG_{ij} \; x \; Y_{ij} \quad \forall i, \forall j \qquad (14)$$

$$PTCOST = \sum_{j=1}^{J}\sum_{i=1}^{I} UCT \; x \; D_{ij} \; x \; ETBAG_{ij} \; x \; Y_{ij} \quad \forall i, \forall j \qquad (15)$$

$$PEPCOST = BCCOST \; x \; ((\sum_{j=1}^{J}\sum_{i=1}^{I} ETBAG_{ij} \; x \; Y_{ij}) \,/\, BCSIZE)^{exp} \quad \forall i, \forall j \qquad (16)$$

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) to (19).

$$PBFIT = PETBFIT + PELBFIT \tag{17}$$

$$PETBFIT = \sum_{j=1}^{J}\sum_{i=1}^{I} ETP \ x \ ETPF \ x \ ETBAG_{ij} \ x \ Y_{ij} \quad \forall i, \forall j \tag{18}$$

$$PELBFIT = \sum_{j=1}^{J}\sum_{i=1}^{I} ELP \ x \ XELPF \ x \ ETBAG_{ij} \ x \ Y_{ij} \quad \forall i, \forall j \tag{19}$$

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) to (19) are subjected to performed under the following constraints.

$$\sum_{j=1}^{J} ETBAG_{ij} \ x \ Y_{ij} + ELBAG_i = SMBAG_i \quad \forall i \tag{20}$$

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

$$\sum_{j=1}^{J} y_{ij} \le 1 \qquad \forall i \tag{22}$$

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

$$y_{ij} <= z_j \qquad \forall i \tag{24}$$

$$\sum_{j=1}^{J} z_j \leq N \tag{25}$$

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 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 Northeastern Thailand where 13 sugar mills are located. Based on the production year 2002-2003, 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 both the data related to the GWP and economics are 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 (a-d) 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 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 no. 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 liters 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 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 case (b) and (c): the results are similar. All of the excess 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 2 274.67 tons of bagasse per day. The ethanol plants can produce 343 476 liters 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 2 368.24 tons of bagasse per day. 357 604 liters 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 Northeastern 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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Figure 1

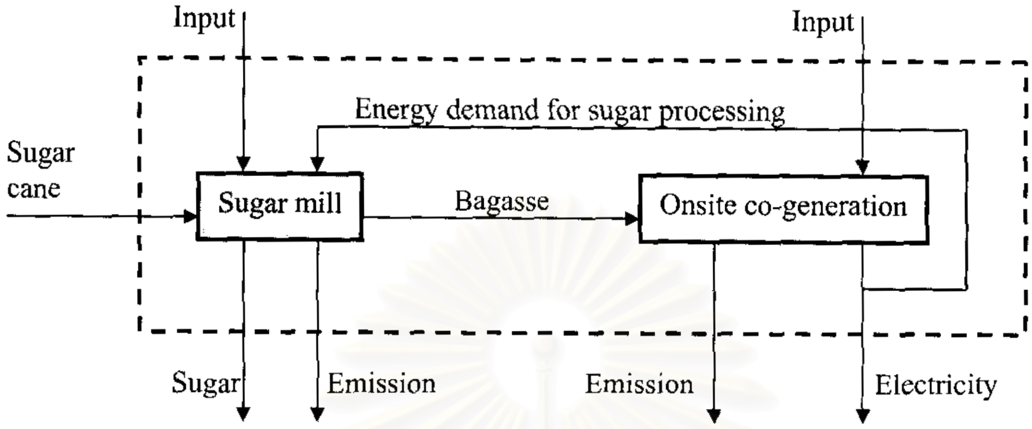


Fig. 1. Typical processes of the sugar industry.

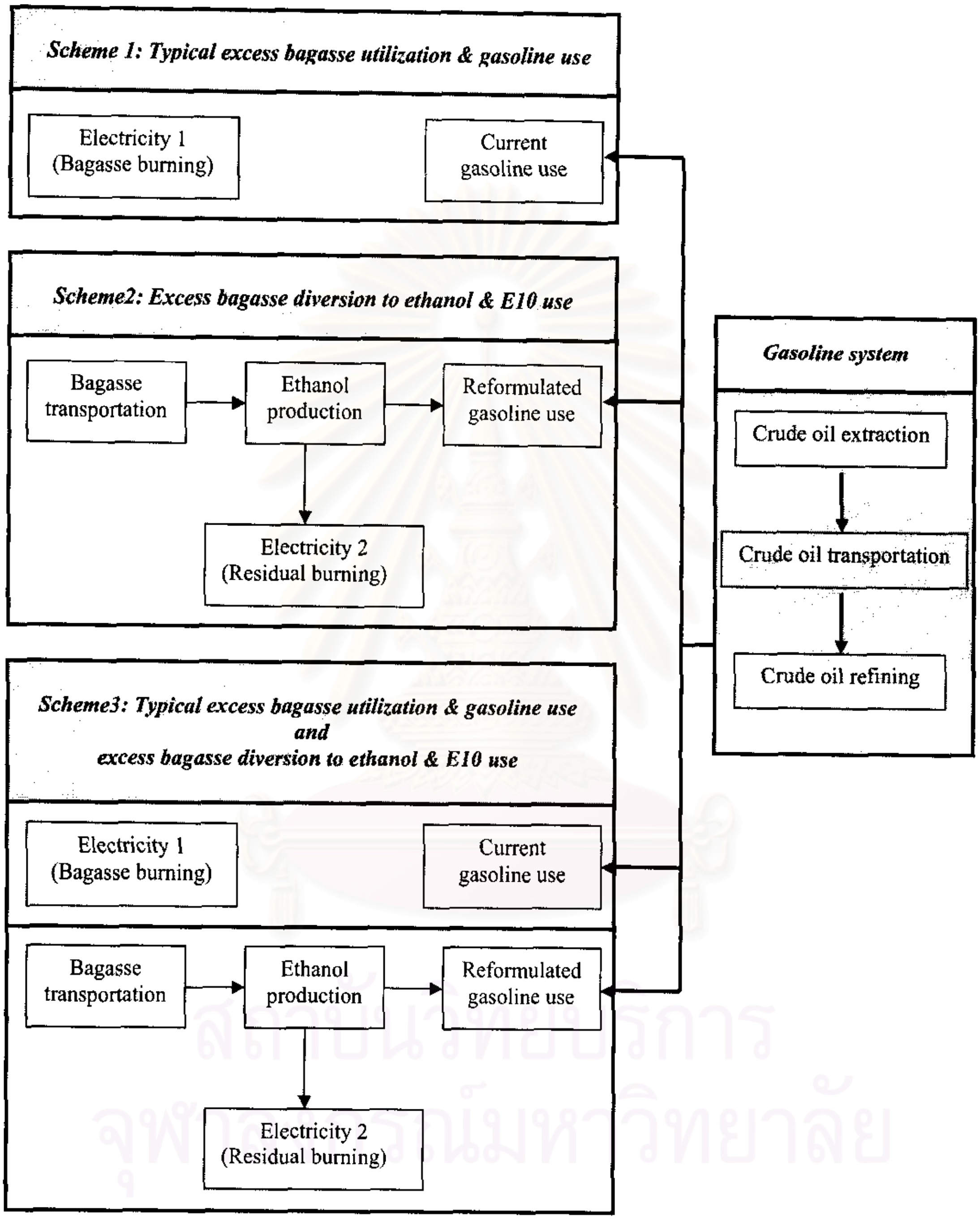


Fig. 2. Structure of the studied model (adapted from Kadam, 2002).

Figure 3

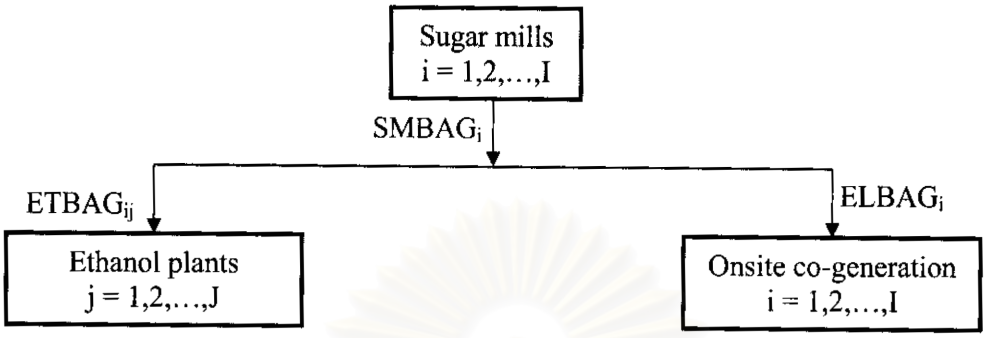


Fig. 3. Excess bagasse utilization and management system for sugar mills.

Figure 4

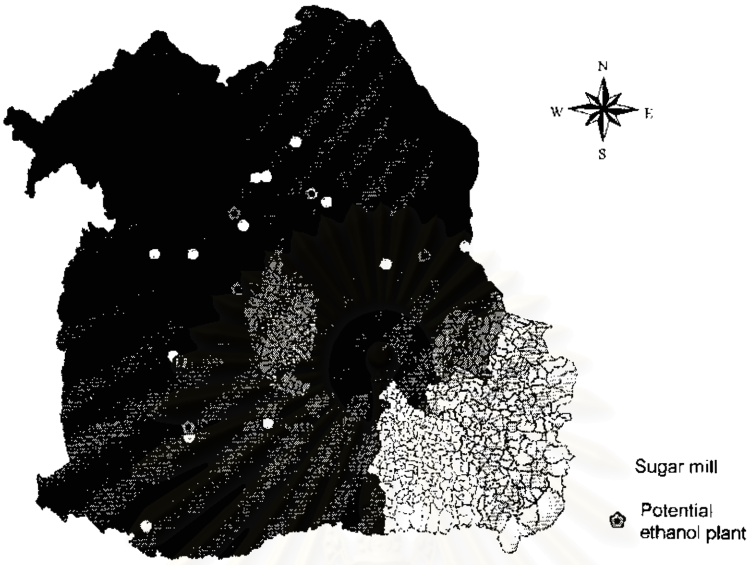


Fig. 4. Locations of all sugar mills and potential locations of the ethanol plants.

Figure 5

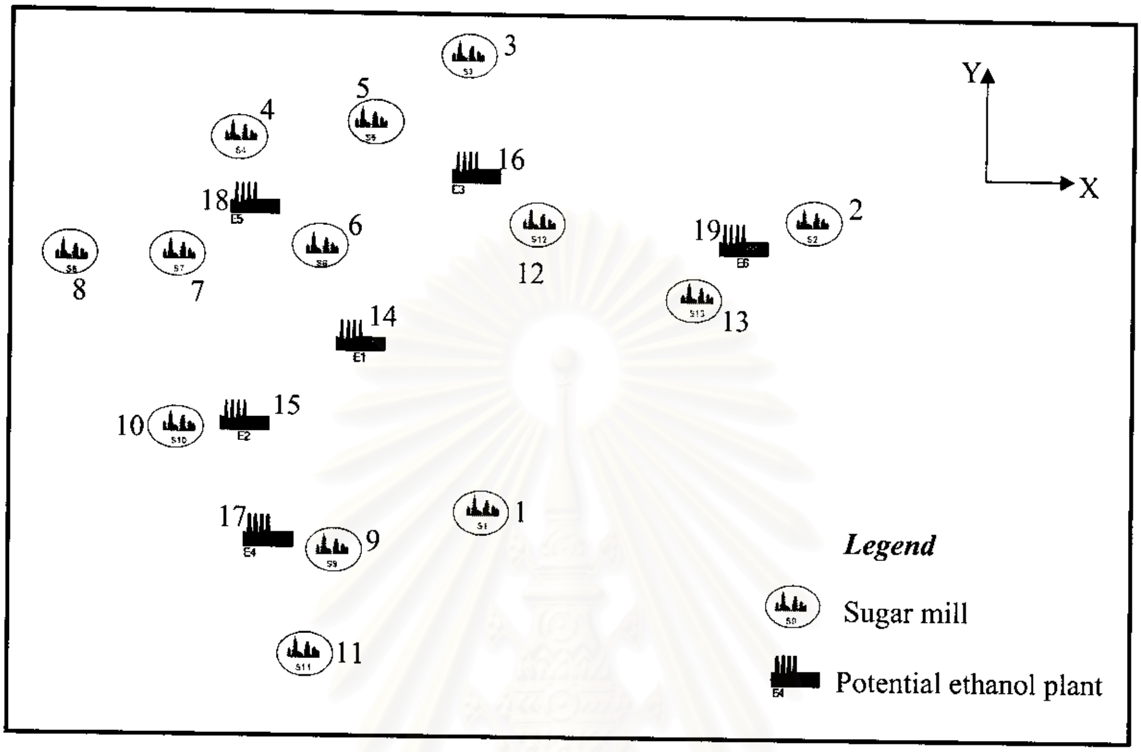
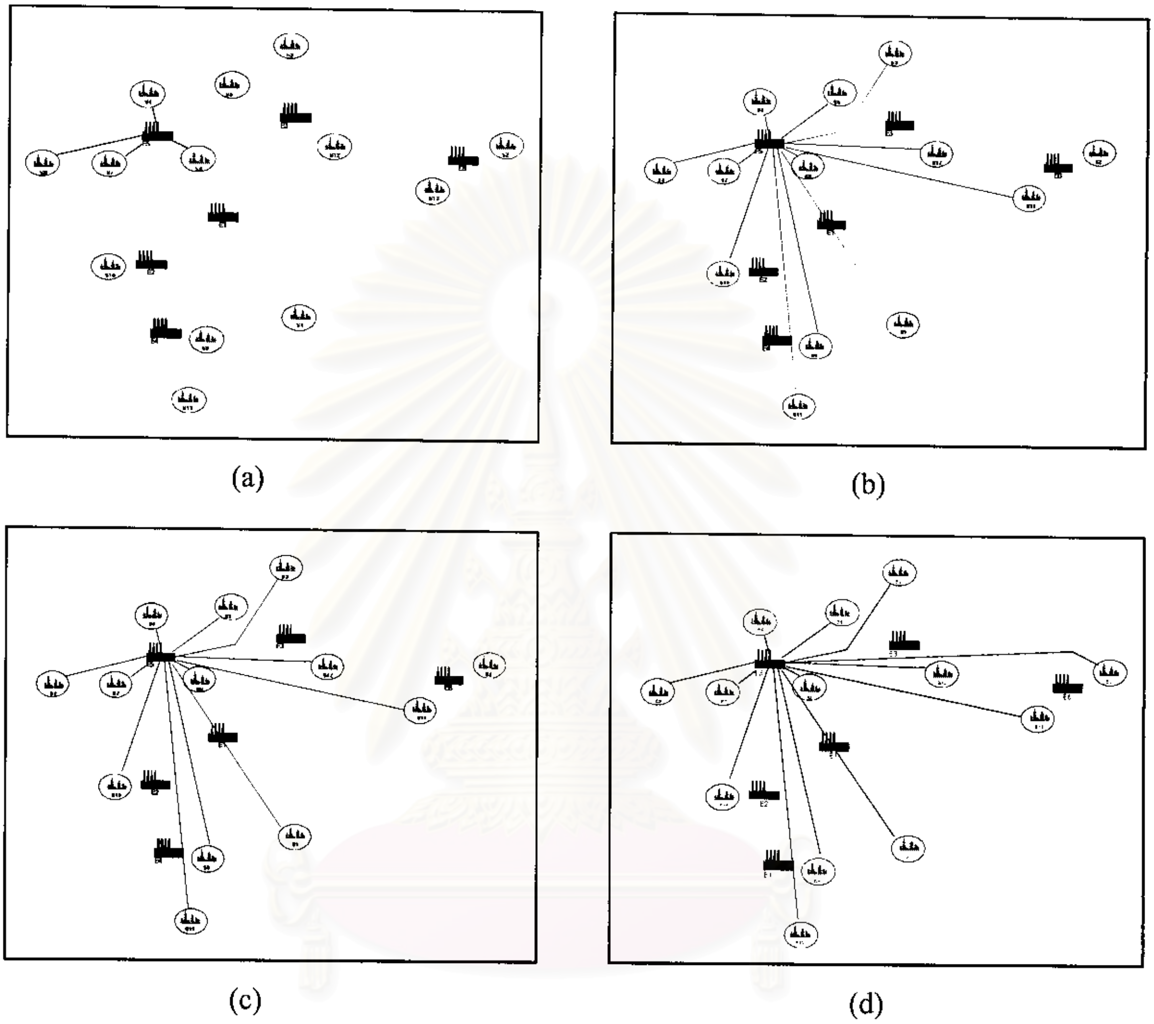


Fig. 5. Simplified locations of all sugar mills and potential locations of ethanol plants.

Figure 6



(a)

(b)

(c)

(d)

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

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

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

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 ▪Electricity generation from conventional technologies practicing in Thailand	1. AP-42, 1995 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) x 2.3(L) x 2.5(H) m^3) ▪Crude oil extraction and transportation ▪Crude oil refining ▪Diesel transportation and stock at fuel station including fueling to vehicle ▪Tailpipe emission ▪Truck average speed of 60 km./hr.	1. Japan Transport Cooperation Association, 2004 2. SimaProV5.1
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) ▪Utilization of E10 as an alternative fuel for gasoline vehicle in Thailand. ▪Crude oil extraction and transportation ▪Crude oil refining ▪Gasoline transportation and stock at fuel station including fueling to vehicle	1. Kadam et al.,1999 2. SimaProV5.1

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

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 ▪Calculation for price of excess bagasse equivalent to amount of the electricity generated ▪Average price of electricity	1. Therdyothin, 1992 2. PEA, 2005
Transportation of excess bagasse	▪Capital cost of truck with trailer ▪Cost for maintenance ▪Cost of fuel consumed during transportation ▪Crew cost	1. Truck and trailer supplier 2. Japan Transport Cooperation Association, 2004 3. PTT, 2006
Ethanol production and utilization of ethanol as E10 fuel	▪The base case size for ethanol plant of 2 000 dry metric tons of excess bagasse per day ▪Cost of base case including capital cost and operation and maintenance cost ▪Scaling exponent of 0.7 ▪Bagasse derived ethanol production ▪By-product electricity production (burning ligneous residual) ▪Price of ethanol ▪Price of the 91 octane rating gasoline ▪Average price of electricity	1.Kadam, 2002 2.Wooley et al., 1999 3.Aden et al., 2002 4.PTT, 2006 5.PEA, 2005

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.

Table 5

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

BIOGRAPHY

Mr. Bancha Buddadee was born on June 6, 1972 in Udornthani Province, Thailand. He obtained his B.Eng (Mechanical Engineering) in 1994 from Khon Kaen University and M.Eng (Sanitary Engineering) in 1999 from the Infrastructural Hydraulics and Environmental Engineering (IHE), Delft, The Netherlands. Bancha is working for the Faculty of Engineering, Ubonratchathani University, as a lecturer since 1997. His major responsibilities are teaching and research. He had some experiences in the wastewater treatment plant design, operation and management. He also involved in several projects such as design of municipality wastewater system (Jakarat Nakornratchasima, Thailand), provincial strategic planning on energy (Nakornphanom, Mukdaharn, and Kalasin, Thailand), demonstration and promotion of biodiesel for used vegetable oil, and etc. He pursued his Philosophy of Doctoral Degree studies in the International Postgraduate Program in Environmental Management at Chulalongkorn University, Bangkok, Thailand in October 2002 and completed the program in October 2007.