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SETTING UP FUEL SUPPLY STRATEGIES FOR LARGE-SCALE BIO-ENERGY PROJECTS USING AGRICULTURAL AND FOREST RESIDUES

A METHODOLOGY FOR DEVELOPING COUNTRIES

Martin Junginger
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Regional Wood Energy Development Programme in Asia, FAO Bangkok

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Preface

It all began one day about a year ago when I walked into André's office, asking for some topics for my MSc thesis. After being offered several topics involving Brazil, Shell and Thailand, I had made up my mind pretty fast: I was going to see Bangkok! Well, more than a year has past since, and looking back, it was a great experience. I met lots of extraordinarily people, experienced 'the Thai way of doing things', saw many fascinating places and ate food as hot as it can get… and I have many many people to thank for that.

First of all I was in the very lucky position to have four (4!) supervisors: André Faaij and Richard van den Broek in Utrecht, who always gave helpful advice both in Holland and (via email) when I was in Thailand. Thanks for always giving me new inspiration and for never even sighing when I asked you to read the x-th draft version of my report. And in Bangkok Auke Koopmans and Wim Hulscher. Thank you Wim for instructing me how to behave in Thai offices, thank you Auke for giving me very helpful advice, helping to keep up my head up when things temporarily did not go the way I had hoped and reminding me of 'TIT' (this is Thailand). Also the rest of the RWEDP-staff was of great help advising, being great colleagues, making appointments for me and driving me around. Zheng, thanks a lot for showing me around in Bangkok, all the nice talks around dinner and the trip to Angkor Wat (I will never forget both Angkor Wat and the journey itself).

Unfortunately, I did not manage to learn much more Thai than how to count to ten, and so I am very grateful to Pong, Ooh, Tooh, Kam, Kung and especially Bom for showing me around Khon Kaen and translating both my difficult questions and the sometimes even more confusing answers. And all those other friendly and helpful people: Khun Chittiwat, Khun Boonlue, Khun Pijarana, Dr. Lacrosse, Prof. Dr. Bhattacharya, Khun Verapong, Khun Dusit and many others. Especially I would like to thank Khun Somjot (and his family), for helping me at the Manchakheree plantation, showing me the beauty of Isaan, a real cockfight and real Thai hospitality, and Khun Kanong for helping me to collect data at the sugar mill.

But I also could not have made it without all the support from home: My-Phung, my parents, Georg, Tien-Phat, Tim, Andreas, Bas Lebbing and many more, thanks for all the long phone-calls, emails and chat-sessions (internet is a great thing, especially when you're abroad).

Last but not least I would like to thank a number of institutions who made this whole project possible: first of all FAO-RWEDP for providing the financial and logistical support and a great working atmosphere, but also the Bureau Buitenland, the Utrechts Universiteitsfonds and Greenfields International.

Martin Junginger
June 2000

Abstract

Background and objective

In the Southeast Asian region, residues from the agricultural and forestry sector represent a large biomass potential. If all process-based agricultural residues alone were to be utilized, they would contribute between 25-40% of the total primary commercial energy production in various Southeast Asian countries. However, the successful utilization of these residues for electricity (and heat) production in large-scale conversion plants strongly depends on a secure fuel-supply. In the past, several projects faced difficulties such as limited accessibility, logistical problems, seasonal availability, increasing residue prices and increased utilization for other applications. It is therefore desirable to set up a methodology to assess these risks before investments are made. The objective of this paper is to develop a coherent methodology to set up fuel supply strategies for large-scale biomass conversion units. This method will explicitly take risks and uncertainties regarding availability and costs in relation to time into account. It will mainly focus on residues from the agricultural and forestry sector. In order to demonstrate the methodology, a case study was carried out for the north-eastern part of Thailand (Isaan), an agricultural region. The research was conducted in collaboration with the Regional Wood Energy Developing Programme in Asia (RWEDP), a project of the UN Food and Agricultural Organization (FAO) in Bangkok.

Methodology

The methodology consists of several consecutive steps. In the *first step*, from the main crop types and corresponding field-based and processed-based residues the Gross Technical Potential (GTP) is determined by multiplying the amount of crop produced with a Residue-to-Product Ratios (RPR). Also the seasonal availability of each residue type and the physical and chemical properties are determined. In addition, the variations in harvest volumes are taken into account. In the *second step*, the fractions which are not available due to physical constraints, labor availability, environmental constraints and current harvesting methods are subtracted from the GTP. Furthermore, the necessary harvesting and pretreatment costs are analyzed. For every residue type, this results in the Net Supply Potential (NSP) and a supply price. In the *third step* all amounts utilized by competing applications are determined. Residues may be used as fuel, fodder, fertilizer, fibre, feedstock and further uses. Possible competitors are farmers, low-income population groups and various industries. In *step 4* the Net Available Potential (NAP) is determined by subtracting all amounts utilized by competing applications from the NSP. Also ranges in the supply- and demand prices are compared. After determining the location and conversion technology of the biomass plant in *step 5*, logistical requirements such as transportation and storage are assessed in *step 6*. For each of these steps, the possible ranges in parameters are determined and used in the final *step 7* to set up different fuel supply scenarios.

By setting up a reference scenario and (amongst others) a worse- and best case scenario, decision makers are able to see if the fuel supply for a biomass power plant is secure in terms of quantities and costs, and how these conditions may vary in the future. Also it is possible to evaluate different biomass conversion plants for their feasibility in the study area.

Results from the case study in Northeastern Thailand

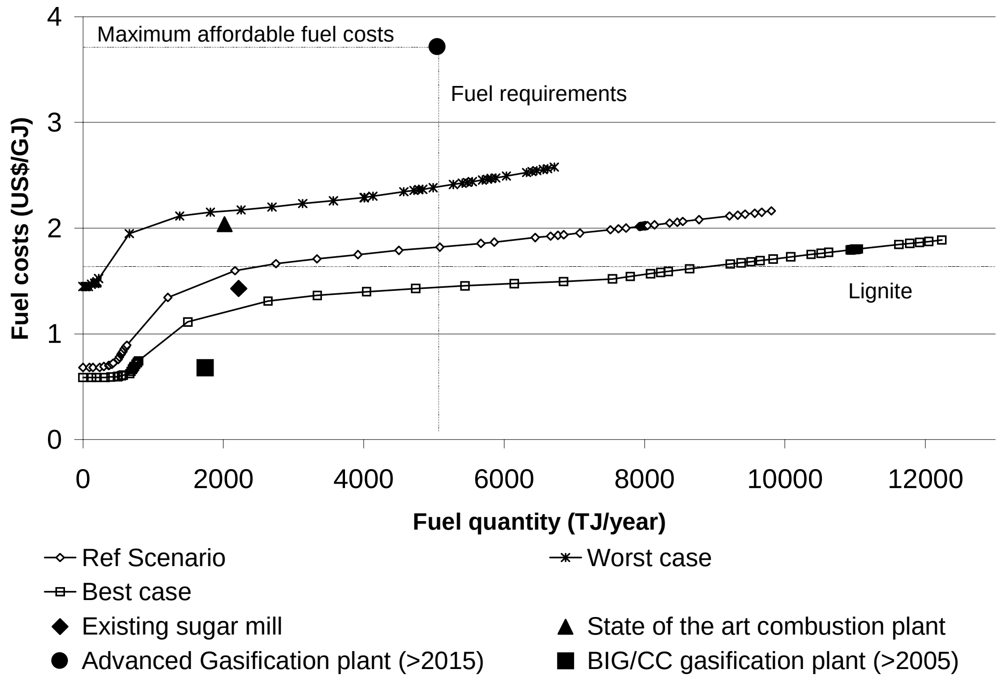
The 170,000 km^2 area of Northeastern Thailand has a large agricultural sector and numerous eucalyptus plantations which makes it a suitable area for bio-energy projects. Most data was collected in the province of Khon Kaen (10,700 km^2). The main residue types identified were rice husk, rice straw, bagasse, sugarcane tops and leaves, eucalyptus waste wood and eucalyptus bark and sawdust. Furthermore, also the use of eucalyptus logs was considered. *Rice husk* is currently the cheapest residue source due to diminished demand as a source of energy by the brick industry. Current degree of utilization varies strongly per site and lies between approximately 50-75%. Prices currently lie between 1.6 - 2.7 US$/tonne but may rise to 8 US$/tonne in the near future. *Rice straw and sugar cane tops and leaves* both are not or only marginally utilized at the moment. Supply costs in baled form at the field lie between 14-18 US$/tonne. A possible threat to use of these sources as fuel is the use of both residues as fibre material by the pulp and paper industry. *Bagasse* was found to be utilized presently for almost 100% by the sugar mills as boiler fuel or as fibre material for Medium Density Fibreboard (MDF). *Eucalyptus waste wood* (branches with diameter between 3-6.5 cm) is available only in very limited quantities, at approximately 7.4 US$/tonne at the plantation. About 50% of the NSP is utilized for charcoal making. *Eucalyptus bark and sawdust* is already utilized for 100% as boiler fuel by the pulp and paper industry. *Eucalyptus logs* are utilized for 75% by the pulp and paper industry. Costs vary between 14-16 US$/tonne at the plantation and 20-21 US$/tonne at the paper factory. Furthermore, it was found that rice- and sugarcane harvests can vary strongly and that the field residues from both crops are only available during a short period during the year. Transportation costs are also subject to possible variations depending on the availability of an own fleet or the use of local hauliers. A number of scenarios was set up with the ranges found in this study. For these scenarios, fuel supply curves were constructed (for an area of approximately 7800 km^2) demonstrating which amount of biomass is available for a specific price. In Figure A1, the reference scenario, the worst-case and the best-case scenario are given.

The economic feasibility of four different power plants with different efficiencies and fuel requirements were then evaluated for northeastern Thailand: a sugarmill in Northeastern Thailand, a 24 MW_e 'state of the art' combustion plant, a 29 MW_e BIG/CC gasification plant (>2005) and a 110 MW_e advanced gasification plant (>2015). A maximum viable fuel price was determined for each plant type by using data from literature on investment and O&M costs, data on current pay-back tariffs in Thailand and an assumed IRR-rate of 15%. The maximum viable fuel prices and the fuel requirements were then compared with possible supply situations in Northeastern Thailand. For each conversion option the maximum affordable fuel price is indicated by a dot in Figure A1. In order to obtain a viable project, the maximum fuel price must lie above the reference scenario fuel supply curve.

Discussion and Conclusions

All process-based residues are largely utilized, e.g. as boiler fuel or fibre material. Only rice husk is available to a certain extent. Rice straw and sugarcane tops and leaves represent by far the largest net available potential, but those are only available at higher costs. The eucalyptus waste wood potential is only very limited. Residue prices can vary between 0.6-3.6 US$/GJ, residue quantities can vary 6.7-12 PJ/year.

Figure A1 Comparison of the Reference, Worst- and Best-case Scenario, (progressing averages) and maximum affordable biomass costs for various biomass power plants (at 15% IRR). A power plant can be considered economically viable if its dot is situated above the reference scenario.



Four major risks were found for the fuel supply in Northeastern Thailand in the near future. The *first* is an increased demand for residues as fuel, especially rice husk. The *second* risk is the possibility of a bad harvest. The *third* risk factor is the possible increased demand of rice straw and sugarcane tops and leaves as raw material for the pulp and paper industry. The *fourth* factor is the cost of transportation and logistics.

At the chosen IRR-rate, only the 'state of the art' combustion plant may be economically viable at the moment. As a long-term-perspective, the large-scale gasification plant does seem promising. Based on the state of the art combustion plant, it is roughly estimated that in the total study area approximately 520 MW_e could be realized.

In order to gain more insight into the risks mentioned before, it is recommended to investigate to what extend rice straw and sugarcane tops and leaves may replace eucalyptus as fibre source, as this is deemed to be the biggest long-term threat to biomass availability. Also it is desirable to investigate different brick production methods and to investigate the optimum harvesting and baling conditions for sugarcane tops and leaves for the Thai situation. Also more case studies in other developing countries are desirable to determine the further applicability of the methodology.

Application of the methodology has identified several important risk factors and has shown how these factors can influence the fuel supply both in terms of quantity and costs for potential biomass-fueled power plants in the study area in a significant way. It is recommended to use a methodology as developed here for future large-scale biomass projects in order to integrally assess the possible fuel supply risks.

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Chapter 1 Introduction

Background

In most South East Asian developing countries the demand for energy (and especially for electricity) was rising sharply before the Asian crisis and may well increase in the mid-term future. This has caused increased consumption of fossil fuels in the past, which in turn increases CO_2-emissions and causes other negative environmental impacts. Also, the import of fossil fuels puts a strain on the economy of most developing countries due to the dependency on imported energy carriers. Biomass, in the form of existing agricultural waste and residues, is an energy source that is usually locally available and is carbon neutral when used in a sustainable way.

In current literature different estimates are given for the present and future biomass potential. Koopmans [Koopmans, 1998] estimates a gross potential of about 33 EJ (of which 7 EJ from processed-based residues) for the South East Asian region (including China) for 1994. If only the 'processed-based' residues were to be used, they would contribute between 25% (Indonesia, Malaysia, Thailand) and 40% (Philippines, Vietnam) to the total primary energy production of these countries [RWEDP, 1996]. Hall et al. [Hall et al., 1993] estimate a total *collectible* amount of all crop and forest residues of about 8 EJ in the same region, which would result in similar contributions to the total primary energy productions. For the year 2010 the share of processed-based residues is estimated to increase to 10 EJ while the total biomass potential from residues increases to 46 EJ [Koopmans, 1998].

The current utilization of the potential is estimated to be relatively low, varying between 2-28% (with the exception of Vietnam, 54%) [Koopmans, 1998]. An additional benefit is that utilization of residues may solve possible disposal problems and associated environmental problems. Also, conversion of residues will not lead to net additional CO_2 emission, as decaying residues also produce CO_2 and other GHG's. Finally, agricultural and forest residues are generally relative 'clean' biomass streams with low content of e.g. heavy metals or sulfur.

During the last decades numerous projects have been set up for energy production to make use of these existing biomass resources. Especially in developing countries with limited fossil fuel resources such as India, Thailand, Malaysia, the Philippines and others, projects have been set up to utilize residues such as rice husk and rice straw, palm oil residues, wood wastes and other streams, especially for production of electricity.

However, guaranteeing a reliable and constant biomass fuel supply especially for larger conversion plants has proven to be problematic in many cases. Bio-energy power plants usually have a lifetime exceeding 15 years or so. Also to be economical, they generally have to be operated at base load. Last but not least, the costs of exploitation are (very) sensitive to the biomass fuel costs. All too often, a steady biomass supply over a long period at constant price levels has proven to be *the* bottleneck for bio-energy projects. Below, some of the main reasons why this occurs so often are discussed.

First of all, even estimates of (gross) technical potentials may vary strongly: e.g. in four studies determining the bagasse-based cogeneration potential in India, potentials of 2.8, 3.5, 3.8 and 5.1 GW where found [Bakthavatsalam, 1999]. The same applies to Thailand, were bagasse-based cogeneration potentials estimated by three studies were respectively 190 to 296, 329 and 415 MW. These differences may be caused by lack of good quality, detailed data and different assumptions. Also many studies do not investigate how these potentials can vary over time due to e.g. bad harvests and their effects on the fuel availability.

Even if the gross technical potential is determined accurately for a certain region, it is often not clear, what prices will have to be paid, and how much of these residues are already utilized by other competitors or could be utilized in the future: For example, during the last decades wood has become increasingly scarce in many regions in South-East Asia, and local industries turned to other fuel sources. For instance a tenfold-price increase in just 14 months was observed, when the Nepali carpet industry increasingly used rice husk as boiler fuel. Another example is the brick industry in Thailand where rice husks and wastes from rubber plantations are used instead of wood. Other obstacles may be existing harvesting equipment from developed countries which may not be suitable, and operation costs can be far higher than expected due to different field conditions [USAID, 1991]. Also many dispersed collection sites with small amounts of residues can seriously limit the collectable amount of residues. For example a proposal to establish a 40 MW rice husk fired power plant in the Philippines had to be cancelled because of the complex logistics to collect rice husk from the many surrounding rice mills [RWEDP, 1998b]. Similar cases are known from India [Koppejan, 1999]. Summarizing, the main risks for larger bio-energy projects are uncertainties in gross technical potentials, difficult accessibility of residues (for various reasons), utilization by competing applications, variations in prices and logistical risks.

Objective and Scope

A continuous and reliable fuel supply is a vital part of every power plant. It is therefore desired to develop a methodology on how to make an assessment of the mentioned risks and the way these risks affect the biomass supply in terms of quantity and price for a local / regional level. Improving insights in those risks will facilitate realistic planning for bio-energy projects, which is essential for investors. The goal of this paper is to develop such a methodology.

In literature, only a limited number of guidelines exist on how to assess the availability of residues and / or how to set up fuel supplies for biomass conversion plants in developing countries. Koopmans [Koopmans & Koppejan, 1998], and Clancy [Clancy, 1994, 1995] describe problems of utilizing residues in general, but not correlated to the fuel supply of a large power plant. Massaquoi [Massaquoi, 1988] and Tripathi [Tripathi et al., 1998] developed methodologies to assess the availability of (agricultural) residues for power plants, but only briefly discuss connected risks. Perlack [Perlack et al., 1997] presents guidelines on how to set up fuel supply for electric power plants from dedicated crop plantations, but not from residues. Katz [Katz, 1998] gave a brief presentation on the steps in the realization of a (residue) biomass-based power generation project for developed countries, but only with little attention to the fuel supply. Faaij [Faaij et al., 1997a] assesses amongst other issues the availability, supply patterns and costs of various biomass waste streams for the Netherlands.

The objective of this paper is to develop a coherent methodology to set up fuel supply strategies for large-scale biomass-conversion units. This method will explicitly take risks and uncertainties regarding availability and costs in relation to time into account. This paper aims at providing general guidelines, which are not country-specific. These guidelines cannot provide 'perfect fit'-solutions but aim to give general help for overcoming barriers and setting up supply strategies. It will mainly focus on residues from the agricultural and forestry sector[1].

This paper does not deal with economical risks concerning the conversion plant itself (e.g. variations in installation costs, O&M costs, interest rate, revenue estimates etc.) or political risks (e.g. changing government policies and legislation on Power Purchase Agreements (PPA), pay-back tariffs etc.). This study focuses on electricity or both electricity and heat production (CHP) with plant scales between 10-40 MW_e. This range is chosen because due to rules of economies of scale. In large-scale plants the benefits of increased efficiency outweigh increased transportation costs, allowing a lower price per kWh (see e.g. [Dornburg, 1999]) which in turn may allow higher biomass costs. However, fuel-supply risks tend to get higher with increasing plant size, which makes it more important to assess them for large(r) conversion plants.

The methodology does not focus on a specific conversion technology, though it should be stressed that the technology must be able to handle a wide variety of biomass fuels with different characteristics because many biomass residues are not available year round and various fuels are needed for a constant supply. The methodology allows for comparing different technologies (with known investment and O&M costs from literature) and evaluation for different fuel supply scenarios.

In order to demonstrate the methodology, a case study was carried out for the north-eastern part of Thailand (Isaan), an agricultural region. The research was conducted in collaboration with the Regional Wood Energy Development Programme in Asia (RWEDP), a project of the UN Food and Agricultural Organization (FAO) in Bangkok.

In Section 2 of this paper the methodology will be presented. In Section 3 the economic, agricultural and energy situation of the study area will be described. In Section 4, the outcomes from the case study will be given. In Section 5, the results of the case study and the applicability of the methodology will be discussed.

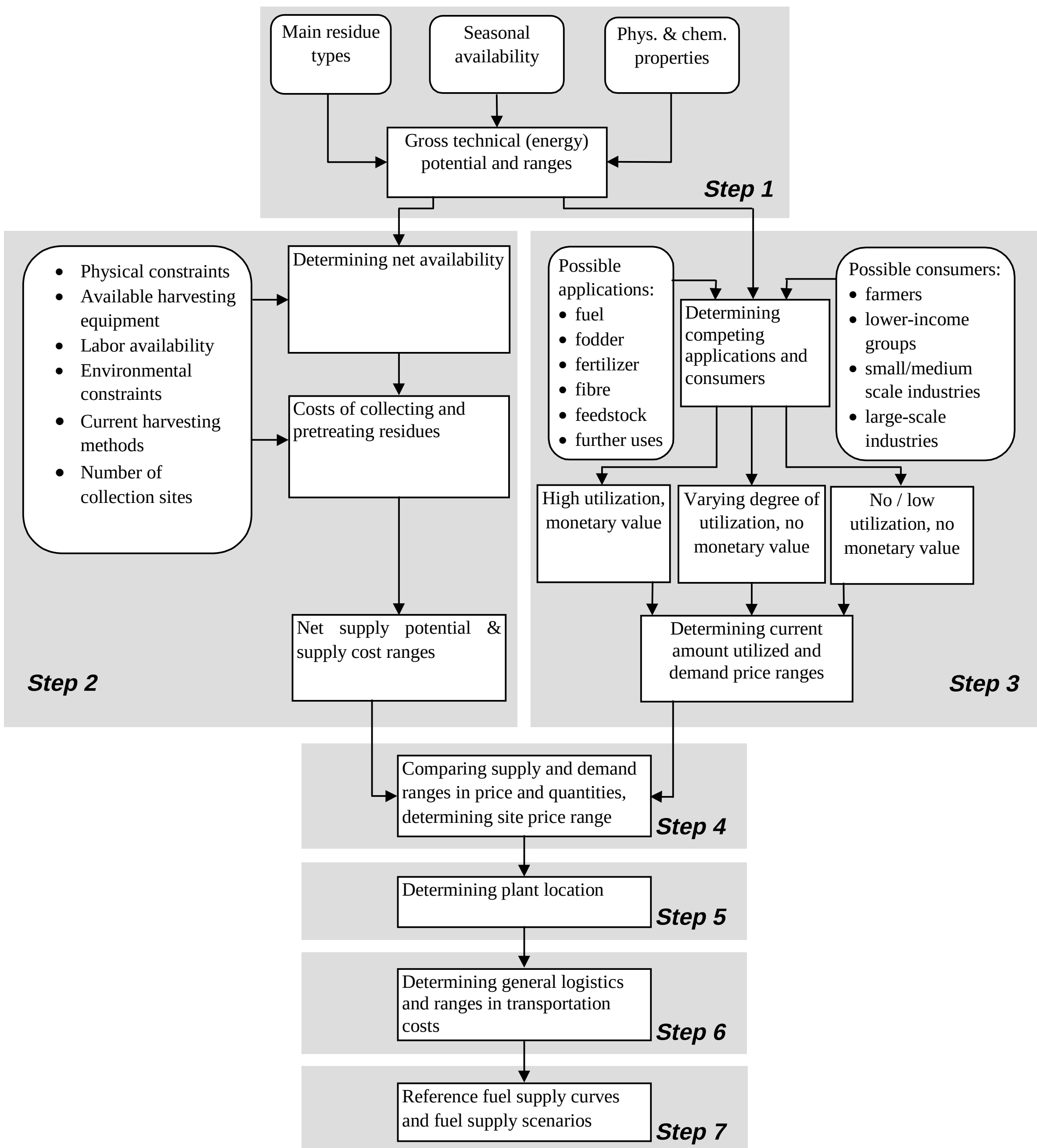
[1] There are a number of possible other biomass / residue / waste sources streams which however tend to have several disadvantages: municipal solid waste (MSW) is generally very wet in developing countries, biomass from dedicated crop-plantations may be more expensive than residues and are not available on the short-term while for animal manure, different specific conversion technologies like digestion are usually preferred. However these streams normally have the advantage that they are available all-year and can therefore potentially be considered as a secondary backup fuel.

Chapter 2 Methodology

Introduction

The methodology is divided into several consecutive steps. An overview of the different steps of the methodology is given in Figure 2.1. In each step, potential problems are described, as well as the methods and data requirements to obtain the necessary solutions. The general principle is to explicitly reveal uncertainties at each step and determine ranges in which parameters may vary.

Figure 2.1 Overview of the different steps



Step 1 Determining the gross technical potential (GTP)

The objective of this first step is to determine the main crop- and residue types in the study area, and calculate the annual production of different residues. On basis of the annual production and the physical properties, the annual energy potential can be established. Also the seasonal availability will be investigated.

Step 1a Determination of conceivable residue types

Methods and data requirements

As a first step, boundaries have to be set for the area to be investigated. These may be political or physical boundaries and the size may be chosen depending on the planned size and scale of the project considered. However the borders can be changed if this proofs to be advantageous in later stages of the resource assessment.

Next the main forms of agricultural and forestry activities should be identified. Also, a *brief* inventorization should be done to assess other possible fuel sources e.g. municipal solid waste, waste from other industrial sector (e.g. paper industry), animal manure etc. For the major crops determined, the corresponding residue types have to be identified. The main two residue-categories are processed-based residues (from both annual and perennial agricultural crops and wood) and field-based residues. Processed-based residues are created at one easily accessible place when a product is processed. Field-based residues remain in the field or forest where the crop is harvested and are normally less concentrated. Examples are given in Table 2.1.

Most data can be obtained by consulting national/regional statistics, the corresponding government authorities (ministry of agriculture, ministry of forestry etc.), corresponding research institutes, agricultural /forestry branch organizations and available literature. In case these sources do not yield sufficient data, written surveys for the main producers/processing industries in the research area may be helpful. In literature, the residue types corresponding to most common agricultural and forestry products are described [Koopmans & Koppejan, 1998].

Uncertainties

Attention should be paid to the data quality. The data basis for statistics may be very important. In some cases data may be gathered annually. In other cases data are only collected for one base year and then extrapolated for following years (using assumptions which may cause significant errors over longer periods of time). Also different statistics may use different base data and assumptions which may cause varying results. Preferably expert opinions from the relevant industries and universities should be consulted, but also these may vary greatly and may be biased depending on the background of the expert. It is also important how much annual production of crops may vary due to e.g. bad harvests and how high chances for a bad harvest are. Possible maximum deviations must be known and used for the fuel supply scenarios (see Step 7). For further calculations, a conservative estimate for the annual production should be used.

Table 2.1 Overview of different biomass residue types

Processed-based residues		Field-based residues	
Agriculture	Forestry	Agriculture	Forestry
• Rice husk	• Bark	• Rice straw	• Tree tops
• Bagasse	• Sawdust	• Cotton straw	• Twigs
• Coconut shells			• Leaves

Step 1b Determination of gross technical potentials (GTP)

Methods and data requirements

The annual residue production is normally not recorded. There is little chance that data on residue amounts is recorded directly at national or regional level, as this is a problem even in highly developed countries. This is caused by the fact that in most countries the bodies responsible for forestry, agriculture and energy considered the production and use of residues as peripheral. In addition residues by their very nature are difficult to measure [Barnard & Kristoferson, 1985]. If the residues are already (partially) utilized, limited amount of data may be available. For example in the sugar industry, bagasse is used in many countries as fuel by the sugar mills, and residue amounts produced are often known.

In most cases the amount of residue will have to be calculated indirectly from the amounts of goods produced (e.g. timber, rice, palmoil etc.). This information is more likely to be available at national or regional level. In order to determine the amount of residues created, it is necessary to know the 'Residue to Product Ratio' (RPR) [Koopmans & Koppejan, 1998]. The RPR indicates how much residue (mass) is created per amount of product (mass). This method is particularly used for annual crops. A similar method uses 'Residue to Area Ratios' (RAR), which is based on the amounts of residues per cropped/forest area used more often for perennial crops [Koopmans & Koppejan, 1998], [RWEDP, 1997]. Using these ratios the gross technical potential (GTP) can be determined (in tonnes / year).

In principle the same data sources as mentioned in step 1a) should be used. In addition, field experiments may be necessary to determine or confirm RPR/RAR-values.

Uncertainties

For process-based residues, RPR-values may depend greatly on the efficiency of the machinery used in the study area. For example a circular saw may produce more sawdust than a band saw [Miranda, 1997]. For field-based residues, similar limitations apply. RPR - values may heavily depend on the used machinery and the way crops are harvested (e.g. at which stem length the crops are cut off). The harvesting practices may differ even between regions. When using values from literature, it is very important that the moisture content is given as this value can vary greatly between green and air-dry biomass. In addition, RPR-values both measured in the field and given in literature may vary due to variations in weather, specific crop type grown, water availability, soil fertility etc.

The RAR-method may also contain great uncertainties. Yields may depend on many different factors: soil quality, water availability, type of management (traditional or advanced), cropping density, crop variety etc. Also land-use may differ from year to year. These factors can result in large differences in the amount of residue obtained from a particular cropping area.

Besides one must take into account seasonal/annual variations in yields. Possible variation ranges in crop yield and thus in residue amounts created [Downing & Graham, 1996] must be known. In general, yields in developing countries tend to increase due to use of fertilizers and pesticides, the use of crops with higher yields due to genetic manipulations etc. So there may be a general trend towards growing yields which may be extrapolated towards the future using existing statistics of the past and expert judgement [Tripathi et al., 1998]. However the relationship between growing yields of crops and growing amounts of residues may not always be linear, as more efficient crops types often have lower RPR-values.

Thus, ranges should be determined within which the RPR- and RAR-values and annual yields may vary. Moderate or average values may be used to determine the average gross technical residue potential, but the ranges should be used for the fuel supply scenarios analysis (see Step 7).

Step 1c Determination of physical and chemical properties and the gross energy potential

Methods and data requirements

In order to calculate the annual energy potential, the physical and chemical properties of the selected residues must be determined. The following variables are required for following steps:

- moisture content of the freshly harvested (green) and air-dried residues
- the corresponding LHV’s or HHV’s
- the density and morphology of the green / air-dried / pretreated residues
- drying behavior under local circumstances
- the chemical composition (e.g. C, N, H, O, S, P content, ash content, heavy metals, trace elements etc.)

By multiplying the gross technical potential with the LHV the gross technical energy potential (GTP_E) can be estimated (in TJ/year). The chemical composition may indicate possible environmental problems (e.g. high heavy metal contents, high NO_x-emissions), the probable adequacy of the ashes as fertilizer or special demands for the conversion plant in case of a high ash or alkali contents. In literature, varying values are given for these properties for a great variety of forest and agricultural residues [Koopmans & Koppejan, 1998], [Bhattacharya & Ram, 1990].

Uncertainties

In literature, often heating values are given without mentioning if the residues are green or airdry. Also moisture content or chemical composition may vary due to various parameters (soil quality, use of fertilizer, etc.). In addition, both lower and higher heating values may be calculated on a wet basis, a dry basis and a dry and ash-free basis [Worldbank, 1999]. Simply adopting values from literature without checking these parameters may lead to serious errors. Preferably field/laboratory tests should be conducted to determine the physical and chemical properties of the local residues. This may lead to a more accurate determination of the (fresh/ air-dry) moisture content and possible variations. Also long-term storage behavior should be determined in order to determine possible reduction in moisture content or loss of dry matter.

Step 1d Determining the seasonal availability of each residue stream

Methods and data requirements

The average length (and variations) of the harvesting season should be determined per residue type. While some (perennial) crops may be harvested all year round (e.g. wood thinnings), most residues from annual crops are only available during and a brief period after harvesting season.

In addition, the amount of residues becoming available may not be the same every month during the harvesting season. An example of an overview of the seasonal availability is given in Table 2 [Tripathi et al., 1998]. The required information is likely available at agricultural/ forestry branch organizations and local farmers.

Table 2.2 Seasonal availability of different agricultural crops in India [Tripathi et al., 1998]

Residue	Availability											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maize Stalk							●	●	●	●	●	●
Maize Cobs							●	●	●	●	●	●
Cotton Stalk	●	●	●							●	●	●
Mustard Husk				●	●	●						
Jute & Mesta Sticks							●	●	●	●	●	●
Rice Husks				●	●	●	●	●	●	●	●	●
Groundnut Shells				●	●	●				●	●	●
Athar Stalk	●	●	●							●	●	●

Uncertainties

In most cases, the possible variations in harvesting length and period are well-known for all major crops types, and little uncertainties are expected at this step. However, if the start and length of the harvesting season can vary considerably, these ranges should be used in the fuel supply scenarios.

Step 2 Determining net supply potentials (NSP) and supply costs (C_S)

This step focuses on aspects which limit the amount of residues which can actually be supplied considering constraints related to e.g. available equipment and current harvesting methods. Also the costs and risks of collection and possible necessary pre-treatment such as sizing, baling, drying etc. on or near the site of production are discussed.

Step 2a Limitations of collection of field residues

Problem description

In case of some process-based residues this step can be skipped, as they are generally produced in large volumes at one specific place and easily accessible (e.g. bagasse). However, in case the processing of the crops takes places at many different sites, this step is relevant. In most cases the available agricultural and forest field residues are dispersed over a wide area. The in Step 1b calculated gross technical potential for field residues will most likely only be available partially due to several interconnected factors:

First of all **equipment constraints** play an important role. Collection methods may vary greatly between developed and developing countries, but also per region in developing countries. Mechanization of the harvesting process and/or collection of the residues may greatly influence the effectiveness, but may also require high investments which may not be feasible for many farmers. Furthermore, advanced mechanical equipment used in developed countries may not be suitable due to **physical constraints**: steep slopes, wet soils, small size of fields and low-quality infrastructure may make (part of) the cropped area inaccessible to mechanical harvesters or may cause harvesting to be much slower and more inefficient than in developed countries. In case that mechanical harvesting is not possible, **labor availability** may be an issue. In many situations labor is cheap and available. However residue collection is generally labor intensive, and farmers may be busy selling the crops, harvesting other crops or carry out other maintenance work on their fields. In general only a low priority will be given to collecting residues unless a reasonable price is paid [Clancy, 1995]. Also in exceptional cases, due to religious or cultural reasons the use of certain type of residues may be undesirable to harvest or use for the local population [Massaquoi, 1988].

Another issue are **current harvesting methods**: Often agricultural residues are burnt before the harvest (e.g. burning sugarcane tops and leaves to facilitate manual harvesting), burnt after harvest or ploughed back into the field in order to improve soil quality or suppress the growth of weeds which makes them inaccessible as well. Utilization of residues will further be discussed in Step 3. Another aspect is the **possible environmental damage** caused by the collection of field residues. When ploughed under or left on the field, they may bring back valuable nutrients to the soil and help prevent erosion [Barnard & Kristoferson, 1985]. Finally, the **number of sites** and amounts per site where residues may be loaded onto trucks may limit the net availability.

All these factors determine the net supply potential (NSP, the collectable fraction of the GTP).

Methods and data requirements

In order to estimate the collectable fraction, it is important to determine the local degree of mechanization, the topography of the area, current harvesting methods, the costs and availability of labor, the number of crop-processing sites and their respective output volume. Furthermore, it may be important to familiarize with local political systems and hierarchies of authorities, local cultural divisions of labor and authority between men and women and local cultural and religious values [Perlack et al., 1997]. Using this information, possible constraints from the first four factors may be estimated. When assessing the number of sites where crop-residues are produced, one should check if a significant amount of residues is produced on a regular basis over an extended period of time (e.g. 10 tonnes per week over a period of 6 months). If amounts are too small or produced irregularly, this may lead to serious logistical problems and it may be considered no to include these sites.

The environmentally collectible fraction is rather difficult to determine. The beneficial effects of leaving residues in the field or forest may vary greatly depending on crop or tree type, soil type, weather conditions etc. In some cases, the effect of residues as a fertilizer may be minimal, and possible replacement by chemical fertilizers may result in a great increase in both crop and residue production. On the other hand, removing a top layer of residues protecting the field may cause soil erosion and washing out of nutrients. In addition, in forests, dead wood may form an important habitat for many insects and removing it may influence the biodiversity. So, while in some situations the effects of removing residues from the fields may be marginal, in other cases the effects may be dramatic. In general, removing residues from soils which are known to be susceptible to erosion may easily cause damage [Barnard & Kristoferson, 1985]. In some cases, current harvesting methods may also indicate the environmental risks. For example, if residues have been burnt in the field over a long period of time with no unfavorable effects for the soil, it is likely that collecting the residues and returning boiler ashes to the fields will have no adversary effects. Also experiences from other countries with same crop and soil types may be helpful [Unger, 1994].

Once these factors are known, the NSP of residues available can be calculated. This is the actual maximum amount of residues that can be supplied. Also the methods on how to collect the residues and the accompanying costs can be estimated. In case only manual collection is possible at the moment, one may try to estimate the costs of mechanical harvesting from reference situations in other regions or countries. However, it is stressed that before doing so, the corresponding circumstances (e.g. topography, size of fields, costs of fuel and labor etc.) must be compared. One should also assess the possibility of harvesting crops and residues (normally left in the field) in one piece and separating them at a central site, thus making them more easily accessible. The information needed may be found at local producers of harvesting equipment, statistical offices, local universities, farmers, agricultural /forestry branch organizations, but also from reference situations in literature.

Uncertainties

While physical and environmental constraints are likely to remain constant over a long period of time, farming practices and equipment and labor availability may change more quickly. Past developments in labor prices, use of fertilizers, mechanical harvesting equipment etc. may help to indicate changes in the future. It is emphasized that circumstances may vary regionally, e.g. mechanical harvesting equipment may be available in one region but not in an adjacent region due to e.g. different topography, poorer farmers etc. Assessing the local circumstances is therefore crucial. Also, in the past the adoption of mechanical harvesting has led to costs far higher than estimated due to e.g. higher operations costs than anticipated. Before setting up a complete power plant relying on previously not practiced mechanical harvesting, (small-scale) field-testing is strongly advised.

Again, ranges should be used which take into account possible variations of the net supply potential caused by e.g. enhanced harvesting practices.

Step 2b Pretreatment of residues

Problem description

The moisture content of fresh residues is normally very high (40-60%). This causes untreated residues to have a low heating value. Also many residues (both field- and process-based) are difficult to handle and bulk densities are generally rather low. This makes them difficult to transport efficiently and to store them.

Methods and data requirements

These properties can be improved by pretreating the residues. Many residues may be sized (e.g. chipped), dried in the field, densified (e.g. to bales, pellets or briquettes), pre-stored and dried in a shed etc. It would exceed the frame of this paper to describe all existing pretreatment methods in detail. Many publications are available in literature describing methods for specific residues/specific regions, e.g. [Gemtos & Tsiricoglou, 1999], [BTG, 1996], [USAID, 1991],[Bhattacharya & Ram,1990].

One must consider which pretreatment steps can also be carried out at the processing plant (e.g. drying). Pretreatment at the production site should mainly focus on optimizing the transportation qualities (e.g. increased density).

The necessary pretreatment equipment (e.g. balers or chippers) may not be available and will have to be purchased. It is important to assess if pretreatment can be carried out by local farmers or middleman, or if collection and pretreatment will have to be coordinated and carried out by the power plant.

Uncertainties

In many countries experiences have been gained on what techniques can be applied for which kind of residues. However, again caution must be applied as techniques successfully applied in one country/region may sometimes not be suitable for other regions or other crop types. For example, straw balers successfully applied in developed countries may not be suitable for baling cane tops and leaves. Therefore, before adopting techniques from other countries, the exact conditions in terms of labor costs, logistical requirements, differences in crop/residue types etc. should be assessed and compared.

As the costs for pretreatment often represent a relatively high share of the total price for field-residues, great attention should be paid to optimizing these procedures.

Step 2c Determining supply prices (C_S)

From local labor costs, the costs of available equipment, the weight and density of the untreated (or dried on the field) residues, possible transport distances to one collection site (e.g. a site at the border of a forest accessible to trucks), costs of pretreatment machines already available and costs of equipment that will have to be purchased, the collection and pretreatment costs can be calculated. Again, from variations in labor prices, harvesting efficiencies etc. ranges should be estimated in which the price of supplying and pretreating residues may differ.

It should be noted that for process-based residues, in some cases the supply costs may even be negative, as for some residues (e.g. rice husks) money may have to be paid for the waste disposal. However, these negative costs should not be used. Once the demand for these residues increases, these costs may turn positive. Instead, the supply costs will be based on labor and pretreatment costs.

Step 3 Determining competing applications, utilization (UP) and (shadow) demand prices (C_D)

Problem description

Once the net supply potential is identified, the existing competing applications must be determined and the share of the available residues that is already in use. In many developing countries, residues are already utilized to some extend. The existing applications can be summarized as 'the 6 F's' ([Koopmans & Koppejan, 1998], [Clancy, 1994]): **F**uel, **F**odder, **F**ertilizer, **F**ibre, **F**eedstock and **F**urther uses). Examples for each of them are given in Appendix A. Every specific residue type is usually suitable for one or several of the above-mentioned applications [Barnard & Kristoferson, 1985]. Generally speaking, field-based residues are more often used as fertilizer and fodder, while process-based residues are more often used as fuel, fibre and feedstock. Main consumers are **farmers, lower-income population groups, small / medium-scale industries** and **large-scale industries**. The extent to which residues are utilized depends greatly on the local demand by these consumers.

This will be elucidated for the application of residues as fuel: During the last decades wood has become increasingly scarce in many regions in South-East Asia due to deforestation. The increased scarcity and price of wood and charcoal may often have caused that the local population and small/medium-scale industries partially turned to residues as fuel sources. In some cases these groups may have no alternatives as fossil fuels are too expensive. Also many medium and larger-scale crop- and wood processing sites may have started to utilize their residues at the local plant for heat production or co-generation. On the other hand, the use of electricity and fossil fuels such as LPG and coal may partially have replaced wood and charcoal in the industrial and residential sector.

Methods and data requirements

There are basically three situations possible:

Situation 1: residues already have a monetary value and it is imperative to analyze the degree of utilization by the different consumer groups and price ranges of residues. Prices of residues may e.g. have varied strongly over the years and also during the year (due to the seasonal availability). These may also indicate the maximum price level a consumer can afford to pay (C_D). In case of utilization as fuel, availability and prices of wood, charcoal, fossil fuels (e.g. LPG, kerosene, lignite) should be assessed and the degree to which they can technically and economically possibly substitute the residues. In other words, can the residue be replaced by other fuels, and at what price range this is likely to happen. It must be noted, that the influence of small/medium-scale industries on availability and prices can be very site-specific, while large-scale industries may influence a whole region as they often require large amounts of residues.

Situation 2: residues are utilized but without monetary value. For example, both field-based residues (e.g. wood residues left in the forests/plantations or straw on the fields) and process-based residues may be used by the lower-income group as free (or cheap) fuel source or other uses [Koopmans & Koppejan, 1998], [RWEDP, 1997a]. If these residues are harvested and utilized on a large scale, this groups may not be able to compete economically for these residues. Even when some monetary compensation is given, it may be that payments are made to someone other than the person to whom the original benefit accrued and this may lead to social disruptions in the local community [Koopmans & Koppejan, 1998]. In this case, the supply costs (C_S) for the residues can be used as demand price (C_D) , but the fraction utilized at them moment (and the fraction likely utilized in the future) should not be considered to be available. Another application mentioned before maybe fertilizer. In these cases farmers may be reluctant to supply these residues, unless they are sufficiently compensated.

Situation 3: residues are not utilized at all at the moment. In this situation, the minimum estimate price should be set at the supply prices described in the previous step. An approximate maximum price (also called shadow demand price) may be set by comparing the energy content of the residues (in GJ/ton) with the energy content and price of the cheapest available fossil fuel, i.e. if the heating value of one tonne of biomass is approximately one third of the heating value of one tonne of coal, the price for one of biomass may also be set at one third of the price for one tonne of coal. It is assumed that in case residue prices exceed fossil fuel prices, competitors would switch to fossil fuels. In case that the supply price is higher than the shadow demand price, (which may occur for field-based residues due to high collection and pretreatment costs) the supply price should be maintained.

Considering these factors one should estimate the current price elasticity and possible future trends, and accordingly set price margins and a (shadow) demand price (C_S) and current and expected future amounts demanded by competing applications (UP). The amounts of residues used for other purposes (UP) must be subtracted from the net supply potential (NSP). Also these competing applications may greatly influence the price which has to be paid for the residues. Therefore it is very important to assess the current uses of the residues, how and why the percentage has de- or increased during the years, the possible alternatives of each of the consumer groups and the resulting potential future demand development.

It is emphasized that situations may vary not only per country, but also per region or even district. It is therefore very important to assess the situation at as many sites in the research area as possible. For data acquirement, the local industries should be visited and interviewed. The amount of wood and charcoal used and the rate of deforestation may be recorded on a regional or national level. International institutions like the Regional Wood Energy Development Programme (RWEDP) of the Food and Agricultural Organization also have data on use of wood and biomass per capita for most South-east Asian countries. Local experts from universities may also help to forecast trends for the biomass consumption in a region.

Uncertainties

In situations 2) and 3) it is difficult to estimate to what extend other competing applications will make use of the residues in the future and what influences this will have on the price. The (minimum) supply price may be used for the initial situation. In time, prices may rise and the shadow-demand price (based on fossil fuel) may indicate a worst-case situation in which the residues have become extremely scarce. Both prices, should be used in the fuel supply scenarios.

One major drawback of this method is, that is based on the value of the residue as fuel. The particular residue may be clearly more valuable as fibre source or fertilizer. Experiences and prices from other countries or studies may proof to be very valuable for these cases.

In order to secure a fuel-supply, preferably long-term contracts should be made with a limited number of suppliers [DeBlaay, 1994]. Working with more suppliers is more difficult and is a less efficient use of resources. On the other hand, long term-contracts may result in a loss of flexibility. Also, even if contracts are signed with suppliers to deliver the residues for a fixed price, caution should be in applied. The prices may rise sharply once the market has developed and other competitors are interested in the residues. Also, though the legal status of the contracts may be binding, forcing the supplier to fulfill their obligations may prove to be very difficult. It is advisable to assess the willingness of landowners / mill owners to participate in supplying residues, which advantages they anticipate, and what they are willing to contribute.

Step 4 Determining the net available potential and prices per site / region

At this point from the previous steps, the following data per site/region and *per residue type* (and therefore per season) must be known:

GTP : The gross technical potential [tonnes / year]
GTP_E : The heating value of the GTP on basis of the combined LHV's [GJ / year]
C_S : Supply costs per tonne of (pretreated) residue [$ / tonne]
NSP : Net amount of (pretreated) residues that could be supplied (disregarding competing applications) (in [tonne] or as % of GTP)
UP : currently utilized potential (in [tonne] or as % of NSP)
C_D : (shadow) demand price [$ / tonne]

The net available potential (NAP) per residue type can now be calculated:

$$NAP = GTP\,[tonne] * NSP\,[\%] * (1-UP)\,[\%] \quad \{I\}$$
$$NAP_E = NAP * LHV \quad \{II\}$$

NAP : Net available potential per year per residue type [tonne /year]
NAP_E : Net available energy potential on basis of the LHV [GJ/ year]

The costs of the residues at the site/field (C_{site}) depend on the which situation sketched in the previous step applies: in situation 1), the existing price ranges should be used. In situation 2) and 3) the ranges between supply price and maximum shadow price should be used.

It is emphasized that transport costs are not included at this stage. Transport costs depend on the choice of form, location and scale of the conversion plant and may determine a major fraction of the final price that will have to be paid at the conversion plant. These aspects will be discussed in the next steps.

Step 5 Choice of location and scale of conversion plant(s)

Once the net amounts of residues available are determined, one must determine the location and preliminary size of the conversion plant. Basically three options are possible:

Option a) Residues may be co-fired in an existing fossil fuel plant.

Option b) The residues may be utilized for an existing small/medium scale cogeneration plant at a crops / wood processing mill.

Option c) The residues may be converted at a new (to be built) large-scale stand-alone conversion plant.

Advantages and disadvantages of each option are briefly discussed in Appendix B. At this stage, it is important to know the location and preliminary biomass fuel demand per year in order to be able to determine logistics and transportation costs, which will be discussed in the next step.

Step 6 Transportation costs and general logistics

Step 6a Transportation costs

Problem description

Transporting the residues from the production site to the conversion plant may be complex, especially if there are production sites dispersed of a wide area. The regional infrastructure, such as road network and road quality (paved, unpaved), their quality during different seasons of the year and resulting possible limitations for trucks, physical boundaries (e.g. rivers, canyons etc.) and the average distance of each production site to the nearest road / junction may severely influence the range in which residues are available. Other limiting factors are energetic densities of the residues, number of available trucks, average truck capacity and efficiency etc. Road transportation is usually preferable to transportation by train or ship due to the higher flexibility and the dispersed nature of the residues.

Methods and data requirements

In literature often maximum transport distance using trucks are given. For example, Tripathi et al. [Tripathi et al., 1998] assume a maximum transport distance for residues of 50 kilometers for India. Other sources report maximum distances between 80-100 km. However, in practice actual maximum economically viable distance depends on a number of local factors such as infrastructure, but also on the size of the plant (larger plants can afford higher fuel prices due to relative high efficiency and lower specific capital costs). Maximum distances should therefore not simply be adopted from literature, though they may provide a general idea on what is viable. In general the infrastructure in developing countries may be less developed, residue density may often be very low and local truck capacities and efficiencies are generally lower than in developed countries.

Once the transport distances are known, transportation costs per ton of residues can be calculated based on the distance, and general transportation costs, the density of the residues and the load capacity of the truck.

Transport costs may be calculated by using the formulas involving parameters such as cost of fuels and drivers, average transportation speed, truck capacities etc. [Tripathi et al., 1998]. Further relevant factors and costs are investment and maintenance costs of the trucks, inaccessibility of certain areas, possible delays, profit margins for the owner of the truck etc. Preferably, cost indications should be collected by survey from local hauliers or farmers as they normally take all these factors into account. Also, it is necessary to assess the transportation costs of the main crops / timber, as they also have to be collected from the same areas and have to deal with similar logistical problems. From the survey, different price indications will be obtained, which should be used in Step 6 as possible variations in transportation prices. It should be noted that many residue types may have a low density (even after pretreatment). Therefore in some cases not the maximum mass but the maximum volume may be the limiting factor. If possible, the costs per tonne and per cubic meter should be determined.

Uncertainties

Even when data on transportation is collected on a local level, uncertainties may remain large. Professional hauliers (middlemen), farmers and industries with their own cargo fleet may quote very different prices. This may be caused by different aspects: hauliers in general want to gain a profit (of which the height may vary) on top of the net transportation costs, while industries with their own cargo fleet will most likely only quote their net costs. Farmers often cannot quantify their costs exactly as it is only a secondary activity, and distances and amount of cargo may vary, so they may make rough guesses about costs.

Deciding on which data should be used also depends on the option of an own cargo fleet of the conversion plant, or if it has to rely on transportation by middlemen or farmers. This may also depend on the number of sites from which residues are to be collected: in case of a limited number of collection sites, an own fleet may be feasible. In case of many dispersed sites (e.g. when collecting field residues), the transportation may have to rely on middlemen and farmers, which may increase transportation costs considerably.

Step 6b General logistics

Problem description

Next to the actual transport of the residues, pretreatment and storing of the residues may be necessary both before and after transportation to the conversion plant.

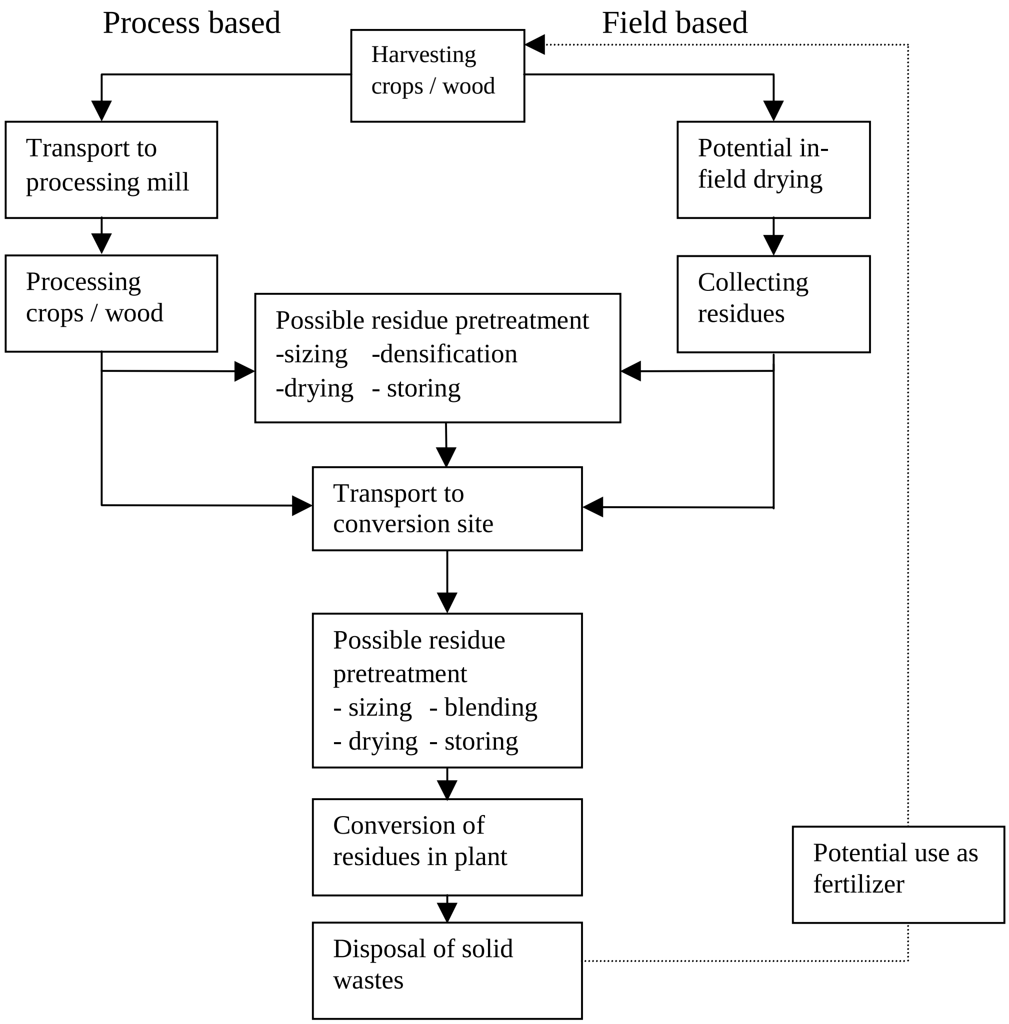
Methods and data requirements

One should consider which pretreatment steps are best to be carried out at the production site, and which pretreatment steps can be carried out more economical at the central processing site. Sizing the residues at the production site is necessary in most cases to compress the residues in order to reduce transportation costs. Drying and storing the residues at the production sites may sometimes also be an attractive option if storage space is available and weather conditions allow drying. However it is also necessary to keep a considerable fuel reserve at the power plant in order to compensate temporal supply shortages, especially when the plant is fueled on only one or two residue types. Also drying may be possible using excess heat produced by the biomass conversion plant [BTG, 1996].

Storing residues at the processing site over longer periods of time may be necessary due to the seasonal supply, but may lead to high decomposition losses, depending on the residue type [Perlack et al., 1997] (if moisture contents are high) or result in increased fire hazard (if moisture contents are low). When considering the size, design and location of the storage facility one must consider the distance to the conversion plant, physical and chemical properties of the fuel, additional fuel preparation requirements, back-up storage capacity and reliability of fuel supply, seasonal weather conditions and operational requirements of the conversion plant [Perlack et al., 1997], [BTG, 1996]. Another logistical issue is the disposal of waste. The ashes may be used for various applications (e.g. fertilizer) depending on composition and quality, but also environmental considerations may limit its applications. It may be worth investigating in how far this can compensate for the removal of field residues, and if this is an economical option.

The simplified logistic chain is given in Figure 2.2. In reality, it may be more economical to collect, store and / or pretreat the residues at intermediate storage sites. This depends on a number of factors, such as the size of the conversion plant, truck transport capacities, available amounts of residues per site and per season. It would exceed the scope of this paper to discuss these factors in more detail. A number of studies have been carried out in developed countries to optimize the logistics chain ([BTG, 1996],[Mol et al., 1997], [van der Meijden & Gigler, 1994]).

Figure 2.2 Logistics chain: Necessary pretreatment and transportation steps for field-based and process based residues



Step 7 Calculating a reference fuel supply curve and setting up scenarios

It is now possible to calculate a total price per ton of biomass per residue at the conversion site. This is the sum of the farm/mill gate price, the transport price and potential additional pretreatment and storage costs. In case of different residues with varying availability throughout the seasons, the delivery price must be determined for the different seasons.

$$C_{plant} = C_{site} + C_{transp.} \quad (+\, C_{stor} + C_{pretr}) \qquad \{III\}$$

$$E_{plant} = R_{net,i} * LHV_i \qquad \{IV\}$$

C_{site} : costs per tonne of residue at each production site [$ / tonne]
$C_{transp.}$: transportation costs from each production site[$ / tonne]
C_{stor} : storage costs per tonne (per month) of residue [$ / tonne (/month)]
C_{pretr} : pretreatment costs at the plant [$ / tonne]
C_{plant} : costs per tonne of residue at the plant gate [$ / tonne]
$R_{net,i}$: net amount of residue i that is supplied to the plant [tonne]
LHV_i : the lower heating value of residue i [GJ / tonne]
E_{plant} : energy potential of residue stream i at the plant [GJ]

Alternatively, all costs can be expressed in $ / GJ. Using these formulas, for each site a price can be determined. The prices and amounts in this calculations should be based on the current situations. Next, the different production sites may be sorted by the delivery price starting with the cheapest one. Consequently doing this per site and per season, fuel supply curves can be set up where the price per GJ can be set against the total amount of available fuel (in TJ).

Now it can be estimated what the *average* delivery price will be depending on the biomass volume. In general, the larger the amount of biomass required, the higher the average price will be (due to increased transportation costs). However, these calculations do not determine the most economical size of the plant alone. Two other important factor must also be considered: The larger the installation, the larger will be initial investment costs. On the other hand larger installation are more efficient, and the production costs of electricity / heat may be lower. Combining these three factors may result in an optimum size. Studies for developed countries show that economic optimum of systems lie at a medium-to-large scale range in developed countries [Dornburg, 1999].

The fuel supply curve constructed in this manner represents a reference case based on the current situation. This reference scenario can now be varied by using the parameters as given in Table 2.3.

Table 2.3 Parameters for the fuel supply scenarios

Ranges in	Derived in
Gross technical energy potential due to variations in	Step 1
Harvest volume (effect on gross technical potential)	
Harvesting season length	
RPR-values	
Physical properties (MC, LHV)	
Net supply potential due to variations in	Step 2
Supply costs (Equipment costs, labor costs)	
Pretreatment costs	
Amounts Utilized	Step 3
Demand prices	
Transportation costs	Step 6
Storage costs	
Decomposition losses	
Pretreatment costs	

Making use of the parameters given in Table 2.3 and the ranges established in the previous steps for each of these parameters, several fuel supply scenarios should be set up. It is suggested to use the following scenario types:

I) The ‘worst-case’- scenario. This scenario must demonstrate the risk if ‘everything goes wrong’. For example, it can be assumed that harvests of either one or several crop types are exceptionally low so that the gross technical residue potential is reduced to the lowest value in the determined range (e.g. 30% lower than the average potential). At the same time transportation costs increase to the maximum value (e.g. due to bad road conditions) and also the supply price increases. In general, one may *vary two or three of the most sensitive* *variables causing the price of biomass to rise*. This scenario should make decision makers aware of possible maximum risks. If possible, the probability of e.g. bad harvests may be derived from statistics. It may also be seen as scenario for the first month / years when starting problems have not yet been overcome.

II) Conservative scenario's. While in the previous scenario all parameters are set unfavorable, in these cases only *one parameters should be varied*, e.g. average harvest volumes but increased utilization by competitors.

III) The optimistic scenario should display a situation where not only *most variables remain the same as in the reference scenario*, but some *parameters may lie more advantageous than expected* (e.g. the average farm / millgate price lies lower than expected, transportation costs are lower due to an optimized logistic chain or available residue amounts increase during time).

Simultaneously, when plant size and conversion technology are known, estimates can be made for the maximum price per tonne of residue which is viable for the plant owner (C_{max}). This price may depend on factors such as prices of fossil fuels, the price at which electricity is sold, the size and efficiency of the plant and the cost of the capital investment. A maximum price per kWh can be calculated as followed:

$$C_{max} = (C_{electr.} - ((C_{acc} + C_{O\&M}) / R_{electr.})) * Eff_e \qquad \{V\}$$

C_{max}	:	maximum costs per tonne of residue [$ / MJ]
$C_{electr.}$	:	electricity price per kWh
$C_{acc.}$	:	annual capital charge, based on a desired Internal Rate of Return
$C_{O\&M}$	:	annual O&M costs
$R_{electr.}$	:	number of kWh generated per year
Eff_e	:	Electric efficiency of the plant [kWh / MJ]

The maximum costs may also be expressed in costs per tonne. It should be noted that the maximum price is set for the plant gate and thus includes transportation costs, and potential pretreatment and storage costs.

Using these maximum prices in combination with the fuel supply curves for the various scenarios, the feasibility of each plant type can be estimated. For example, a power plant may be able to operate within the reference scenario but may run into serious supply problems under the 'worst-case' scenario or even in one of the conservative scenarios. Decision makers and investors thus may assess the possible fuel supply risks.

Chapter 3 Case study setting

General Information

The methodology described in the previous chapter was put to the test in the Northeastern part of Thailand. However, before presenting the results from this case-study the agricultural, economic and energy situation of Thailand, the Northeastern region and in Khon Kaen, a province in the Northeastern region in which most data was collected, is described.

Thailand measures approximately 513,000 km^2, which equals about 14 times the size of The Netherlands. It borders to Malaysia in the south, Myanmar in the west, Laos in the Northeast and Cambodia in the east. Thailand can be divided in four regions. The southern part is situated between the Gulf of Thailand and the Andaman Sea, and best known to foreigners for its many islands and tourist attractions. In the central part the capital Bangkok is situated, the biggest city in Thailand with more than 6 million inhabitants. Chiang Mai, the second-largest city of the country is situated in the Northern part of the country. Finally the Northeastern part, also known as 'Isaan' or the Khorat Plateau is the least developed area of Thailand. Isaan was chosen for the case-study. For a map of Thailand, see Appendix C.

Thailand's economic and energy situation

Thailand has achieved an exceptional record of economic development over the last 30 years, as witnessed by the rapid expansion of the national economy at an average rate of 7.8 per cent per annum up until 1995 [NESDP, 1999]. Despite the impressive rate of economic growth, most of Thailand's economic activity and prosperity has remained concentrated in Bangkok and the surrounding provinces. When economic crisis hit the South-east Asian region in 1996, economic growth came to a halt. Even though by the year 2000 economy seems to recover slowly, many industries still suffer from the effects of the economic crisis [BP, 2000a].

In the early 1980s Thailand was relying for over 90 % on imported energy, mainly in the form of petroleum. During the last two decades Thailand has greatly reduced its dependence from imported fossil fuel sources by exploiting its domestic fossil fuel resources, but still was relying for 43.4% on imported sources in 1997 [DEDP, 1997], [NEPO, 1997]. However the use of lignite (in the north) has caused high SO_2-emissions [TDCSE, 1999], utilization of natural gas (in the south) caused damage to forests by pipeline-constructions [Cummings, 1999] and several large hydro-power projects caused social and environmental problems [TDCSE, 1999].

For the total energy supply, renewable energy sources such as fuel wood, charcoal, paddy husk and bagasse are the major contributor. However, while in absolute terms this source is still growing (growth in 1997 4.1% compared to 1996), its share in the total supply is declining (-2.8% compared to 1996) [DEDP, 1997]. It should also be noted that the main consumers of renewable energy are the residential and commercial sector and the manufacturing sector in the form of fuelwood and charcoal. In terms of electric power, renewable sources contribute about 2% to the installed capacity.

Concurring with the economic growth up till 1995, the total installed capacity increased from 7805 MW in 1987 to 20359 MW in 1997 in order to satisfy the accompanying increase in electricity demand. Due to the economic crisis, the annual growth rate of electricity peak demand reduced from 11% in 1995 to 9% in 1997 and even became negative to –2% in April 1998 [TDCSE, 1999]. As this drop in demand was not anticipated, Thailand now faces an generating overcapacity between 45 % and 52% until at least the year 2003 [BP, 2000a]. For comparison, before the crisis this reserve margin averaged 8.6%.

In order to reduce the overcapacity, the Electricity Generating Authority of Thailand (EGAT) is not planning to build any new power plants except to those already committed. The future additional demand will be served by power projects implemented by private power producers with the backdrop of deregulation and privatization of the electricity supply industry. Most of the additional capacity in the national grid will come from committed independent power producers (IPP), Small Power Producers (SPP) and power purchases from neighboring countries such as Laos. While IPP's exclusively use fossil fuels, SPP's are those which use either renewable energy or waste materials as fuels, or those which utilize fossil fuels but generate power using co-generation systems, and do not have (by definition) a capacity of more than 90 MW_e.

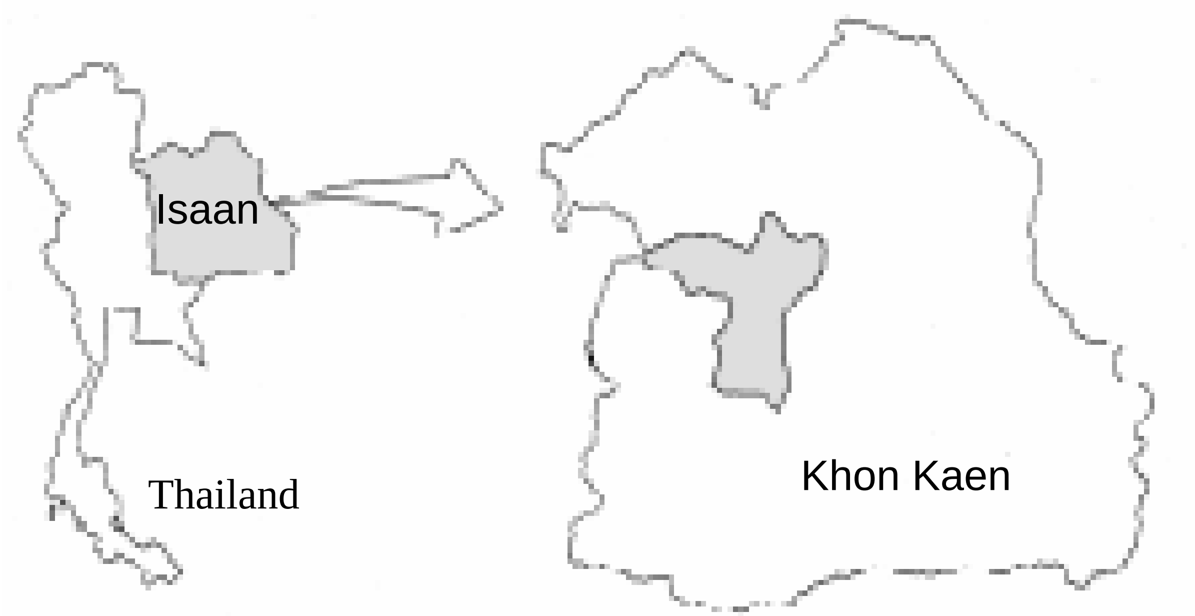
In December 1999, 42 SPP projects were known in operation with a total capacity of 2893 MW (approximately 13% of the total installed capacity), of which 1582 MW were sold to the grid. It should be noted that of the 2893 MW capacity, 421 MW (14,6%) are created by 19 SPP's using biomass (mainly sugar factories, rice mills and saw mills). Of the 1582 MW delivered to the grid, 120 MW (7.6%) spare produced by these SPP's. The other SPP's use fossil waste materials and fossil fuels. Until the year 2003, 14 more SPP's are scheduled to become operational, raising the total capacity to 4412 MW, of which 2277 MW may be sold to EGAT [NEPO, 1997].

Summarizing, in Thailand currently 421 MW of electricity generating capacity is present, fueled by process-based residues, contributing 2% to the total installed electricity generating capacity. However, the installed capacity may in some cases not be used for the larger part of the year, e.g. sugar mills operate normally only 4-5 month per year. It is likely that more biomass-fueled power plants will start operating in the future, though this strongly depends on the tariffs-structure. At the moment, SPP's using biomass fuels and operating less than 4672 hours per year can get non-firm contracts and only receive an energy payment per kWh delivered. SPP's operating more than 4672 hours per year receive an energy payment and a capacity payment [EGAT, 2000]. The energy payment depends on the long-run avoided energy costs resulting from purchasing electricity from the SPP, and averaged 4.86 US$¢/kWh.

Energy and agricultural situation of North-East Thailand / Khon Kaen

Thailand has four main regions with specific agricultural forestry industries and accompanying residues per region. For example, the major part of the Thai sugarcane industry is situated in the central and Northeastern part of Thailand, while coconuts and palm oil industries are for almost 100% located in the southern part of Thailand. It was decided to limit the scope of this study to the North-eastern region of Thailand, also known as 'Isaan'. It

Figure 3.1 Thailand, Isaan and Khon Kaen Province



covers approximately 170,000 km^2 or about 1/3 of the country. Most of the area is the Khorat plateau with the height averaging between 100-200 meters above sea-level. Most of Isaan is fairly flat with mountain ranges in the west and south, and the Mekong river in the north and east where Isaan shares the border with Laos and Cambodia.

Isaan is mainly an agricultural dominated region, the main crops being sugarcane, rice and cassava. Other minor crops are maize, soybean and kenaf. sugarcane production has risen over the last few years as climate conditions seem to be ideal for cane [Sindelar, 1999] while cassava production has steadily declined. Also about 900,000 tonnes of eucalyptus wood is produced annually (see also Figure 3.2). The cultivation of rice is the main occupation of most farmers in the rainy season, which last approximately from May to October with averages between 1,200-1,400 mm per year. Soil quality is the poorest in the country, and it is estimated that roughly one third of the area is not suitable for cultivation. It is also the poorest region of Thailand, with the per capita income of 25,000 Baht (575 US$) which is only 63% of the national average [TCC, 1999].The region has a well developed infrastructure, and over 97% of the villages have access to electricity. Yet most people use charcoal or fuelwood for cooking, as bottled LPG or electricity is available but too expensive.

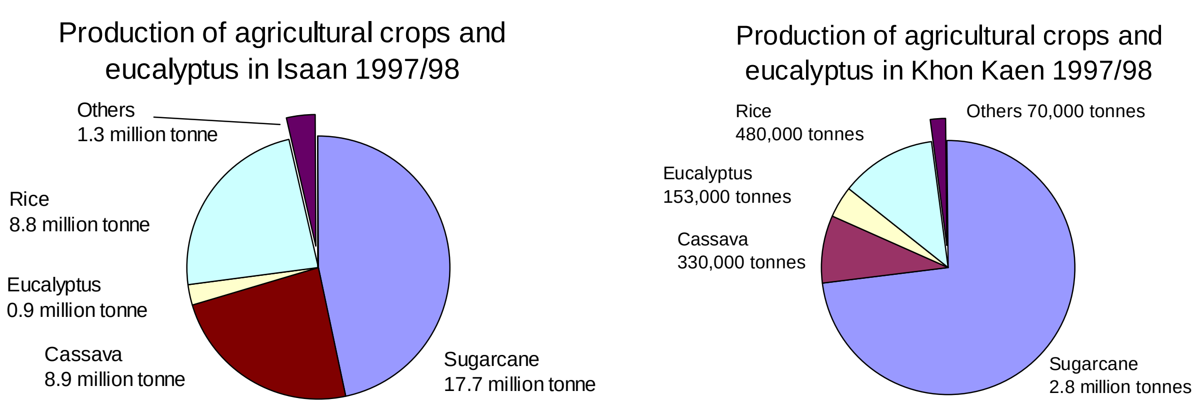
The natural forest cover has decreased severely during the last decades from above 30% (1973) to 13% (1987) in the Isaan region but has since then remained rather stable (12% in 1997), as most forest area lies in national parks and a logging ban is in effect. However, in some provinces of Isaan, the forest cover is as low as 5%.

In order to restore forest land in Isaan, the Royal Forestry Department has promoted the planting of fast-growing tree species involving the state-owned Forest industry Organization (FIO) and the private sector. This has led to some larger (state-owned) and many small (private) eucalyptus plantations. These are commercial fast-growing tree plantations for the pulp and paper industry. In 1998 approximately 900,000 tonnes of eucalyptus wood were harvested in Isaan, not including the waste wood used for charcoal production. In the past there has been quite some resistance against eucalyptus plantations by farmers as they experienced negative impacts on soil fertility, ground water levels and other problems [BP, 1999]. The main consumer of the wood is the pulp and paper industry. Other minor uses are for construction poles, charcoal making and as fuelwood.

Isaan does only possess very limited amounts of fossil fuels. The only thermal power plant in the region is a 710 MW natural gas power plant situated in Nam Pong, Khon Kaen province with very limited remaining fuel reserves. Furthermore there are six hydropower plants situated in the North-East of Thailand with an installed capacity of 244 MW and SPP's (sugar mills) with another 5.9 MW capacity in 1998 [KKSO, 1999]. Isaan is not capable of satisfying its electricity requirements on itself and had to import 43.8% of the electricity consumed from other parts of Thailand and from Laos in 1998 [TDCSE, 1999]. While this situation may have temporarily improved due to the economic crisis, future prospects are not bright, as the Nam Pong power plant will have to reduce its capacity due to the limited gas resources in the year 2001. Two additional hydro plants with a total capacity of 1800 MW are planned to be built until 2011. The electricity supply from the existing hydropower plants has been unreliable in the past due to variations in rainfall [TDCSE, 1999].

The shortage of domestic resources for electricity production on one hand, and the possible use of the biomass residues created by the agricultural sector on the other were the main reasons for choosing the Isaan region as research field. In particular, the province of Khon Kaen was selected as an example for the Isaan region, as it is one of the larger provinces in Isaan and its distribution in agricultural products are similar the those of the whole of Isaan, though the production of sugarcane is higher in Khon Kaen than average for Isaan. For a map of Khon Kaen, see Figure 3.1 and Appendix D.

Figure 3.2 Production of major agricultural products in Isaan and Khon Kaen Province 1997-1998 in green tonnes [NSO, 1998]



Khon Kaen province lies in the center of the North-eastern region and borders eight other provinces. With its 10,800 square kilometers it is the sixth-largest province in the Northeast. It is divided into 25 sub-districts called Amphoe. Approximately 1.7 million people live in the province of Khon Kaen, of which 140,000 in the province capital. [Cummings, 1999]. The available infrastructure is very good, as a national highway passes through Khon Kaen from Bangkok to Laos and another main road passes from west to east through the province. A number of secondary roads connect all amphoes to each other and the main roads. In general roads are asphalted and kept in a good condition in order to transport agricultural crops. The biggest University of the Northeast is also situated in Khon Kaen.

Chapter 4 Applying the methodology

Step 1 Determining the gross technical energy potential

As described in the previous chapter, the main agricultural/forestry crops are sugarcane, rice, cassava and eucalyptus. Data on annual production volumes was collected from the national agricultural statistics, the local statistical office of Khon Kaen, and by interviewing local factories and rice and sugar mills in Khon Kaen. The resulting average yields and variations are given in Table 4.1. Also the average amount of corresponding residues (in tonnes and TJ) are presented.

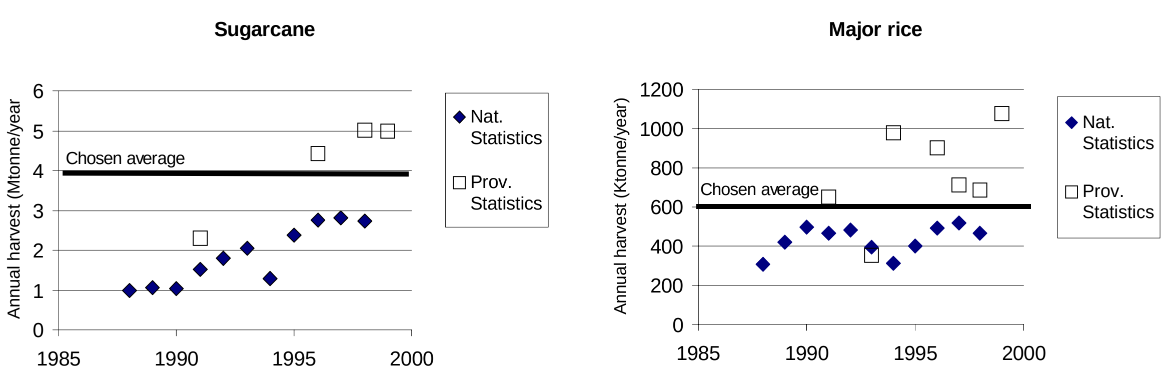
Table 4.1 Major crop types and accompanying gross technical potentials in Khon Kaen

Crop type	Estimated (min/av./max) production (10^3 tonne/year)	Residue type	RPR-value*	Average amount of residue (10^3 tonne/year)	Gross technical energy potential (PJ/year)
Rice	400 / 600 / 800	Husk	0.267	160	2.2
	400 / 600 / 800	Straw	1.757	1,050	14.3
Sugarcane	3,000 / 4,000 / 5,000	Bagasse	0.29	1,160	8.6
	3,000 / 4,000 / 5,000	Tops & leaves	0.265	1,060	17.0
Cassava	350 / 300 / 200	Stalks	0.162	50	0.7
Eucalyptus	n.a. / 150 / n.a.	Waste wood	0.46	70	0.6
	n.a./ 150 / n.a.	Bark & sawdust	0.25	40	0.3
Total				**3,590**	**43.7**
Secondary fuel					
Eucalyptus	n.a. / 150 / n.a.	Main logs	1	150	1.3

n.a. : not available
* : for source see table 4.2

Several remarks have to be made. In the first place, the national and provincial statistics for sugarcane and rice varied considerably (see Figure 4.1). The reasons for the differences between the two statistics could not be determined. The provincial statistics are deemed to be more accurate, as they were collected on sub-provincial level (for rice), and corresponded with the data obtained from the sugar factories. Nevertheless, conservative values were chosen for the average and minimum values as especially the rice harvest is subject to strong variations.

Figure 4.1 Comparison of national and provincial agricultural statistics of Khon Kaen province



Second, no governmental data was available on the total amount of eucalyptus plantations in Khon Kaen. The only data source available was the pulp and paper mill in Khon Kaen [PPPM, 1999] and no variations in yields are known. However, as eucalyptus is a perennial crop, the annual production is assumed to vary only to a limited extend.

Rice straw, bagasse and sugarcane tops and leaves account for over 90% of the gross technical potential. It was decided to disregard cassava stalks in the rest of the analysis because its production has steadily declined over the last ten years. In 1996/1997 market prices had dropped to a level were net returns had become negative [OAE, 1997]. The total amount that may be cultivated in the future is highly uncertain. Furthermore cassava, unlike rice and sugarcane, has no process-based residues, the stalks accounts for only 1.6% of the total technical energy potential and they are already extensively used as domestic fuel and as planting stock.

It was decided to investigate eucalyptus waste wood and bark and sawdust as potential residue source, in spite of the relatively small potential, as it can be harvested all-year round and easily stored. Also the use of the main eucalyptus logs, though not a residue, was evaluated as secondary backup fuel.

In Table 4.2 the main physical characteristics and the seasonal availability of the six main residue streams are given. The seasonal availability of each stream is given. This will be discussed in more detail in the next step in which an overview of the net seasonal availability is given (see Figure 4.4).

Table 4.2 Main characteristics of the selected residue streams

	Rice husk	Rice straw	Bagasse	S.c. tops & leaves	Eucal. Waste wood	Eucal. Bark & sawdust	Eucalyptus logs
RPR	0.267[2] (0.2-0.35)[1,2]	0.452[2] (0.452-3)[1,2]	0.29* (0.14-0.33)[1,2]	0.265* (0.1-0.3)[1,3,6]	0.46*	0.25*	n.p.
M.C. green, wb	n.a.	n.a.	52% (48-55%)[1]	59% (tops)* 17% (leaves)*	52%* (53-58%)[5]	55-60%*	52%* (45%)[4]
M.C. airdry, wb	12.4% (10-13%)[1]	12.7% (7-13%)[1,2]	n.a.	10%[a] (7.9-11.2%)[3]	20%* (7-11%)[5]	n.a.	20%* (18-25%)[4]
LHV green (GJ/tonne)	n.a.	n.a.	7.4* (7.4-9.5)[1]	n.a.	7*	6.3*	7*
LHV airdry (GJ/tonne)	14* (13.4-14.3)[1,2]	13.6* (13.4-13.8)[1,2]	n.a.	16* (15.8-17.4)[3]	14*	n.a.	14*
Bulk dens. loose / baled (kg/m^3)	130[2] / n.p.	60[2] / 140*	85[2] / 150*	n.a. / 147[3]	500* / n.p.	170 / n.p.[2]	500* / n.p.
Seasonal availability	All year (min. July-Aug.)	Dec.-.Jan.	Dec.-April	Dec.-April	All year (max. Dec.-April)	All year	All year (max. Dec.-April)

*	:	own data / calculation
n.a.	:	not available
n.p.	:	not applicable

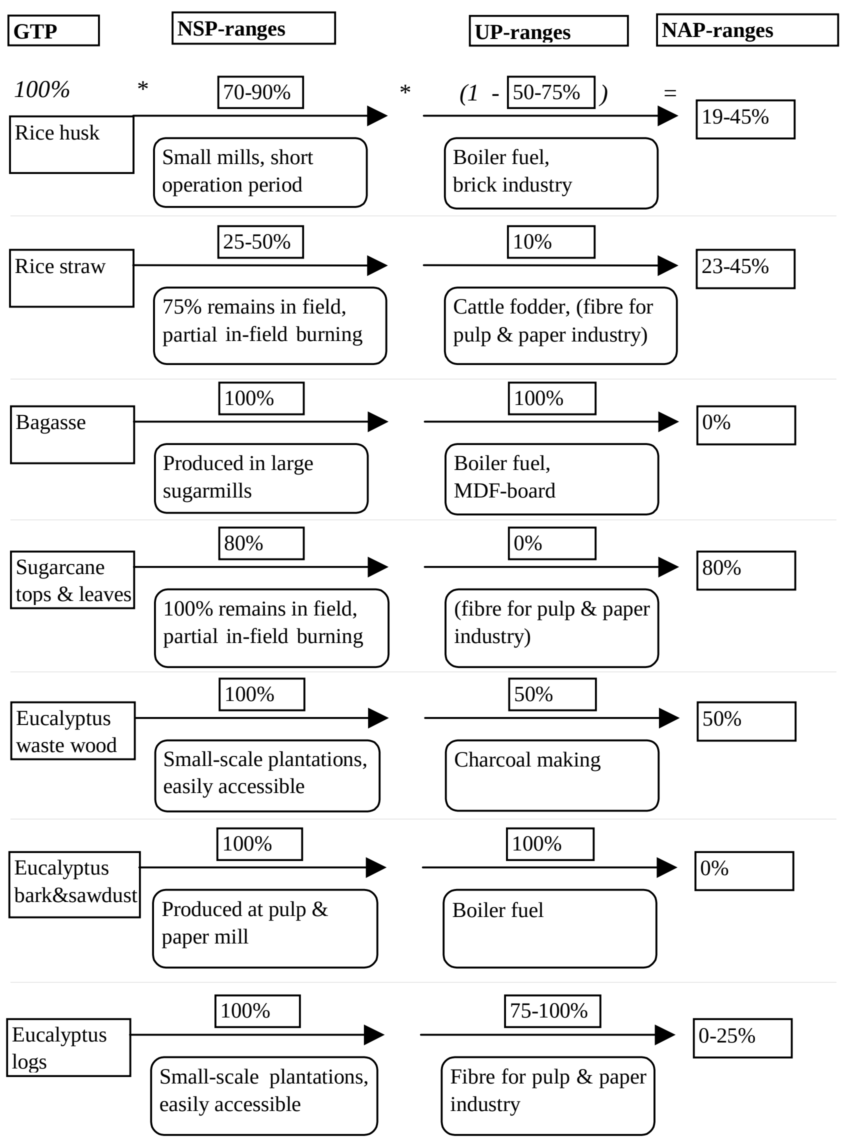
Numbers between brackets indicate ranges found in literature; 1 : [Koopmans & Koppejan, 1998], 2 : [Bhattacharya & Ram, 1990], 3 : [USAID, 1991], 4 : [van den Broek & van Wijk, 1998], 5 : [Southitham, 1999], 6 : [TASL, 2000]

Step 2 & 3 Determining net supply potentials and costs and determining competing applications, utilization and (shadow) demand prices

General information

Isaan is the least developed region in Thailand, and wages are below the national average. Farmers can earn between 4-5.4 US$ per day at harvesting sugarcane or eucalyptus trees. Mechanization in general is very low, and basically all planting and harvesting of rice, sugarcane and cassava is done by hand. Unless stated otherwise, all data on prices and available quantities etc. were obtained by interviewing local farmers, mill-owners, the Khon Kaen statistical office and others sources. All prices were converted from Bath to US dollar (1 US$ = 37 Baht, February 2000). An overview of the availability and utilization of each residue type is given in Figure 4.2

Figure 4.2 Overview of the availability and utilization of each residue type, GTP = Gross Technical Potential, NSP = Net Supply Potential, UP = currently Utilized Potential, NAP = Net Available Potential, NAP = GTP * NSP * (1-UP)



Rice husk

Supply: In Khon Kaen province, 3300 rice mills are registered, but only 25 rice mills produce more than 20 tonnes/day over a extended period of time. Most small rice mills are only used for short periods of time to satisfy local demand. Due to the economic crisis many medium-sized have ceased to operate. It is estimated that 70-90% of the available rice is milled in the large rice mills. Thus, the net supply potential is 70-90% of the gross technical potential. These large rice mills normally store large amounts of rice and are able to operate for 10-11 month per year with a minimum supply in July and August. Pretreatment for transportation is not common.

Demand: In the past, some mills utilized 50-70% of the available rice husk as fuel for process energy requirements. However, in the last years most mills tended to abandon burning rice husk, as it was economically more attractive to buy electricity for process requirements and sell rice husk. Only very large rice mills with capacities over 500 ton/day have recently started to burn rice husk for steam and electricity production [TPS, 1999], [COGEN, 1999].

The main consumer of rice husk is the brick-industry (in most cases approximately 90% of all rice husk consumed). The brick-industry uses rice husk as fuel to burn bricks, and has little or no other low-cost fuel alternatives. Charcoal, sawdust or lignite are either too expensive or difficult to obtain [Lebbing, 1999]. Other minor consumers are noodle-factories, and farmers which use the rice husk as poultry bedding and fertilizer. Demand and prices per site depend strongly on the number of brick factories and the demand for bricks in the vicinity and also on the time of the year (in August-October rice husk is more scarce). Prices have varied in the past between 1.4 - 5.4 US$/tonne, though 8.1 US$/tonne were mentioned in times of extreme rice husk scarcity. At the moment, due to the low activity in the construction sector prices varied between 1.4 US$/tonne in Chumpae (50% of the net supply potential is utilized) and 2.7 US$/tonne in Khon Kaen city (75% is utilized) (For locations see Appendix D). For comparison, in a recent nationwide survey [NEPO, 1999b], it was estimated that only 20-50% of the net supply potential is utilized, again varying strongly per location.

In case rice husk is used on a large scale as fuel for power plants and the demand for bricks increases again, prices may rise to or above 5.4 US$/tonne, depending on the recovery of the building sector and corresponding demand for bricks, and new developments in brick-making. As maximum (shadow) demand price, 8.1 US$/tonne is assumed.

Rice straw

Supply: Due to current harvesting practices, about 75% of the rice straw remains in the field, and only 25% is easily accessible for baling as it is deposited after threshing at a central site near a road. Thus, the current net supply potential is only 25% of the gross technical potential (corresponding RPR-value is 0.452 [Bhattacharya & Ram, 1990]). Some of the remaining straw in the field is burnt, the rest is left to decay or cattle is allowed to graze in the fields. At this moment, rice straw is not baled in Isaan. In central Thailand, rice straw is used as cattle fodder for the dairy industry, and collection and baling costs result in 13.5 US$/tonne for bales of approximately 50 kg, both for manual or mechanical baling [NDI, 2000]. This price was also assumed for the study-area.

It may be possible to collect all the straw currently remaining in the field (which would result in a RPR-value of 1.757). However, large-scale mechanical harvesting equipment is not available, as investment costs are high and rice fields are rather small (average 0.8-1.6 ha), often separated by rows of trees or small dykes, and soils are often very wet which would make mechanical harvesting laborious and inefficient. Manual harvesting the whole plant may be possible, but would result in a lower rice yield during threshing. No data is available on the increased labor and necessary compensation costs. As a conservative estimate, it is assumed that another 25% can be available, increasing the NSP to 50% of the GTP. It is estimated that this would be possible at a 30% higher price (17.6 US$/tonne), as costs for collection would be higher while baling costs would remain identical.

Furthermore, rice straw is only available during the rice-harvesting season in December and January with a possible variation of 1-2 weeks depending on the length of the rainy season. Removing most of the straw of the field is not likely to have a negative effect on the soil, as currently a large percentage is burnt in the field. The loss of minerals can possibly be compensated by using the ash resulting from the conversion plant as fertilizer (as it is already current practice in the sugar industry). In addition the environmental problems of in-field rice straw burning would be eliminated.

Demand: A small fraction is used as cattle fodder (approximately 10% of the amount remaining in the field). Apart from that, rice straw is currently not utilized in Northeastern Thailand. However, in case a shortage of pulp and paper feedstock occurs (see eucalyptus), there is a chance that rice straw may increasingly be utilized for pulp. Rice straw has a lower quality fibre than eucalyptus and supply prices are comparable (13.5 vs. 13.5-16.2 US$/tonne). Therefore it is unlikely that the pulp and paper industry is willing to pay more for rice straw than for eucalyptus, and thus the (shadow) demand price is set equal to the supply costs of rice straw.

Bagasse

Supply: All bagasse is created at large-scale sugarcane processing factories, and basically the NSP equals the GTP. Bagasse is produced during the harvesting season, from begin December until mid of April (with an approximate variation of 10 days).

Demand: Bagasse is utilized by the sugar factories for 80-90% as boiler fuel for own steam/electricity requirements. Of the 46 sugar mills currently in Thailand, 14 use their excess bagasse to generate additional electricity which is sold to the grid. One of them is situated in Khon Kaen. Three other sugar mills (in Khon Kaen and surrounding provinces) sold their excess bagasse to either a particle board factory or a MDF-board factory for 1.35-2.7 US$/tonne. In both cases these were in first instance established near a sugar factory to deal with the excess bagasse problem, and belong to the same industry group. It was reported that in years of bad sugarcane harvests, these factories have a supply shortage of bagasse and have to use eucalyptus wood as feedstock. It is assumed that most other sugar mills in Isaan either use their excess bagasse to generate electricity or sell it to industries which use bagasse as resource. Thus, it is assumed that the current utilization is 100%. In literature the net availability of bagasse was estimated to be 4.5-7% of the total production [NEPO, 1999b].

Sugarcane tops and leaves

Supply: Over 99% of the cane is harvested manually. Local harvesting methods vary strongly per region. Most farmers prefer to burn the sugarcane leaves before harvest (harvest facilitation, elimination of snakes). However, some sugar mills try to prevent pre-harvest burning by paying less for burnt cane, as the sugar quality is inferior compared to sugar from unburned cane. Currently, between 10-56% of the tops and leaves are burnt before harvest. Also after harvest, some farmers tend to burn the remaining tops and leaves in order to destroy weeds and use the resulting ash as fertilizer for the new sugarcane plants, which are planted soon after the harvest. It can be expected that as soon as the tops and leaves can be sold, this practice will diminish and that an estimated 80% of the gross technical potential will be available. As in the case of rice straw, the depletion of minerals can be prevented by using the boiler ash and filter cake as fertilizer.

The average harvesting season length is about 125 days with a variation of 5 days. Harvesting starts at the end of November or the beginning of December (mainly depending on the length of the rainy season in the particular year) and will continue until the begin / mid of April. The tops and leaves are available during this time period.

To collect and transport the tops and leaves, basically two concepts were investigated: either the tops and leaves are left in the field for some days to dry, and then are baled by a mechanical baler, and loaded on trucks for transport. Alternatively, the whole plant may be harvested mechanically or by hand and loaded on trucks, and the tops & leaves may either be removed at the sugar mill or crushed with the cane (resulting in a lower sugar recovery but a much higher amount of bagasse). Neither of these methods is currently practiced in Thailand.

In order to estimate possible labor and transportation costs for the whole-plant harvesting option, a small-scale field experiment was carried out (for results see Appendix E). For the second possibility, data was used from an experiment on mechanical baling of sugarcane tops and leaves in the field in Thailand [USAID,1991]. After adjusting for inflation, the (supply) price for producing round bales of average 371 kg is approximately 16.5 US$/tonne at the field, which is comparable with prices for rice straw baling. This price includes the costs for renting equipment (such as tractors and balers) and for labor. In contrast to rice straw harvesting, mechanical baling of sugarcane does not seem to be a problem, as fields are generally large(r) and easily accessible. Recent experiments in Brazil with similar harvesting equipment indicate costs between 12.2-15.1 US$/tonne [CTC, 1998], which are taken as supply costs for more optimistic scenarios. Recent experiments in India with manual and mechanical baling of sugarcane tops and leaves report prices between 7.9-11.5 US$/tonne [TASL, 2000]. However, as no further detailed data on local circumstances was given, this information was not used in the scenarios.

When comparing these two transport routes, transporting baled sugarcane leaves and tops and leaves is clearly the more economical option (mainly caused by the very low bulk density of the whole plants, see Appendix E) and was therefore used for further calculations.

Demand: Much like rice straw, sugarcane tops and leaves are not utilized at all. The leaves are not suitable as cattle fodder. Burning the leaves may destroy weeds and serve as fertilizer, but again, returning the ashes may compensate for this effect. Once more, the pulp and paper and the particle- and MDF-board industry may be interested in sugarcane leaves as raw material.

Eucalyptus logs

Supply: Currently there are approximately 12800 ha of eucalyptus plantations in Khon Kaen of which 8000 ha are cultivated on small private farmer plantations with an average size of 1.3-1.7 ha. Another 4800 ha are under the supervision of either the Royal Forestry Department (RFD) or the state-owned Forest Industry Organization (FIO). Annually these plantations produce approximately 150,000 tonnes of eucalyptus wood [PPPM, 1999]. Prices at the plantations varied in 1999 between 13.5-16.2 US$ per tonne at a minimum diameter of 2.5 inches (6.35 cm).

Collection is preferably carried out from December to April, as labor availability is high in these months, and low during the rainy season during which most farmers plant rice.

Demand: The major consumer of the eucalyptus logs is the Phoenix Pulp and Paper mill situated in the North of Khon Kaen. It is the only pulp and paper mill in the Northeastern region and consumes 153,000 tonnes of eucalyptus wood, which is (according to the mill itself) almost 100% of the eucalyptus produced in Khon Kaen. The Phoenix Pulp and Paper mill paid between 19.9-21.1 US$ / tonne in 1999 (at the paper mill). At the moment, there a was a slight oversupply of eucalyptus, and it was estimated that approximately 75% of all eucalyptus was utilized.

Supply and demand for eucalyptus strongly depend on the world price for pulp. Prices varied in the past from 24.3 US$ (1995) to 19.9 US$ (1999) [BP, 2000b]. At this moment, many farmers are pessimistic about the future of the eucalyptus market and sell their trees prematurely, abandoning eucalyptus growing. However, the long-term expectations for the demand of paper pulp in the Southeast-Asian region are very high: in China alone the pulp demand is expected to rise from current 30 million cubic meter per year to 55 million cubic meters in 2015 [BP, 1999]. In order to satisfy this increased demand, the Thai cabinet recently approved a one billion US$ Sino-Thai pulp and paper project in February 2000 [BP, 2000c]. An additional 32000 ha are to be allocated in the eastern and northeastern part of Thailand to produce 700,000 tons of pulp annually. Whether this project will be realized may strongly depend on the availability of suitable land and the attitude of farmers and environmental groups. If insufficient pulp is available, the price for eucalyptus logs may rise to or above 1995-levels, availability would be 0% and the pulp and paper industry may look for alternatives such as rice straw and sugarcane tops and leaves as raw materials. If however the Sino-Thai pulp and paper project continues and prices rise again, a fraction may be available. It is assumed that in order to compete with the pulp and paper industry, the price for eucalyptus logs would at least have to be 24.3 US$. This price (unlike the others) includes transportation costs and would have to be paid at the conversion plant. It is assumed, that at this price level growing eucalyptus is attractive for farmers, and (as a rough estimate) about 25% of the current GTP could be supplied.

Eucalyptus waste wood

Supply: Most eucalyptus trees are harvested after 5-6 years, as farmers often cannot afford to wait longer. The smaller part of the eucalyptus logs (diameter below 6.4 cm), branches, twigs and leaves are not used for the pulp and paper industry. Collection and loading costs of logs and branches with a diameter between 3-6.5 cm are approximately 7.4 US$/tonne. In a small scale experiment (see Appendix F) the ratio between wastewood and logs was determined to be approximately 0.46 : 1. As a rough estimate, 69,000 tonnes of waste wood are annually created per year in Khon Kaen. Due to the small size and easy accessibility of the plantations, the accessible fraction was judged to be 100%. Again, collection is preferably carried out from December to April.

Demand: Approximately 50% of the available waste wood is used for charcoal. It is estimated that 70% of all charcoal consumed in the Isaan region originates from eucalyptus wood. The remaining 50% of the waste wood is assumed to be available. Local charcoal factories report paying prices between 8.1-9.5 US$/tonne of this waste wood including transport costs. It may be possible to obtain 100% of the net supply potential by outbidding this price, but extensive use may result in the further (illegal) deforestation of natural forest in order to satisfy the charcoal demand. For further calculations, it is assumed that 50% is available. Availability of this stream is also directly connected to the economic attractiveness of growing eucalyptus and the future demand for charcoal and fuelwood.

Another estimated 69,000 tonnes of small twigs (diameter below 3 cm) and leaves remain in the plantations. It is deemed undesirable to use these residues, as the long-term removal of twigs and leaves may result in serious loss of minerals and erosion (which is already a problem at many eucalyptus plantations [BP,1999]). Also manual collection of the small twigs and leaves was deemed very difficult, time-consuming and costly compared tot the larger branches.

Eucalyptus bark and sawdust

Supply: All bark and saw dust is produced at the Phoenix Pulp and Paper mill, where it is easily accessible. The NSP is 100%.

Demand: The Phoenix Pulp and Paper mill already utilized 100% as boiler fuel and thus is not available for other applications [PPPM, 1999].

Step 4 Net supply potentials

In Table 4.3 the data collected in the previous step is summarized and the net available potentials (NAP) are given. Noteworthy is the high degree of utilization of the process-based residues. By far, the highest net available potentials are sugarcane tops and leaves and rice straw. The remaining potentials of rice husk and eucalyptus waste wood are marginal. The total average NAP_E is 19.5 PJ/year, which is 44% of the GTP_E. In Figure 4.3 the composition of the GTP, NSP and NAP are illustrated. In Figure 4.4 the seasonal distribution of the net available energy potential is given.

Table 4.3 Overview of various potentials and prices

	Rice husk	Rice straw	Bagasse	Sugarcane tops & leaves	Eucalyptus logs	Eucalyptus waste wood
C_S (US$/tonne)	0	13.5-17.6	0	16.5 (12.2-15.1)	14.9	6.8
C_D (US$/GJ)	2.7-8.1	13.5-17.6	1.4-2.7	16.5	13.5-16.2 20.3-24.3[a]	7.4 8.1[a]

1 US$ = 37 Thai Baht (February 2000)
C_S = supply costs, C_D = demand prices
a : at the site of consumption (i.e. paper mill / charcoal factory), thus including transportation costs

Figure 4.3 Overview of The Gross Technical Potential (GTP), the Net Supply Potential (NSP) and the Net Available Potential (NAP)

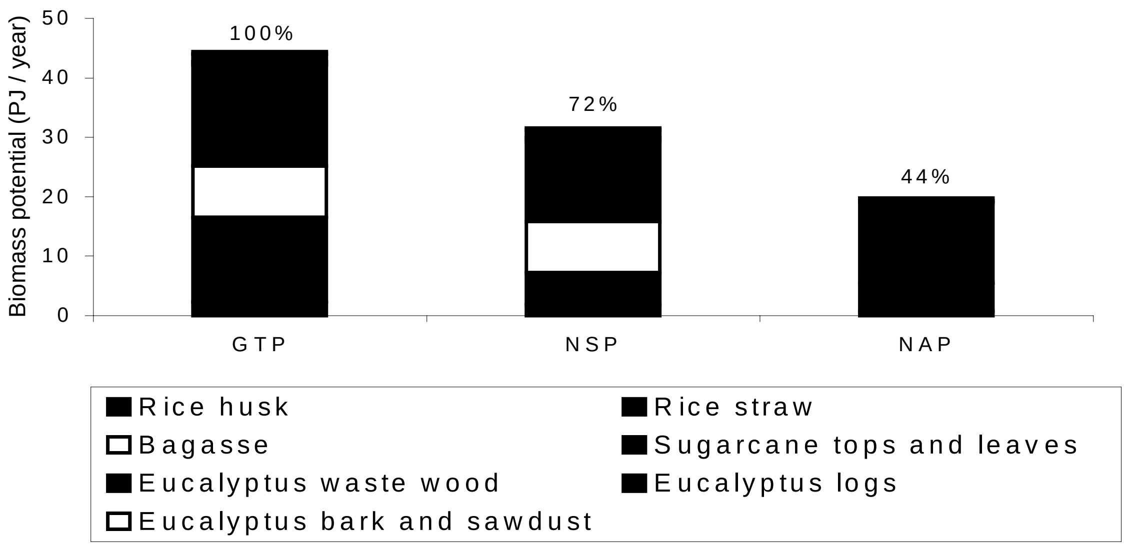
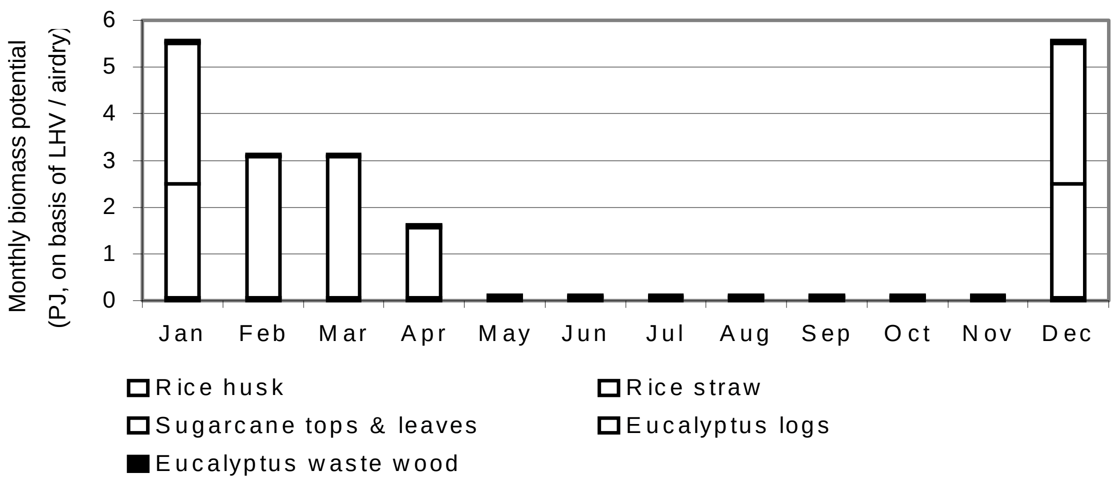


Figure 4.4 Seasonal distribution of the net available energy potential



Step 5 Choice of location and scale of conversion plant(s)

As mentioned in the previous section, sugar factories are one of the major industries which produce electricity as small power producers during the sugarcane season. The average sugarcane factories in Thailand have a capacity between 15,000 and 30,000 tonnes of sugarcane per day, and have an electricity generating capacity between 12-30 MW_e of which all or the major part is required for the milling process. As to March 2000, 14 of the 46 sugar factories in Thailand deliver electricity to the grid during the sugarcane crushing season, on average between 3-8 MW. In Isaan there are currently thirteen sugar mills of which five deliver electricity to the grid during the sugarcane harvesting season [NEPO, 1999a]. It is interesting to determine if it would be possible to increase the electricity production by using the electricity generating capacity of the sugar mills during the harvesting off-season. On the other hand, Isaan has almost no fossil fuels, and possesses only one fossil fuel plant which limits the options for cofiring biomass in Isaan. Therefore a sugarmill in Isaan was selected for a fuel supply case study. As particular study area, the area was chosen from which farmers delivered sugarcane to the sugarmill. About 90% was situated within 65 km transportation distance and 10% between 65 and 90 km transportation distance to the sugarmill. The total area in which sugarcane was collected was estimated to be about 7800 km^2. This is relatively arbitrary, but considering the local infrastructure situation, it is a representative case for demonstrating the methodology.

Step 6 Transportation costs and general logistics

Step 6a Transportation costs

Local transport within 100 km is carried out by pick-up trucks and open 6-wheel and 10-wheel trucks. Paddy is transported to the rice mills in cars and small trucks, while sugarcane is transported for the larger part in 10-wheel truck and to smaller extend in 6-wheel trucks. Rice husk is also transported in both 10-wheel and 6-wheel trucks. Large 18-wheel trucks are not used for transports below 100 km. Transport in containers is also not common for distances below 100 km [Dick, 2000].

For comparing and calculating transportation costs, it was assumed that 10-wheel trucks are used. As reference situation, data was used provided by several sugarcane factories for transportation of sugarcane [MPV, 2000]. The transportation costs are shown in Figure 4.5 (line A). Fixed costs lie at 32 US$ per truckload, while variable costs lie at 0.41 US$/km/truckload. Transports are carried out either by the farmers themselves, or by middlemen. Commercial hauliers [Dick, 2000] gave price indications with higher fixed costs but similar variable costs (line B). The commercial cost estimates are given for one single transport and closed trucks. In Isaan only open trucks are used, which are cheaper in general. Also price offers will most likely be lower when transports are performed on a large scale. In addition, information was gathered from local industries (a rice mill, a MDF-board factory [KKMDF, 1999]). Their transportation data was less detailed and indicated similar fixed costs but 20-30% lower variable costs (line C). This may be plausible, as current waiting times (up-to 24 hours) at the sugar mill are included in line A, but are probably avoided in line C. Also the transportation of low-density cargo requires less maintenance costs, less fuel and transportation speeds are higher. For the average calculations for transportation costs, line A was used. For a scenario with maximum transportation costs, line B was used, while optimistic scenarios use line C.

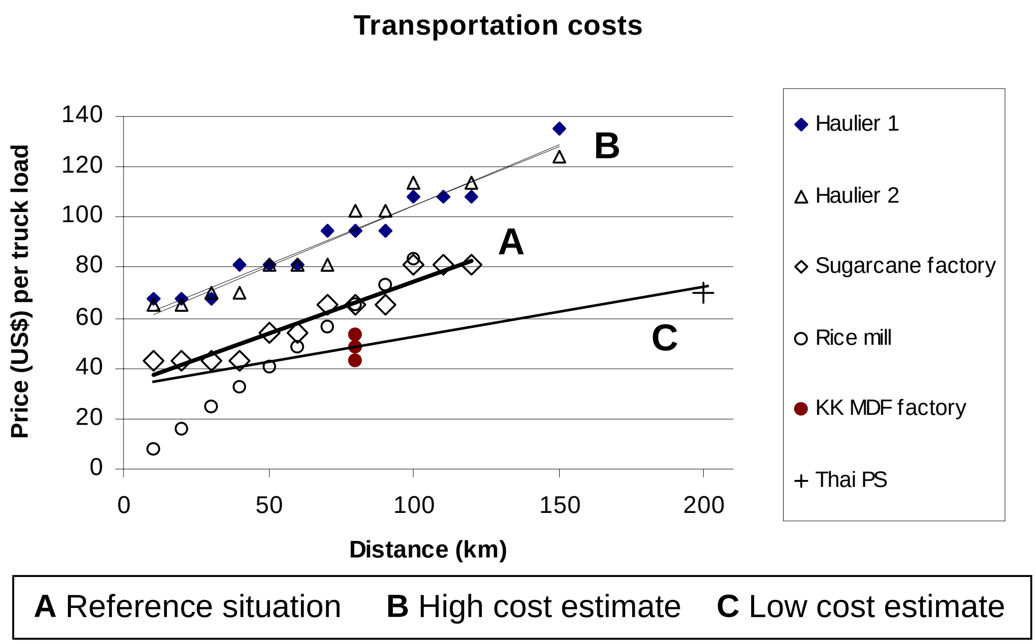
Several remarks have to be made. First of all, the legal maximum weight for a 10-wheel truck is around 12 tonnes. In practice up to 20-22 tonnes of sugarcane or eucalyptus are stacked on a truck. When caught by the police, normally a small 'fine' is paid. However, many agricultural residues are bulky and have a low density, which makes the loading volume capacity more important. However, volumes of different 10-wheel truck types varied between 25 m^3 and 42 m^3. In Table 4.4 the average maximum capacities of a 10-wheel truck per residue type are given and transportation costs for 10 km and 80 km distances (based on line A).

Table 4.4 Data on transportation costs

	Rice husk	Rice straw	Sugarcane tops & leaves	Eucalyptus logs	Eucalyptus waste wood
Load cap. 10 wheel truck (tonne)	6 (5-7)[c]	4.5[a]	4.4[a] 0.7[b]	20	20
Transportation costs (US$) For 10 km / 80km	6.2 / 11.0	8.3 / 14.7	8.5 / 15.0	1.9 / 3.3	1.9 / 3.3

a : in baled form
b : as part of whole plant
c : depends strongly on volume of truck, and loading technique

Figure 4.5 Costs for one-way transportation by 10-wheel truck (max. capacity 22 tonnes)



The transportation costs may also depend on the total amount of biomass that has to be transported. At present, an average sugarcane factory requires 90,000 truckloads of sugarcane within four months, while the pulp and paper factory requires approximately 50,000 truckloads within a year (based on 10-wheel trucks only). Assuming that transport is carried out by farmers and middlemen and a power plant requiring 2 PJ biomass (scale between 20-30 MW_e depending on efficiency), it would (in the worst case) require about 32,000 truckloads in four months. In this case it is not likely that a truck shortage will occur, and line

A will probably give a reasonable price indication. However, if 8-10 PJ have to be transported, a truck shortage may occur, and additional trucks may either have to be purchased by the power plant or hired from other regions, which would likely cause a short-term increase in prices up to the costs given in line B, but may also result on the long-term in a larger and more efficient fleet.

Step 6b General logistics

For shredding rice straw, costs are approximately 4.1 US$/tonne [TPS, 1999] using wood shredding equipment, so those costs may be lower if more specialized equipment was used. For baled sugarcane trash, shredding costs of 1.6 US$/tonne are reported [TASL, 2000]. For eucalyptus wood, costs for chipping logs and waste wood are 2.5 US$/tonne [PPPM, 1999]. For storage of the residues, approximately 0.14 US$ are assumed per month per cubic meter. This assumption depends on the availability of storage space close to the conversion site, the storage technique and the possibility to store baled sugarcane tops and leaves and rice straw at intermediate sites. Also safety-measures for fire protection are included in this price range [Kadam et al., 2000].

Average storage times vary greatly per residue type. Due to the seasonal availability of rice straw and sugarcane tops and leaves, these streams will have to be stored over several months. Eucalyptus will have to be stored for at least one month in order to allow moisture content to reduce from 52% to 20%. It is assumed that no residues are stored longer than 12 months. No information was available on possible dry matter losses. No losses were assumed.

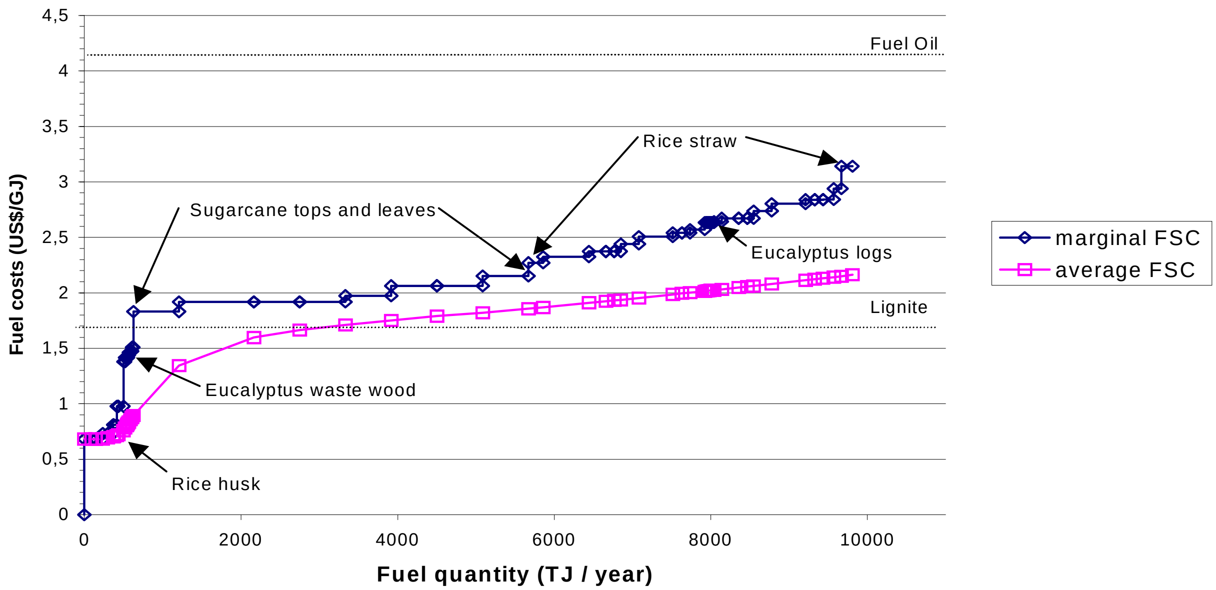
Table 4.5 Overview of storage and pretreatment costs

	Rice husk	Rice straw	Sugarcane tops and leaves	Eucalyptus waste wood	Eucalyptus logs
bulk density (kg/m^3)	130	140	147	500	500
average storage time (month)	-	5	3	1	1
average storage costs (US$/tonne)	0	5.0	2.7	0.28	0.28
Shredding/chipping costs/ (US$/ tonne)	0	4.1	1.6	2.5	2.5

Step 7 Calculating a reference fuel supply curve and setting up scenarios

Firstly, the reference fuel supply curve was drawn up. This fuel supply curve was constructed by using the current conditions, i.e. current prices, average harvest volumes and average transportation costs. Two types of supply curves are given in Figure 4.6 for this scenario. The marginal supply curve presents the absolute costs of every residue stream. The progressing average curve represents (at any point of the curve) the total average costs of all biomass utilized at that point (i.e. the total amount of biomass divided by the total amount of costs). As indicated in the graph, rice husk represents the cheapest stream, followed by eucalyptus waste wood. Sugarcane tops and leaves represent the potential between approximately 0.8 and 6 PJ, followed by rice straw (between 6 -10 PJ). The eucalyptus logs stream is situated at approximately 8 PJ and represents an almost negligible potential. Prices in the marginal fuel supply curve vary from approximately 0.7 US$/GJ (rice husk) to 3.2 US$/GJ (rice straw). For comparison, the current price per GJ of (domestic) lignite and (imported) fueloil are also given (based on situation in January 2000).

Figure 4.6 Reference Fuel Supply Curves. In the reference case, about 9.8 PJ are available varying in price between 0.7-3.2 US$/GJ. The upper curve represents the marginal biomass costs, while the lower curve indicates the average biomass costs.



Based on this reference scenario and the determined ranges in which parameters may vary, a number of scenarios were set up. As a first scenario (Fuel) the possible effects of an increase in demand for residues as fuel (eucalyptus waste wood and rice husk) are estimated. The next scenario deals with the possibility of a bad harvest season for rice and sugarcane (Harv). This scenario may also be seen as an increased demand for rice straw and sugarcane tops and leaves. In scenario (Trp), the transportation costs are assumed to be higher than in the standard case. The 'worst case'-scenario (Worst) combines all these assumptions, while in the optimistic scenario (Best) assumes more advantageous transportation costs, lower costs of baling sugarcane tops and leaves, and a high harvest volume. The specific variables changed per scenario are given in Table 4.6. The fuel supply curves for each of these scenarios are given in Figure 4.7 (marginal) and Figure 4.8 (average).

Table 4.6 Overview of parameters changed in various scenarios

Scenario Ref	Reference scenario, based on current situation
Scenario Fuel	Eucalyptus waste wood not available, rice husk availability 25%, 8.1 US$/tonne
Scenario Harv	33% reduction in availability of rice straw, rice husk and sugarcane tops and leaves
Scenario Trp	Higher transportation costs (see figure 4.5, line B)
Scenario Worst	'Worst Case', combination of Scenario Fuel, Harv and Trp
Scenario Best	'Best Case', low baling costs of sugarcane tops and leaves (12.2 US$/tonne), low transportation costs (see Figure 4.5, line C), 33% increase availability rice husk and rice straw, 25% increase availability sugarcane tops and leaves

Figure 4.7 Various scenario's in comparison to the reference fuel supply curve (marginal costs)

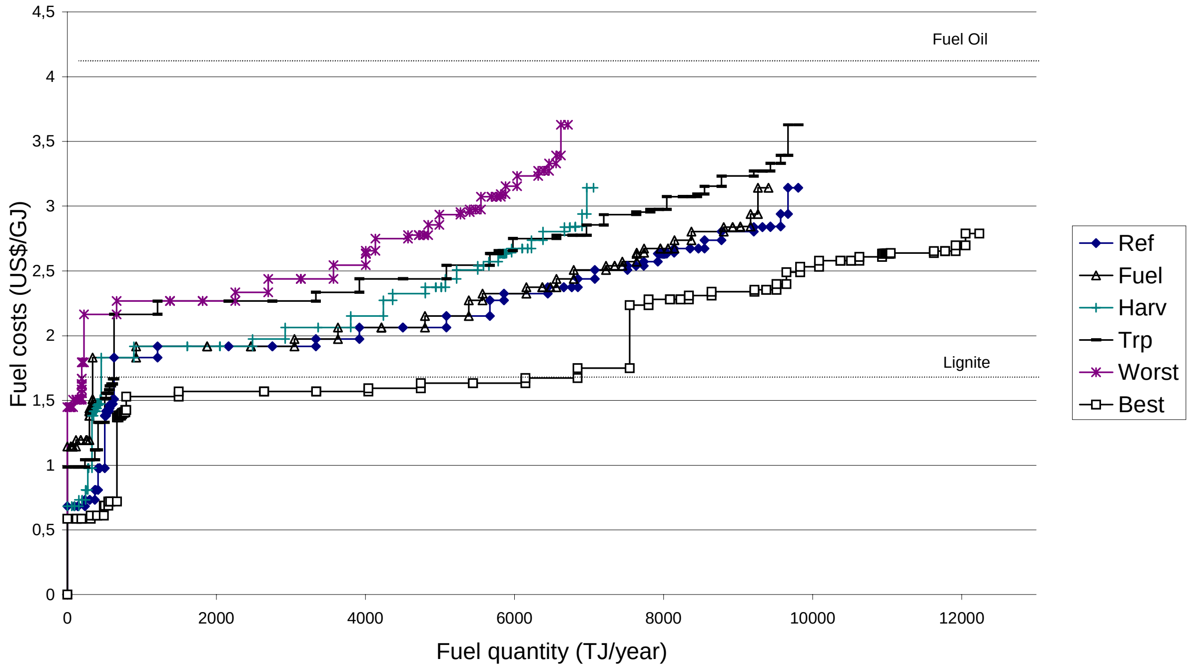
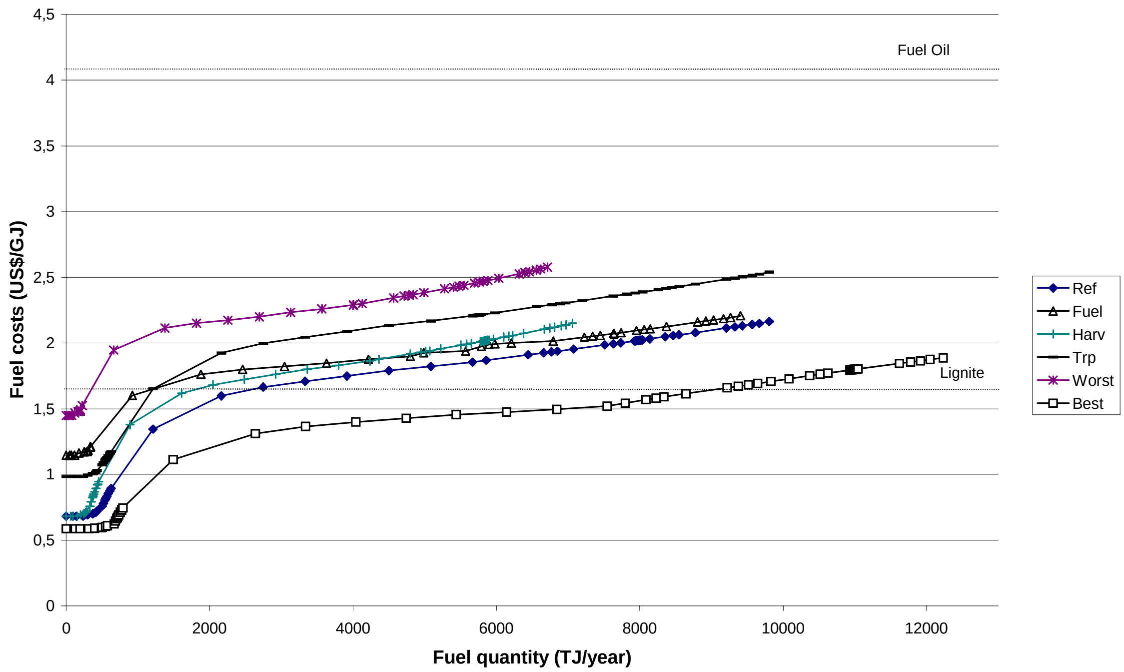


Figure 4.8 Various scenario's in comparison to the reference fuel supply curve (average costs)



Evaluating various biomass power plants for the supply situation in Isaan.

In order to evaluate the consequences of these scenarios, the maximum biomass fuel costs were calculated for four stand-alone biomass power plants.

As a first biomass power plant, an existing sugarmill in Isaan was selected. The sugarcane factory is currently delivering 6 MW_e to the grid during the crushing and refining season, which is about 170 days. In the same period, the mill produces another 14 MW_e for its own process requirements. The net electric efficiency at lower heating value is 9.5%. The mill does not get any capacity payment at the moment. It is assumed that the electricity generating period will be extended by another 122 days to 292 days (total load factor of 80%). In these 122 days the factory will deliver the full 20 MW_e to the grid. Furthermore it is assumed that the mill will have access to rice husk and eucalyptus waste wood during the total operating time, but will have to store sugarcane tops and leaves near the sugarmill for an average period of three months.

The sugar mill will receive capacity payments of 6 MW_e for 170 days, and of 20 MW_e for 122 days, and additional energy payments over 122 days. In absence of relevant data it is assumed that no major further investments (e.g. boiler adaptations, transformer adaptations etc.) are necessary. For the additional O&M-costs, data is used from a comparable situation in Nicaragua [van den Broek et al., 2000]. These are adapted for the situation in Nicaragua (e.g. low costs for local qualified labor, no O&M costs for ash disposal). It is assumed that these conditions are also valid for the situation in Isaan.

From this publication also adjusted investment costs and O&M costs were used for three other stand-alone power plants for generating electricity:

- A 24 MW_e ‘state of the art’ combustion plant based on a new stand-alone wood-fired combustion plant to be built in the Netherlands [Remmers, 1997].
- A 29 MW_e BIG/CC gasification plant which may be available within the next five years [Faaij et al., 1997b]
- A 110 MW_e advanced gasification plant which may possibly be available after 2015 [Faaij et al., 1998].

For each plant, a load factor of 80% and a lifetime of 20 years was assumed (see also Table 4.7). A maximum viable fuel price was determined for each plant type by using the investment and O&M costs, data on current pay-back tariff’s in Thailand and an assumed IRR-rate of 15%, considered realistic for the current Thai situation (see also chapter 3, step 7, formula {5}). The maximum viable fuel prices and the fuel requirements were then compared with possible supply situations in Northeastern Thailand. The results are displayed in Figure 4.7. In order to obtain a viable project, the maximum fuel price must lie above the reference scenario fuel supply curve as indicated for each conversion option by a dot in Figure 4.9.

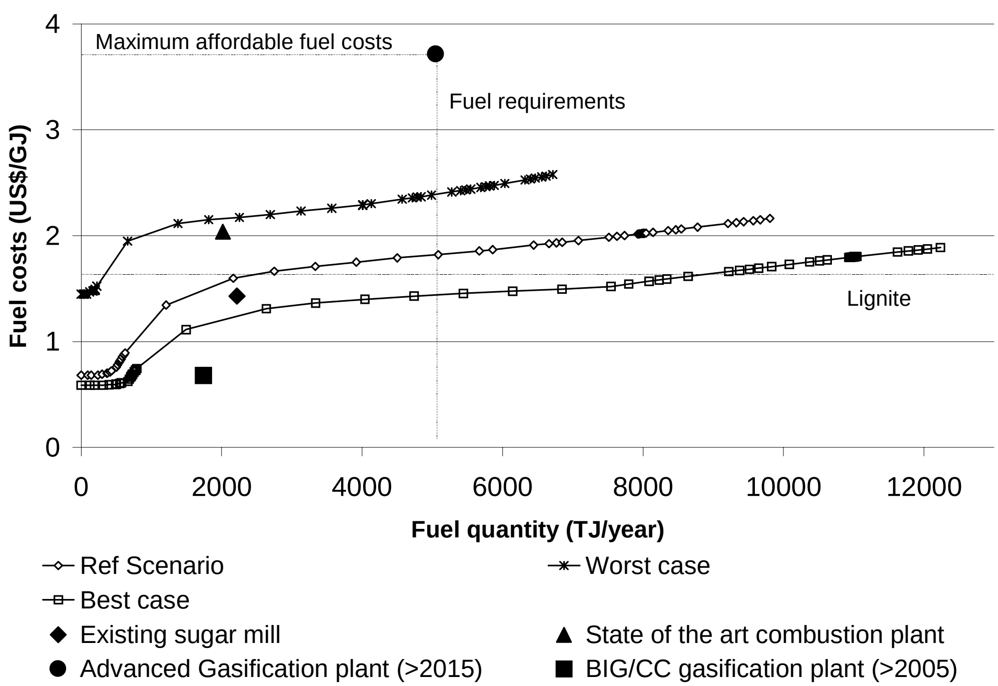
No corrections were made for possible additional investments to handle difficult residues. Especially rice husk (high silica content) and rice straw (high ash content, low melting temperature) are known to be difficult fuels. However, reports from sugarmills in Brazil and Thailand indicate that burning sugarcane tops and leaves (both mixed with bagasse and in pure form) in conventional boilers does not cause any major technical problems. The same is assumed for eucalyptus wood and waste wood.

Table 4.7 Input data on general parameters and various stand-alone biomass power plants

General parameters	Parameter	Lifetime	Load factor	Electricity buy-back tariff[a]	Capacity payment[b]	IRR
	Value	20	80	4.86	114.8	15
	Unit	Years	%	US$¢/kWh	US$/kW/year	%
Type of Plant	**Scale [MW_e]**	**Eff. [%]**	**Investm. Cost [$/$kW_e$]**	**O&M [US$¢/kWh]**	**Max fuel costs (at 15% IRR) [$/GJ]**	**Annual fuel requirement [PJ]**
Existing Sugarmill	6 / 20	9.5	0	1.77	1.145	2.22
State of the art combustion plant[c,d]	24	30	1390	0.89	2.037	2.02
BIG/CC gasification plant (>2005)[c]	29	42	2207	0.89	0.679	1.74
Advanced gasification plant (>2015)[c]	110	55	1448	0.77	3.716	5.05

a : [Koopmans, 2000] b : [EGAT, 2000] c : [van den Broek et al., 1999] d: the capacity and investment costs of this plant are very similar to those of a current combustion plant project in Yala, Thailand [Koopmans, 2000]

Figure 4.9 Comparison of the Reference, Worst- and Best-case Scenario, (progressing averages) and maximum affordable biomass costs for various biomass power plants (at 15% IRR). A power plant can be considered economically viable if its dot is situated above the reference scenario.



Chapter 5 Discussion and Conclusions

Discussing the results of the case study in Thailand

It has become clear that in Khon Kaen, most process-based residues (eucalyptus bark and sawdust, bagasse and rice husk) are largely utilized. Only rice husk is available to a certain extent. Rice straw and sugarcane tops and leaves represent by far the largest net available potential, though these can only be made available at higher costs. The eucalyptus logs and waste wood potentials are only very limited compared to those of sugarcane tops and leaves and rice straw. As can been seen in Table 5.1, the amount of available fuel can vary between approximately 7-12 PJ. At the amount of 2 PJ (approximately required for a power plant of 20-30 MW_e) the average price in the reference scenario is 1.6 US$/GJ. In the best case the *average* price is about 1.2 US$/GJ (25% lower), while in the worst case *average* prices may rise to 2.2 US$/GJ, an increase of 33%. In terms of *marginal* prices, the most expensive stream in the best-case scenario at 2 PJ is available at 1.6 US$, and in the worst-case scenario at 2.3 US$. The differences in quantities are mainly caused by the variations in harvest volumes, while the variations in price depend on the assumed transportation costs and increased demand by other applications.

Table 5.1 Overview of variations in available fuel quantities and average prices

		Fuel quantity (PJ)					
		0 PJ	2 PJ	4 PJ	6.7 PJ	9.8 PJ	12.2 PJ
Fuel price (average)	Worst case	1.45	2.16	2.29	2.58	n.p.	n.p.
	Ref. scen.	0.68	1.55	1.75	1.93	2.16	n.p.
	Best case	0.59	1.20	1.40	1.49	1.70	1.89

n.p. : not applicable

As indicated in the scenarios, four major risks were found for the fuel supply in Northeastern Thailand in the near future. The *first* is an increased demand for residues as fuel, especially rice husk. Due to the economic crisis, the prices for rice husk were at a very low level at the time of the case study. However it is likely that prices will rise in the next few years to the indicated maximum cost. Although rice husk represents only a small fraction of the total net potential, it is still the cheapest fraction, and for all plants with a fuel demand around 2 PJ, it represents 25% of all biomass fuel.

The *second* risk is the possibility of a bad harvest. As was seen in harvest statistics, the amounts harvested may vary rather strongly. However, even in the worst-case scenario, none of the selected power plants faces a supply-shortage, though transport distances will get larger and the average fuel price may rise by 10% as compared to the reference scenario.

The *third* risk factor is the possible increased demand for residues as raw material for the pulp and paper industry and the MDF-board and particleboard industry. This would mainly concern the rice straw and sugarcane tops and leaves fractions. Much will depend on the development of new eucalyptus plantation. While the Thai government is strongly promoting eucalyptus plantations since several decades, previous experiences have made many farmers reluctant to grow eucalyptus. In case that the demand for pulp material will increase by 80% within the next 15 years in the area, another 700,000 tonnes of pulp material would be required, which is about 60% of the net available potential. Though the degree of suitability of sugarcane trash and rice straw is limited due to the low fibre quality, the partial utilization of rice straw or sugarcane tops and leaves as pulp material is deemed to be the biggest long-term threat to biomass availability in the region considered.

The *fourth* factor is transportation costs and logistics. As mentioned before, transportation prices may depend on the amount of biomass that will have to be transported within a short time (e.g. two to four months). However in the case of a fuel requirement of approximately 2 PJ, this is not likely to cause logistical problems, as the truck availability seems to be sufficiently large.

At the chosen IRR-rate, only the 'state of the art' combustion plant may be economically viable at the moment, as it maximum fuel price lies above the reference curve (representing the current situation), and only 0.3 US$/GJ under the worst-case scenario. The existing sugarmill does not seem feasible due to the very low efficiency. The same is valid for the 29 MW_e gasification plant due to the high initial investment costs on the short term for this technology. As a long-term-perspective, the large-scale gasification plant does seem promising, though the fuel supply situation may have changed over 15 years.

However the calculations of these maximum affordable fuel prices should only be considered as rough indications. Mixing various residue types may result in both additional investment costs and O&M costs. Also interest rates and plant life times may vary. On the other hand, in the future taxes may be imposed on electricity generated using fossil fuels, biomass energy may be subsidized, but also the pay-back tariffs may change. Also the chosen IRR-rate (or other economic decision parameters) greatly influence the feasibility of the various plant types. For example at an IRR of 20%, also the state of the art combustion plant would not be feasible.

In terms of feasibility, it must be concluded that field-based residues alone are too expensive at the moment for power generation, and only the state of the art combustion plant (which relies for 25% on process-based residues) seems to be feasible within limits at the current situation.

In this paper, residue prices and quantities were based on data mainly originating from Khon Kaen province. The supply curves were set up for an area of 7800 km^2. It is assumed that in this area two 'state-of-the art' combustion plants of 24 MW_e capacity each can be built. The combined fuel demand would be about 4 PJ, which can be satisfied even under the worst case scenario. Though the fuel prices would be higher for the second plant, the plant would still be feasible under the reference scenario in terms of fuel costs. Thus, in an area of 7800 km^2, a capacity of 48 MW_e could theoretically be installed.

However, it is necessary to determine to what extend these results also apply for the whole Isaan region of 170,000 km^2. Khon Kaen has an above-average production of sugarcane, and two of the fourteen sugar mills in Isaan are situated in Khon Kaen. Assuming a radius of 50 km for each sugarmill, each covering a perfect circle and no mutual overlap, the fourteen sugar mills in Isaan would cover 65% of the Isaan area. In reality, distances between sugarmills are often less than 100 km, and it is estimated that the fourteen sugar mills receive their sugarcane from about 50% of Isaan. In the remaining 50%, significantly less sugarcane and more rice, cassava and other crops are present. In these cases, the situation may differ from the situation in Khon Kaen. Prices of sugarcane tops and leaves, eucalyptus logs, eucalyptus waste wood and rice straw are not expected to vary strongly in different parts of Isaan, while rice husk prices may vary per location.

Thus it is concluded that the obtained results are applicable for approximately 50% of the area in Isaan, and limited applicable for the remaining 50%. If 48 MW_e capacity are assumed for 7800 km^2, about 21 plants representing 520 MW_e could be realized in 50% of the area of Isaan (85,000 km^2), which would be a 54% increase in current installed capacity. Again, this should be considered as a rough indication.

Recommendations

The question remains what the chances are a specific scenario may occur. In the case of a bad harvest, this can be predicted with reasonable accuracy. The average harvest volume was chosen in a way that between 10-25% of the harvest recorded in statistics were below this value. Thus, as an estimate the chance of a 'bad' harvest is also considered to be between 10-25%. However the risks of increased utilization as fuel or pulp material, and rising logistic costs are more difficult to determine, as they depend on a number of factors discussed before. In order to get more insight into the probability of the occurrence of these risk factors, it is recommended to study the degree of suitability of sugarcane tops and leaves as fibre material for MDF-board and paper industry. In order to assess optimum harvesting and baling conditions for sugarcane tops and leaves, the Thai situation could be compared with Brazil, where currently different routes of collecting sugarcane tops and leaves are evaluated. This was not done in this study.

Furthermore, in this study the principle was applied that local population and industries should not be affected in a negative way by a residue-fueled power plant. However, as rice husk is the cheapest available fuel, it is likely that biomass power plants will be able to pay more than brick makers can currently afford. It is there desirable to further investigate different brick production methods and the price elasticity of bricks.

In addition, it was shown that long-term storage of different biomass streams and logistic systems are of importance for a steady fuel supply. More research could be conducted on optimizing the logistic system, e.g. the use of intermediate storage facilities, optimizing the ideal storage conditions and using dedicated equipment such as harvesters and balers.

Evaluating the developed methodology in general

The developed methodology was tested successfully in Northeastern Thailand. There are several remaining remarks and recommendations to be made:

- The methodology was so far only tested in Thailand, a relative well developed country in the Southeast Asian region with a relatively good infrastructure. Data availability was relatively good. Case studies in other (less developed) countries are desirable to determine the further applicability of the methodology, especially in cases where less data is available. This may also reveal further potential risk factors which are yet unidentified (as they may play no important role in Thailand).

- During the case study, only limited data on harvesting field residues could be acquired by actual in-field experiments which meant adapting values from literature was regularly applied to make estimates. For example, no data was found on dry matter losses during storage for sugarcane tops and leaves or rice husk. Preferably more field-experiments should be carried out, though this may be both costly and time-consuming.

- In the methodology, the environmental impacts of utilizing residues on a large scale are somewhat underexposed. It is desired to develop a methodology for environmental impact assessment in developing countries for large-scale biomass projects. In many countries no guidelines or laws exist for this procedure.

- Language barriers and misconceivements can form a source of errors. For example, rice mill owners sometimes simply do not understand why one is interested in prices of rice husk and not prices of rice, which may be much more important to them. Also they often have their own standards of measurements, e.g. not in tonnes but in truckloads which again may differ from site to site. In case one does not the (official) language, the use of qualified translators is recommended.

It can be concluded that application of the methodology has identified several important risk factors and has shown how these factors can influence the fuel supply both in terms of quantity and costs for potential biomass-fueled power plants in the study area in a significant way. It is recommended to use a methodology as developed here for future large-scale biomass projects in order to integrally assess the possible fuel supply risks.

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Notations and equations

$C_{acc.}$	:	annual capital charge
C_D	:	(shadow) demand price [$ / tonne]
$C_{electr.}$	:	electricity price per kWh
C_{max}	:	maximum costs per tonne of residue [$ / GJ]
$C_{O\&M}$	:	annual O&M costs
C_{plant}	:	costs per tonne of residue at the plant gate [$ / tonne]
C_{pretr}	:	pretreatment costs at the plant [$ / tonne]
C_S	:	Supply costs per tonne of (pretreated) residue [$ / tonne]
C_{site}	:	costs per tonne of residue at each production site [$ / tonne]
C_{stor}	:	storage costs per tonne (per month) of residue [$ / tonne (/month)]
$C_{transp.}$	:	transportation costs from each production site[$ / tonne]
Eff_e	:	Electric efficiency of the plant [kWh / MJ]
E_{plant}	:	energy potential of residue stream i of site j at the plant [GJ]
GTP	:	The gross technical potential [tonnes / year]
GTP_E	:	The heating value of the GTP on basis of the combined LHV's [GJ / year]
LHV_i	:	The lower heating value of residue i [GJ/tonne]
NAP	:	Net available potential per year per residue type [tonne /year]
NAP_E	:	Net available energy potential on basis of the LHV [GJ/ year]
NSP	:	Net amount of (pretreated) residues that could be supplied (disregarding competing applications) in [tonne] or as % of GTP
$R_{electr.}$	:	number of kWh generated per year
$R_{net,i}$	:	Net amount of residue i that is supplied to the plant [tonne]
UP	:	currently utilized potential (in [tonne] or as % of NSP)

$$NAP = GTP * NSP * UP \quad \{I\}$$

$$NAP_E = NAP * LHV \quad \{II\}$$

$$C_{plant} = C_{site} + C_{transp.} \quad (+ C_{stor} + C_{pretr}) \quad \{III\}$$

$$E_{plant} = R_{net,i} * LHV_i \quad \{IV\}$$

$$C_{max} = (C_{electr.} - ((C_{acc} + C_{O\&M}) / R_{electr.})) * Eff_e \quad \{V\}$$

Appendix A Examples of applications competing for residues

Fuel: In many countries, industries make (partially) use of residues as fuel, e.g. rice husks for the brick industry, or saw dust [RWEDP, 1998a]. Also many processing mills make increasingly use of their residues as fuel (e.g. sugar mills, rice mills, palm oil mill etc.). In many countries a huge part of the population uses residues as primary fuel for cooking and heating as it is cheap, sometimes the only fuel available. In addition, charcoal (from residues) and cow dung may be used because they give the food a pleasant flavour.

Fodder: Straw and other parts of many plants are used as animal fodder [Shacklady, 1983] or animal bedding [Koopmans & Koppejan, 1998] .

Fertilizer: Many field-based residues are either ploughed back into the soil or are burnt on the field as conditioners and organic fertilizers [Shacklady, 1983]. Also the ash of e.g. burnt rice husks originating from rice mills may be used as fertilizer [Koopmans & Koppejan, 1998] .

Fibre: Coconut husks may be used for mats and matting, floor coverings, brushes and strong ropes. Sugarcane residues may be used for the production of board and paper [Shacklady, 1983].

Feedstock: Ash from rice husks may be used for many applications as feedstock for the computer industry (because of its high silica content [RWEDP, 1998b]), source of carbon an as an insulator for the steel industry [Koopmans & Koppejan, 1998] , as feedstock for soap production [Shacklady, 1983] and as cement additive. Bagasse may be used as feedstock for the paper industry.

Further uses: Wood residues may be used by the furniture industry, rice straw as growing medium for mushrooms

Suitability of different residue types

In general woody crops (e.g. coconut shells, jute sticks) burn well and are therefore popular as cooking fuel but almost unsuitable as fodder or fertilizer. Cereal residues (e.g. straw from rice and wheat) burn too quickly, but may be used as animal fodder, animal bedding and fertilizer. Green crops are in general not suitable as fuel because of the high moisture content, but make relative good fodder and fertilizer. Finally, some processed-based residues like rice husks or groundnut shells have to be densified before they can be used as fuel for rural households, and are therefore not very suitable. They also are unsuitable as fodder or fertilizer [Barnard & Kristoferson, 1985].

In addition there are modern applications which may make use of the residues as feedstock. Examples are production of ethanol as fuel (another form of utilizing biomass) or other chemicals (e.g. cellulose derivatives), production of improved animal fodder for ruminants or even for production of food [Shacklady, 1983]. A number of techniques have been developed for these applications [Soltes, 1983].

Appendix B Determining possible forms, locations and scale of conversion plants

There are several possibility on how and where the residues are converted:

Option a) Residues may be co-fired in an existing fossil fuel plant.
Option b) The residues may be utilized for an existing small/medium scale cogeneration plant at a crops / wood processing mill.
Option c) The residues may be converted at a new (to be built) large-scale stand-alone conversion plant.

Option a) is currently planned as an option for dedicated fuel-plantations (e.g.[Downing & Graham, 1996]) and both field- and process based wood residues (e.g. [Rosillo-Calle & Bauen , 1999]). It does have several advantages. First of all it is relatively cheap. Necessary modifications to the existing power plants depend on the mix of residues, the fossil fuel used primarily and on the extent to which residues are co-fired, but costs are generally low compared to building a new plant. Second, if sulfur dioxide emissions are (too) high, co-firing biomass may be a relatively cheap option to lower the SO_2-emissions [Perlack et al., 1997] as most kinds of biomass tend to contain very little sulfur [Worldbank, 1999]. This may be especially advantageous if the present fossil fuel is of mediocre quality, e.g. lignite with a high ash and sulfur content [Ergüdenler & Isigigür, 1994]. Another advantage is that the plant is little dependant on an constant biomass fuel supply as shortages can simply compensated by fossil fuels. However, co-firing biomass may also have disadvantages. The power plant may not be located near the biomass production sites which may require long transport distances. Residues having (highly) abrasive qualities (e.g. rice husks containing Si) may severely damage the installation and may therefore only be added within limits. Also the biomass will have to meet high demands concerning size and moisture content. In addition the ash content may also be important. Residues may have lower ash contents than e.g. low-quality lignite, but the melting temperature may also be lower which may in some cases cause serious problems.

Option b) This option is currently used by a number of projects (e.g. [COGEN, 1999], [van den Broek & van Wijk, 1998], [NEPO, 1992], [Winrock, 1994], [Rao, 1999]). The biggest advantages is that part of the fuel supply is in most cases secure, i.e. amounts, seasonal availability and physical and chemical properties of the main fuel are normally known. Especially in the sugar-cane industry projects are being developed to make (more efficient) use of existing cogeneration plants. However most crop-processing mills are only able to use their plants during the harvesting season. Different solutions can found to overcome this problem: in Nicaragua some sugar mills are going to use wood from dedicated plantations in the sugar-cane off-season [van den Broek & van Wijk, 1998]. In El Salvador, bunker oil is proposed as fuel during the sugarcane-off season [Winrock, 1994] , while in India, considerations are being made to use other agricultural residues such as rice straw and cotton stalks during the sugar-cane off-season [Rao, 1999]. Most of existing cogeneration plants at sugar mills, rice mills etc. use relatively old inefficient technology, so if modern high-efficient installations are to be used, considerable investments may be required. Especially if installations are planned which make not only use of the residues of the local mill, but also from other sources in the area, the installation capacity will be much higher, and so will be the investments necessary. This may not always be in the interest of the mill-owners. Also, if other residues are to be used as fuel during the main fuel off-seasons, transporting distances and logistical challenges may be high.

Option c) may be the most attractive if huge amounts of residues can be supplied all year long (or at least most of the year) from within a relatively small distance from preferably a limited number of suppliers. Also, many small crop-processing mills may be too small to utilize their residues for own cogeneration, but may want to sell there residues to a large plant. Still, huge financial investments are usually required, but opportunities may also be great as modern and efficient technology may be used to produce either heat or electricity or (preferably) both very efficiently. However, experiences in the US have shown, that once a market for residues has developed, a logistical system has been established and profit is made, additional (competing) plants may be built closer to the residue sources reducing primary supplies for the main plant [DeBlaay, 1994]. Therefore, secondary fuel sources should be investigated in advance and the applied technology should be flexible enough to deal with different kinds of (biomass)-fuels. An advantage of a new plant is the choice of location which may reduce average transport costs. However, for (very) large conversion plants the logistical problems have proven to be very large. Furthermore the plant must also be well connected to the road network and the electricity grid, and (in case of a cogeneration plant) there must be a (constant) heat demand. The produced heat may also (partially) be used to dry the residues.

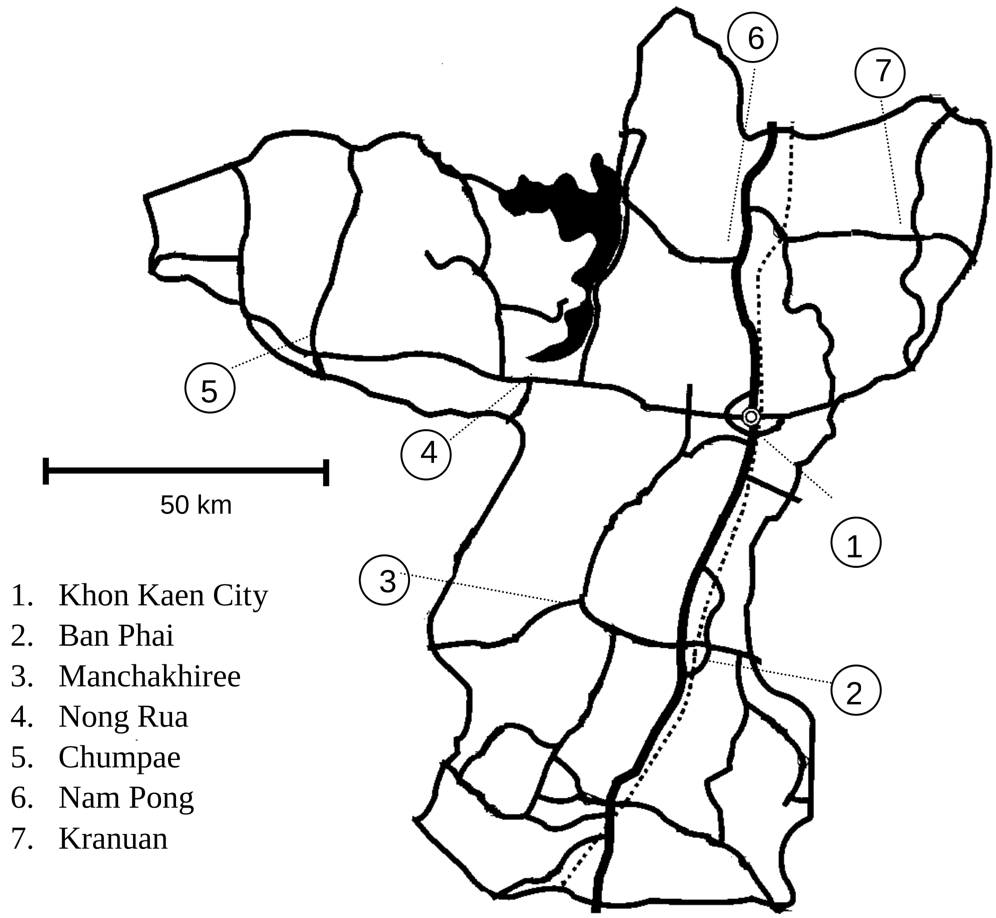
Depending on the number of suppliers and possible number of location(s) the optimal locations may either be determined by using a spread-sheet (in case of limited data size), or by using a GIS-application (in case of extensive data amounts). In general, average transport distances should be minimized. However one has not only take into account the transport distance from a site to the plant, but also the amount of residues available per site.

The choice for one of these options may greatly depend on the objective and background of the decision-maker. Also the choice of technology for option b) and c) may play an important role: the two most dominant forms of converting biomass to electricity or heat and electricity (cogeneration) are combustion and gasification. The advantages and disadvantages of these technologies have recently been discussed [Worldbank, 1999]. Due to the limited availability of biomass the study advises to prefer small-scale power plants. In order to determine which technology should be preferred a detailed feasibility study must be carried out. However, both technologies may make high demands on the fuel concerning moisture content, ash content, elementary composition etc. which may further limit the amount of available and suitable residues. Experiences from the U.S. shows that many large-size biomass—fired plants had to change their fuel composition as new opportunities arose and other sources vanished [DeBlaay, 1994],[Wiltsee, 1999]. Preferably the conversion plant should be designed to handle a broad variety of fuel. Concluding, the location should be chosen regarding:

- The quality of the available infrastructure and average transportation prices
- The electricity and heat demand at the plant location
- The in the study-area available options (a, b and or c)
- The available residue types, amounts and average fuel prices

Appendix C Map of Thailand

Appendix D Map of Khon Kaen province and a list of institutions visited



Isaan

Forest Industry Organization, Khon Kaen
Khon Kaen Provincial Statistical Office
Khon Kaen University, Research and Development Institute
Khon Kaen MDF Board Co., Ltd. Nam Pong
Phoenix Pulp & Paper Public Co., Ltd.
Khon Kaen Sugar Industry Co., Ltd., Nam Pong
Mitr Phu Viang Sugar Co., Ltd, Nong Rua
Manchakhiree eucalyptus Plantation, FIO, Manchakhiree
Faimeechai rice mill, Chumpae
Lamthong rice mill, Chumpae
Sahachai rice mill, Chumpae
Taweepan rice mill, Khon Kaen
Krung Thong rice mill, Khon Kaen
Chaimongkolrung rice mill, Khon Kaen
Thanyasiri, rice mill, Ban Phai
Chaisiri Charcoal factory Co., Ltd., Kranuan
Mitr Phu Khieo Sugar Co., Ltd, Chaiyaphum
Thai-Danish Cooperation on Sustainable Energy, Nakhon Ratchasima
Regional Energy Center, Mahasarakham

Bangkok

Asian Institute of Technology, Division of Energy Technology
Kasetsart University, Faculty of Economics
EC-ASEAN COGEN Programme
Thai Power Supply Co., Ltd.
The Energy Conservation Center of Thailand
Multi-crop harvester Co., Ltd.
Department of Energy Development and Promotion
Royal Forestry Department
Forest Industry Organization

Appendix E Experiment for the determination of the ratio of sugarcane / sugarcane tops and leaves

The experiment was carried out in January 2000 in Khon Kaen province, Isaan.

Goals:

- To determine the amount of sugarcane tops and leaves that may be recovered simultaneously to the harvest of the sugarcane
- To determine the respective harvesting costs and transportation costs
- To determine the moisture content of the cane tops and leaves

Experimental procedure

Harvesting

The selected cane field was about 10-11 month old. The plants were 3.5-4 m high. It was noted that the top leaves were green, while the rest of the leaves (about three-quarter of the total number) was brown-yellow. Two different samples (green and brown leaves) were collected for moisture content analysis.

Six workers equipped with knives harvested 291 bundles in approximately two hours (1 bundle equals 10 sticks of sugarcane). The plants were cut close to the ground, and were bundled including the tops and the leaves.

Loading and transporting

A ten-wheel truck was then loaded by six workers within one hour. The capacity of the truck was 24.24 m^3 (2.3m wide * 6.2 m long * 1.7 m high). The workers tried to stack the bundles, but this was difficult as each bundle had a varying length. The total volume of the plants was almost equal to the maximum loading volume of the truck.

Weighing the plants

By weighing the truck both empty and full, the weight of the whole plants was determined to be 3.29 tonnes.

Manual separation of the tops and leaves

As next step, the workers were told to manually separate the tops and the leaves from the cane stick. It took 5 worker approximately 2.5 hours to separate half of the amount of cane. The complained that this was more difficult than normally, as the plants had to be held up with one hand, while cutting the leaves with the knife. Normally the sticks stand vertically, which makes separation easier. However, as the supervisors were not present during the first hour (they were bringing the samples to the laboratory for moisture content analysis), it is doubtful that all the workers had worked during the first hour.

Weighing the cane sticks

The weight of the cane sticks was determined to be 2.60 tonnes. Thus the weight of the remaining tops and leaves is 0.69 tonnes.

Collecting air-dry samples

After 6 days drying in the field, again samples were taken from the brown leaves, and the green top leaves (which had turned light-green/yellow/brown) and the moisture content was analyzed.

Results

The ratio between the tops and leaves and clean cane sticks:	0.265
The bulk density of the whole plants:	135 kg / m^3
The ‘fresh’ moisture content of the green (top) leaves (wb):	59.2 %
The ‘fresh’ moisture content of the brown leaves (wb):	17.6 %
The airdry moisture content of the green (top) leaves (wb):	7.9%
The airdry moisture content of the brown leaves (wb):	7.9%

Additional data

- Average sugarcane yield is 7 tonnes/rai (1 rai = 0.16 ha)
- 20 workers harvest 3 rai of sugarcane and load it on a truck in 8 hours
- Sugarcane capacity of one 10-wheel truck = 20 –21 tonnes

⇨ one worker harvests approximately 130 kg sugarcane sticks per hour and loads them on a truck.

Discussion and Conclusions

The ratio between the tops and leaves and the clean cane sticks is in very good accordance with literature (RPR-value 0.275).

The moisture content of the brown leaves was found to be 17.6%. After drying in the sun for six consecutive days, the moisture content was reduced to 7.9% (reference values from the Winrock report are 9-11%). Also the green leaves dried from 59.2% to 7.9%. This results in a high heating value, possibly in the range between 16-18 MJ/kg.

Comparing harvesting and loading costs

In the experiment it took six workers three hours to harvest and load 2.6 tonnes of sugarcane. Thus one worker harvests and load approximately 145 kg / hour (these values only provide an indication). Thus the harvesting and loading speed is not significantly different from normal harvesting. It is however clear from the experiment that manually separating the tops and leaves is very laborious, and would have to be done mechanically on a large scale.

Comparing transporting costs

It was found that the 10-wheel truck was carrying 2.6 tonnes of 'clean cane' at almost full capacity. It is estimated that by packing the stacks better and loading the truck higher, **possibly 2.8 tonnes of 'clean cane' and 0.7 tonnes of tops and leaves** can be transported. This is a factor 7 lower than a 10-wheel truck loaded with clean cane sticks, In other words, it would require up to 7 times more trucks to transport the same amount of cane sticks, unless a way is found to increase the bulk density.

It is now possible to assign part of the transportation cost to the sugarcane tops and leaves. Normally a farmer has to pay an amount A to transport 20 tonnes of sugarcane (one truckload) to the factory. In order to deliver 20 tonnes of sugarcane to the sugar factory, seven more truckloads loaded with whole plants are required. However transportation costs per truckload will be lower, as the cargo has a lower density, so seven times amount B will have to be paid.

The total transportation costs for the tops and leaves thus are:

$$7*B(x)-A(x)$$

A(x): Transportation costs for 20 tonnes of sugarcane
B(x): Transportation costs for 3.5 tonnes of whole plants
x: Distance

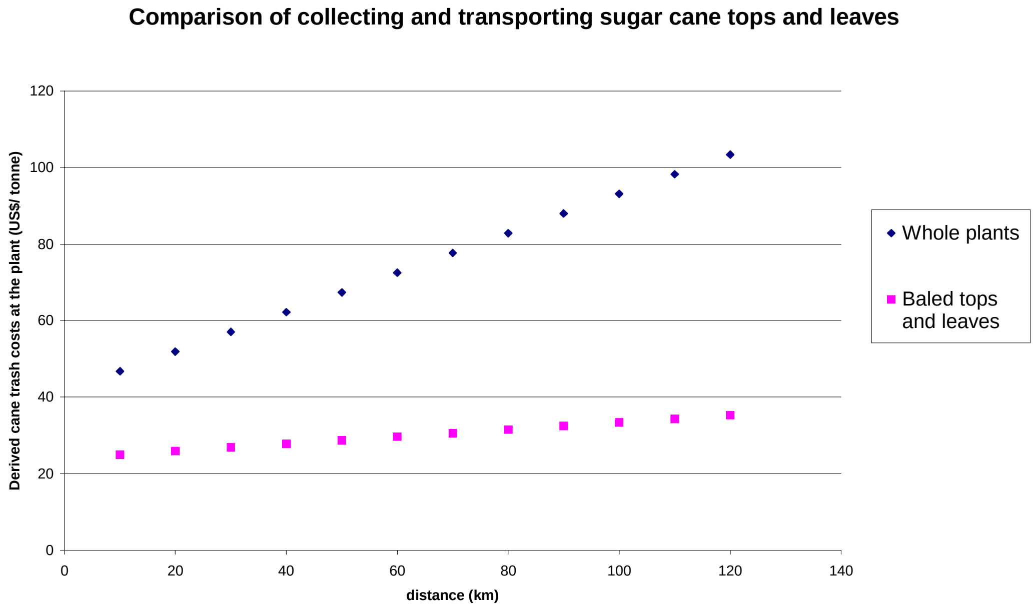
While transporting the 20 tonnes of cane, the farmer will also transport seven times 0.7 tonnes of cane tops and leaves. The transportation costs per tonne of cane are:

$$C(x) = (7*B(x)-A(x)) / (7*0.7)$$

C: Transportation cost per tonne of cane tops and leaves

In Figure E1 the transportation costs are given in relation to the transportation distance and compared to the costs of transporting baled sugarcane tops and leaves.

Figure E1: Transportation prices for cane tops and leaves



It is assumed that the farmers receive no money for the cane tops and leaves. In reality they most certainly will demand a compensation for the increased efforts, e.g. 1-3 US$ per tonne of cane tops and leaves. Furthermore, the costs of mechanically cleaning the cane are not included. In addition, the sugar factory handles approximately 1 truck / minute at the present situation. If all available cane tops and leaves was to be collected, this would mean that 7 trucks per minute would have to be handled – an enormous logistical challenge.

As can be seen from Figure E1, even without these additional costs, the costs of transporting the tops and leaves together with the cane sticks exceeds the costs of transporting baled tops and leaves by far. In conclusion, this route was not evaluated any further. However it may be worthwhile to investigate if the density of the whole plants can be increased when workers gain more experience loading whole plants.

Appendix F Experiment for the determination of the ratio of eucalyptus and eucalyptus waste wood

The experiment was carried out in October 1999 at the FIO Manchakhiri plantation, Khon Kaen Province, Isaan.

Goals

To determine the ratio between **logs** which are normally sold to the pulp and paper industry, and **branches and twigs** with a diameter between 3-6.5 cm (waste wood) that are partially used for charcoal making and residues such as **small twigs and leaves** which remain in the plantation.

Experimental procedure

Eight trees were selected in the middle of a 6 year old second-rotation Eucalyptus plantation, and cut down with a saw. The workers were then instructed to separate the tree into the fraction suitable for the pulp and paper production and the fraction suitable for charcoal production. These two fraction and the remaining fraction of twigs and leaves where then directly weighed in the field.

Results and discussion

The results of the experiment are given in Table F1. The average of the 8 trees can only give a rough estimate on how many residues are left in the field, but the RPR-value of 0.46 has been used for calculations in the main report.

Table F1 weight of tree parts

	Logs (paper fraction) [kg]	Large branches (charcoal fraction) [kg]	Twigs and leaves [kg]	Total [kg]
	35	23	24	82
	41,4	9,5	10	60,9
	25,5	14,5	15,8	55,8
	33	36	28	97
	39	8,6	13	60,6
	24	20	15,5	59,5
(two stems, one trunk)	24+17	13.5+7.2	10+10	81,7
(two stems, one trunk)	40.4+55.4	9+13.4	10+16.2	144,4
Total weight	334,7	154,7	152,5	641.9
Average weight of tree:	41,8	19,3	19,1	80,2
% of whole tree	52,1	24,1	23,8	100
RPR-value	**1**	**0.46**	**0.45**	