On the optimal use of industrial-generated biomass residues for polygeneration

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The content of this thesis reflects the views of the author, who is responsible for the facts and the accuracy of the information presented herein. The opinions, findings and conclusions expressed in this publication are those of the author and not necessarily those of the sponsors or interviewees.
To Raul, Victoria and Sarah
for showing the true meaning of love and
for making my heart smile everyday
Abstract

Increasing energy demand as well as climate change concerns call for an analysis and optimization of energy services. Efficient use of energy resources, mitigation of environmental effects and supply of an increasing demand are just some of the issues that are relevant nowadays in the energy system. In this regard, worldwide efforts are being made to increase the use of renewable energy and to promote energy efficiency measures in order to reduce the emission of greenhouse gases. Thus, sustainable solutions that take a holistic approach on covering the demands of the society are needed. The work presented herein addresses the use of industrial derived biomass residues for energy purposes in various contexts. The analysis was focused on: a) different alternatives to use solid palm oil residues in the Colombian mills for energy purposes including services; and b) the possibilities of implementing biomass-based heat and power plants in the Swedish energy system and their integration with already established biomass processing industries for polygeneration purposes.

The assessment of the palm oil residues consisted of a technical analysis on the possible alternatives for electricity, heat, and biofuels production. For that, a thermodynamic approach was used to evaluate different alternatives. The assessment of biomass power plant integrated with the Swedish industry considered the thermodynamic, economic and environmental factors associated with certain energy conversion technologies. In this case a multiobjective optimization methodology was used to perform the thermoeconomic analysis. This allowed the evaluation of two contrasting scenarios where polygeneration at an industrial level could be suggested: a less economically developed country where environmental policies are limited and industrial energy efficiency has not been implemented; and a high income country with energy and environmental policies well established and energy efficiency measures being encouraged.

Results show that the palm oil industry in Colombia has the capacity of being self-sufficient to cover of all their energy needs using the solid residues available. In the case of the thermoeconomic assessment of biomass-based integrated polygeneration plants in Sweden the results indicate that it is feasible to produce power while supplying the process steam required by nearby industries and district heating.
Keywords: Polygeneration, Optimization, Palm Oil, Biomass, forest residues, Colombia, Sweden
Sammanfattning


Resultaten visar att palmoljeindustrin i Colombia har kapacitet att täcka hela sitt energibehov med hjälp av det fasta avfallet som kommer från palmoljeframställningen. I fallet med den termoeconomiska utvärderingen av biobränslebaserade kraftvärmeproduktionen i Sverige, så indikerar resultaten att det är möjligt att producera el och samtidigt leverera pellets, fjärrvärme och den processånga som krävs av närliggande industrier.
Nyckelord: Polygeneration, optimering, palm olja, biomassa
This doctoral thesis is based upon six publications which are appended at the end of the thesis. The order of the appended papers is arranged according to the two main cases included in this thesis.


A preliminary version of paper 6 was presented by the author on:
- ASME 2013 Power Conference, July 29 – August 1, 2013, Boston, Massachusetts, USA.

The author of this thesis is the lead author of the appended papers I to VI, where numerical modelling, analysis and writing were performed. All work was done under the advice and guidance of Prof. Andrew Martin. Journal paper I, II and IV are published. Journal III and VI are submitted to journals and under review. Conference paper V was presented and published in a peer-reviewed conference.
Other publications related to the thesis but not included in it:

Reviewed conference papers


Non-reviewed publications

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# Abbreviations and Nomenclature

## Characters

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>ACPM</td>
<td>Combustible Oil for Engines (Aceite Combustible para Motores)</td>
</tr>
<tr>
<td>C</td>
<td>Cost</td>
</tr>
<tr>
<td>CDM</td>
<td>Clean Development Mechanism</td>
</tr>
<tr>
<td>CEPI</td>
<td>Confederation of European Paper Industries</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
</tr>
<tr>
<td>CPKO</td>
<td>Crude Palm Kernel Oil</td>
</tr>
<tr>
<td>CPO</td>
<td>Crude Palm Oil</td>
</tr>
<tr>
<td>CREG</td>
<td>Comisión de Regulación de Energía y Gas</td>
</tr>
<tr>
<td>DH</td>
<td>District Heating</td>
</tr>
<tr>
<td>E</td>
<td>Electricity generation/consumption [MW]</td>
</tr>
<tr>
<td>EFB</td>
<td>Empty Fruit Bunches</td>
</tr>
<tr>
<td>EUF</td>
<td>Energy Utilization Factor</td>
</tr>
<tr>
<td>fcr</td>
<td>Annuity factor</td>
</tr>
<tr>
<td>FEDEPALMA</td>
<td>National Federation of Oil Palm Growers (Colombia)</td>
</tr>
<tr>
<td>FFB</td>
<td>Fresh Fruit Bunches</td>
</tr>
<tr>
<td>i</td>
<td>interest rate</td>
</tr>
<tr>
<td>ki</td>
<td>annual insurance rate</td>
</tr>
<tr>
<td>LEC</td>
<td>Levelised Electricity Cost</td>
</tr>
<tr>
<td>LHV</td>
<td>Low Heating Value [MWh/ton]</td>
</tr>
</tbody>
</table>
m Mass flow [ton/h]
MC Moisture Content
MEM Mercado de Energía Mayorista
n lifetime of the plant
NIS National Interconnected System
NIZ Non Interconnected Zones
P Price
PKO Palm Kernel Oil
POM Palm Oil Mill
POME Palm Oil Mill Effluent
Q Heat [MW]
R Revenues
REE Equivalent Electrical Performance (Rendimiento Equivalente Eléctrico)
t time (h/yr)

Symbols

α Power-to-heat ratio
η efficiency

Subscripts

bd biodiesel
bio biomass
cont contingency
dear deareator

x
DH  district heating
el  electrical/electricity
equip  equipment
fib  fibers
fst  biomass from forests (fuel wood)
fw_pump  feedwater pump
gran  granulator
hm  hammermill
ICE  internal combustion engine
ind  industrial
install  installation
inv  investment
maint  maintenance
op  operation
ov  overall
pell  pelletizer
PG  polygeneration
ref,CU  reference value for the useful heat
saw  sawmill
st  steam turbine
th  thermal
u  useful
wat  water
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Biomass-based fuels continue to attract interest for a number of reasons: biomass is a renewable indigenous resource available worldwide; and biomass is a carbon dioxide neutral resource for energy production and transport applications. The entry into force of the Kyoto Protocol with accompanying tools such carbon emission credits, the EU emission trading schemes, feed-in tariffs and electricity certificates have promoted biomass as one of the leading renewable resources for energy purposes. At the same time, the effective capture and continued sustainability of this renewable resource requires a new generation of power plants with high fuel energy conversion.

Among the biomass resources, agricultural residues are widely available. However some of these streams, like palm oil residues, have been overlooked due to upgrading challenges for energy purposes and are often seen as a disposal problem for the processing industries in developing countries. At the same time most of the palm oil mills (POM) in Colombia lack efficient energy systems, normally generating steam at low pressures in low efficiency boilers and using electricity from the national grid for the extraction process. These factors represent a strong driving force for the development of innovative polygeneration plants with combined electricity, heat and refined fuel production based on conversion of solid POM residues.

Forest-derived fuels on the other hand are widely used in Scandinavia. In Sweden, biomass has changed from being a disposal problem for some industries to become an important player in the energy supply thanks to the efforts made by the government, researchers and industry and where energy policies have played an important role. The implementation of emission taxes since 1991 helped to switch from fossil fuel to biomass in the district heating sector and also in the cogeneration sector. This has been further reinforced with the introduction of electricity certificates in 2003.

Beyond fuel switching to renewable resources, higher efficiencies and improved energy effectiveness can be achieved by integrating several processes or equipment in a larger system. Successful integration of different equipment and other measures for increasing the effective use of the raw resource starts by considering first thermodynamic and environmental aspects at the system level and later economic or
thermoeconomic analyses. This thesis tries to identify possible measures that could be implemented in the industrial sector in two countries to foster the efficient use of biomass residues for energy purposes.

1.1 Objectives

The goal of this thesis is to systematically investigate the application of different energy conversion technologies and propose optimal applications of biomass residues for industrial cogeneration/polygeneration purposes in two different locations, Colombia and Sweden. The evaluation of polygeneration alternatives at industrial level in two countries enables the assessment and highlights the differences regarding primary energy savings and use of indigenous resources between: an upper-middle-income country characterized by a tropical climate, abundant agricultural residues, with energy and environmental policies still being drafted, and with limited or non-existing energy savings measures at industrial level and a high income country with abundant forest residues, temperate climate, well-established energy and environmental policies, with a tradition of implementing energy saving measures and with a national goal of decarbonising the energy system by 2050.

In order to evaluate the potential and the possibilities for polygeneration from biomass residues, the thesis is divided in two parts. One part of the thesis is concentrated in maximizing the use of solid residues coming from palm oil extraction, to substitute fossil fuels, reduce emissions and lessen environmental impacts in Colombia through polygeneration plants. The emphasis is on introducing discarded solid residues as feedstock in Colombian palm oil mills to generate electricity, process heat, pellets and biodiesel. The manufacturing of different energy products in an integrated scheme has not been considered previously for Colombian palm oil mills thus offering a unique possibility for the implementation of energy saving measures in a growing industry. The second part of the thesis is focused on evaluating the potential of polygeneration plants and optimizing their implementation together with other biomass-based manufacturing industries in Sweden from technical, economic and environmental perspectives considering the entire raw fuel source-to-product chain. This assessment has not been implemented previously in the case studies selected as representatives for some of the wood-based industries in Sweden. Different cogeneration/polygeneration alternatives were considered and optimized from a technical, economic and environmental perspective for these industries considering competing criteria and thus, providing a set of
optimum solutions that will allow investors or decision-makers to choose the best option.

The objectives of each section are as follows:

a) To assess different alternatives for energy recovery from palm-oil residues by:
   i. Identifying the current energy requirements of the process, palm oil residues availability and possible added value products (e.g. pellets, biodiesel).
   ii. Assessing suitable technologies for utilization of residues from palm oil production for providing different energy products (pellets, electricity, process heat, biodiesel, etc.).
   iii. Designing and modelling of the polygeneration system integrated with the palm oil mill.

b) To perform a thermoeconomic assessment of biomass-based industrial energy processes in biofuel-based polygeneration plants in Sweden by:
   i. Assessing the impacts and possibilities of implementing biomass-based heat and power plants in the Swedish energy system and their integration with already established biomass processing industries (forest industries, wood-based ethanol processing, etc.).
   ii. Considering thermodynamic, economic and environmental factors associated with certain energy conversion technologies in a source-to-product scheme.
   iii. Finding optimized alternatives for different system configurations considering the effect of environmental costs in the choice of the technology as well as possible improvements in biofuel utilization.
   iv. Evaluating the selected technologies through the use of a thermoeconomic and environmental models and identifying the potentially best alternatives in terms of performance, economics and environment.

The results of this study are relevant as they contribute to the development of an energy efficient and environmentally benign process for energy conversion from biomass in the context of two different countries, Colombia and Sweden. It offers the possibility of a distinctive comparison between the countries’ current energy efficiency status in the industrial sector by evaluating selected cases of study. The comparison of the current systems and proposed alternatives from the technical point of view allows for quantification in terms of primary energy savings and polygeneration efficiency. Furthermore, it gives a glimpse of different
measures that could be implemented in lower income countries to boost the energy efficiency in the industrial sector and reducing the energy costs by reducing the energy requirements from the national grid and by manufacturing other products that could help to increase the revenues.

1.2 Scope and limitations
This thesis considers the specific cases of utilization of industrial solid biomass residues for energy purposes. One part of the thesis deals with palm oil extraction and the possible use of solid residues in polygeneration applications (electricity, process heat, pellets and biodiesel). The scope of this part consists of a survey the energy requirements of a specific palm oil mill representative for the industry in Colombia, palm oil solid residues inventory and analysis of possible alternatives to supply the mills’ energy needs. This part was focused on the analysis of different alternatives to cover the palm oil needs and also the manufacturing of other added-value product derived from the oil extraction process in a polygeneration scheme. In this regard, polygeneration options have not been considered so far for the palm oil industry in Colombia and neither the possible production of densified biofuels. The integration of the biodiesel production in the plant (currently being done in separate facilities) as well as the option of generating the required electricity, heat and pellets offers the unique opportunity to assess the possible upgrades in the mills in order to fully use the solid residues and improve their efficiency. This study focuses on these opportunities by evaluating a selected case study representative of the Colombian palm oil industry. Through this analysis, the opportunities of increasing energy efficiency in the agroindustrial sector in Colombia by using onsite generated residues are highlighted. The economic evaluation of the alternatives selected will be performed in a future phase using the multiobjective optimization methodology developed for the Swedish cases. This is suggested in the future work section of this thesis. The results presented in this study provide the background regarding cogeneration and polygeneration possibilities in the palm oil industry and helps identifying the most suitable solutions that use the solid residues and fulfill the requirements established by the Colombian government. It also provides an analysis of the measures for reducing the palm oil industry greenhouse gas emissions by fostering energy savings in the sector thus, helping to reduce the environmental footprint of this industry.

The other part of this thesis was focused on setting up a thermoeconomic optimization methodology and applying it to different case studies in Sweden. The scope of this study included multiobjective optimization considering technical, economic and environmental factors.
Two case studies were selected: (i) a sawmill contributing with district heating to a nearby location and (ii) a heating plant interested in evaluating the possibilities of cogeneration/polygeneration. The system boundaries were specified based on the requirements of each case. For both cases, the boundaries did not include the biomass extraction and transport stages. However, a complete source-to-product chain could be analysed if required and has been included as future work in this thesis. The multiobjective optimization allowed making a complete evaluation of the possible improvements in terms of biofuel utilization to reach higher fuel utilization by analysing different technologies and configurations from a source-to-product viewpoint. It helped to identify the optimized alternatives for different system configurations and evaluate the effect of environmental costs in the choice of the technology. In summary, the assessment facilitated the identification of the best alternatives in terms of performance, economics and environment and the possible generation of higher value products or cost reduction of already existing products by implementing polygeneration schemes. Through the multiobjective optimization it is possible to select from a set of optimized solutions for conflicting objective functions. By doing so it is possible to quantify the net effect that the suggested measures might have in the plant technical and economic performance and in the final products.

A more detailed description of the methodology considered for both parts of thesis is included in the next section.

1.3 Methodology

For each of the sections included, energy recovery from palm oil residues in Colombia and forest fuels in Sweden, a research methodology was applied based on the objectives, available data and requirements of the projects.

For the case of energy recovery from palm-oil residues in Colombia, data was gathered about the availability of solid residues in the mill, residue disposal practices, energy needs of the palm oil mill and current energy supply options. Different alternatives were suggested including pelletization of two of the solid residue, EFB and fibers. The pelletization of these residues and subsequent gasification was investigated experimentally as part of another doctoral thesis presented by Erlich (2009). In the work presented here, different system configurations were proposed and analysed in terms of efficiency, power output, and possible contribution to the national electricity grid and emissions reduction. Emphasis was placed on maximizing the use of solid residues for energy purposes. From this analysis, several alternatives were proposed that fulfil the national regulations, supply the palm oil
mill needs and use the solid residues more effectively. Each of these alternatives was proposed based on the investment required by the palm oil mill. An analysis is expected to be done in the future to highlight the best alternatives using the multiobjective optimization applied to the Swedish case studies.

For the thermoeconomic assessment of biomass-based energy processes in Sweden, an optimization methodology was established to be able to evaluate different cases. This included the economic modelling along with the use of genetic algorithms for multi-objective optimization, in order to evaluate the different alternatives and select the best option for a given industry in a specific set of economic conditions. This approach helped identifying the effects that the integration of different processes and energy industries and their optimization might have on the final product price. The methodology was applied to analyse the different alternatives for a sawmill that will generate electricity, district heating and pellets and for a district heating plant that can be upgraded to generate electricity, more district heating and process heat and pellets.

1.4 Structure
The thesis consists of six chapters that are organized as explained below and are linked as illustrated in Figure 1.1.

Chapter 1 gives an introduction to the thesis with the main motivation of the research presented. It also includes the objectives of the work performed for the two scenarios considered, palm oil residues in Colombia and forest fuels in Sweden. This chapter presents a brief description of the methodology used in these two scenarios as well as an outline of the thesis.

Chapter 2 deals with the situation of palm oil mills in Colombia. It highlights growth of this sector at national levels and the goals for 2020. Also, the palm oil extraction process is described as well as the status of the palm oil mills in the country. This chapter also summarizes the current policies related to industrial cogeneration and the internal market perspectives for palm oil.

Chapter 3 explains the Swedish industrial use of wood and wood extraction activities. The wood industry in Sweden is fairly important and most of the consumption happens in the pulp and paper industry and in sawmills. This chapter explains briefly the biomass-based industrial processes.

Chapter 4 summarizes the methodology and results presented in papers I through III dealing with polygeneration using palm oil solid residues.
The results from the papers are further evaluated by including the equivalent electrical performance and the primary energy savings and polygeneration efficiency for the alternatives analysed.

**Chapter 5** presents the methodology and results obtained in papers IV through VI. These papers are focused on the optimization of the use of forest fuels for polygeneration in biomass-based industries in Sweden. In this chapter the primary energy savings and polygeneration efficiency for the cases considered are also discussed.

**Chapter 6** presents a summary of the discussion and conclusions of the thesis. In this chapter it is also summarized and compared the performance results in terms of primary energy savings and polygeneration efficiency for the Colombian and Swedish industrial case studies. Improved energy utilization of solid residues is highlighted based on the results of the previous two chapters.

**Chapter 7** summarizes the next steps to continue the research on energy recovery from palm-oil residues in Colombia and thermoeconomic assessment of biomass-based energy processes in Sweden. This includes the implementation of the multiobjective optimization technology to the palm oil mill in Colombia as well as the consideration of the complete source-to-product chain for the Swedish cases.
Figure 1.1: Research structure scheme
2 Palm Oil Production: Overview and Colombian Focus

This chapter presents the background regarding the situation of the palm oil industry in Colombia and describes the palm oil extraction process. It also discusses the market situation in Colombia regarding palm oil and palm oil-derived biodiesel. National policies for biodiesel integration in the transportation fuel mix are presented as well as different regulations around industrial power generation.

The global demand of palm oil is continuously growing and thus, the production worldwide is also increasing as shown in Figure 2.1. This increase has been favoured due to the high yield and versatility of palm oil which is suitable for edible and non-edible applications. The increase in the palm oil demand in China, India and Europe has cause the strong growth in the palm oil consumption worldwide. In Europe the promotion of biofuel utilization programs has cause the growth in palm oil consumption at industrial level (IISD, 2013). Such increase of biofuel use in the EU and elsewhere is seen as a niche market and therefore, expected to grow in the near future.

![Figure 2.1: Global Palm Oil Production, 1991-2011, not including palm kernel oil (FAOSTAT, 2013)]](image-url)
The upswing in demand has increased the pressure on the palm oil production sector and forced an increase in yield and process capacity. Deforestation has been a source of great concern and some measures have been implemented including the Roundtable on Sustainable Palm Oil (RSPO) aiming at transforming palm oil production into a sustainable chain. The use of marginal land, methane capture from open ponds, use of solid residues have been proposed along with other measures engaging all sectors involved in the production and use of palm oil.

The rise in the demand of palm oil has been translated in an increase in the energy demand and generated waste from the palm oil sector. The problems of waste and pollution have been also the source of growing concern alongside with the deforestation to increase the planted areas. Some of these issues have been addressed in the different stages of development of oil palm plantations and production while others need still to be tackled with sustainable solutions.

Colombia is the fifth producer of palm oil (Figure 2.1) and the first one in Latin America. The plantation of palm oil for commercial purposes started in Colombia in 1945 (FEDEPALMA, 2013a). The cultivation of palm oil has been growing since then reaching 427,368 ha in 2011 (FEDEPALMA, 2013b). From the total area cultivated 62% is currently productive and 48 % is under development (FEDEPALMA, 2013b). The four cultivation areas of African palm oil in Colombia are shown in Figure 2.2.

In 2011, Colombia produced 1,157,308 tons of crude palm oil and crude palm kernel oil from 4,614,610 tons of FFB (FEDEPALMA, 2013b) and consuming around 11 kWh/ton FFB of electricity from the national grid (FEDEPALMA, 2009). Palm oil represents 93% of the national production of vegetable oils and fats (FEDEPALMA, 2013a).
The Colombian palm oil sector, through its national association FEDEPALMA, has set ambitious goal to be achieved by 2020. To accomplish the proposed objectives, the palm oil sector is taking investment actions and joint ventures while the government is supporting infrastructure investments and international negotiations.

FEDEPALMA’s main objectives are (FEDEPALMA, 2013a):

- Multiply seven times the production, passing from 500,000 tons in 1999 to near 3.5 million tons in 2020.
- Increase the productivity per hectare from 3.9 tons of oil in 1999 to 5.5 tons in 2020.
- Increase the palm oil cultivated land from 170,000 in the year 2000 to 743,000 in 2020 with an expected average rate of 8%. The available arable lands fit for palm cultivation are 3.5 million hectares.
- Increase palm oil exportation from 24% of the national production in 2001 to 78% in 2020.
These objectives are aligned with the international and national market demand. It is important to highlight that the growth of the palm oil sector can have a strong impact in the economy if Colombia increases its share of participation in the international market as it has been planned by FEDEPALMA’s.

The recent interest for future development of biodiesel production from palm oil has increased the rate of new cultivated areas in zones not yet established. Moreover, in December 2004 it was approved the law 939 (Congreso de Colombia, 2004) by which oil palm growers and biodiesel producers are granted tax exceptions to encourage new plantations and private investors to satisfy the emerging demand of palm oil for biodiesel purposes. The exceptions include sales tax and global ACPM (Combustible Oil for Engines) tax for a period of 10 years since the start of the production (Congreso de Colombia, 2004) and a fixed price and a fixed income for the producer and a fixed price of the biodiesel in the market adjusted on a monthly basis (Ministerio de Minas y Energía, 2005). The increase in the total area dedicated to oil palm cultivation in Colombia is shown in Figure 2.3. The areas under development include those areas that are cleared after the oil palm trees have reach 20-25 years of productivity, period after which the trees are too high to be harvested and thus, the area is replanted.

![Figure 2.3: Oil Palm Planted Areas (in hectares)
(FEDEPALMA, 2013b)](image)

The cultivated areas in Colombia are distributed according to Figure 2.4. Most of the actual production is located in the east region (39%) closely followed by the central region (31%).
Most of the palm oil production is within the interconnected regions in Colombia where there is access to the national electricity grid (see Figure 2.5). This has been a crucial factor for the development of the palm oil industry as cogeneration is not a common practice in Colombia and thus, does not support the palm oil extraction process.
2.1 Palm Oil Products and By-products

Palm oil is an edible vegetable oil derived from Elaeis Guineensis or African oil palm (see Figure 2.6). This plant grows in tropical warm climates under 500 m above sea level. It originated in West Africa and was brought to the American continent by colonists and merchants. The oil palm has a life of 20-25 years (Yusup, et al., 2011) after which it reaches a height that makes difficult to harvest the fruits and thus, is discarded and new palms are replanted. The oil palm needs around 5 years to become productive.

The products of the processed palm oil fruit include oils suitable for human consumption as well as other non-edible by-products. The products of the palm oil extraction are crude palm oil (CPO), crude palm kernel oil (CPKO), palm kernel meal.

Currently, palm oil is the second most consumed oil in the world and it is used as cooking oil and in bakery and pastry products, ice-creams, instant soups and sauces, frozen and dehydrated meals, etc. A summary of the different palm oil products is shown in Figure 2.7.

Palm oil as well as coconut oil is a highly saturated vegetable fat. Palm oil is semi-solid at room temperatures and contains several saturated and unsaturated fats. The high content of grease solids in palm oil gives the solid/semisolid characteristics to some products as margarine and butter, without a hydrogenation process which has a negative effect on human health. Palm oil has been found to be a reasonable replacement for transfats.

Palm oil is a raw material used widely in the fabrication of soaps and detergents, candles, lubricant greases and base ingredients for paints, varnishes and inks.
Biodiesel from palm oil has become a reality and part of the supported national policies of palm oil producing countries including Colombia.

2.2 Palm Oil Mills

2.2.1 Extraction Process

The palm oil extraction process begins with the harvested ripe Fresh Fruit Bunches (FFB) being transported from the plantation to the Palm Oil Mills (POM). The oil extraction is composed of both mechanical and thermal processes. The FFB is sterilized using steam generated in the POM, which facilitates the separation of the fruit from the bunch. The fruit is then pressed to extract the oil which is clarified in a subsequent step to remove moisture and impurities. In this way, Crude Palm Oil (CPO) is obtained. From the remaining nut or kernel additional oil can be extracted. A simplified scheme of the process is shown in Figure 2.8.
Figure 2.8: Crude Palm Oil Milling Process (Plots Investment Group, 2013)

The different stages in the palm oil extraction process (Figure 2.8) are described below based on (FEDEPALMA, 2013a):

1. **Fruit reception**: the FFB arrives normally by truck to the mill (Figure 2.9). After leaving the FFB at the plant, the trucks are loaded with the empty fruit bunch (EFB). In large installations the trucks are weighted in bridges and the FFB is discharged in a dosage ramp to be emptied in small wagons and start to be processed. The oil palm quality is solely dependent on the bunches arriving to the POM. The mill however can minimize further deterioration of the palm oil quality. The characteristics that affect the composition and final quality of the palm oil are related to genetics, age of the tree, growing conditions, harvesting techniques as well as handling and transport.

Figure 2.9: Fresh Fruit Bunch, FFB (Left); Typical Trucks (Right) (González & Tovar, 2008)
2. **Bunch sterilizing**: FFB is sent to the sterilizers Figure 2.10. In the sterilisers, the FFB is cooked using saturated steam. The cooking action of the FFB serves several purposes:

- The heat from the saturated steam makes easier the separation of the fruit from the bunches in the threshing machines as it weakness the fruit steam.
- The hydrolysis and oxidation process is stopped by destroying the oil enzymes.
- The heat helps proteins to solidify. The “coagulation” of proteins allows the oil to flow easily when pressure is applied.
- As the wet heat weakness the pulp structure, it makes it easier to detach the fibrous material and skin during the digestion process.
- The moisture introduced in the process by using saturated steam acts chemically to break down gums and resins, which have a negative effect on the final product. (causing foam during frying)
- When pressurized vessels are used during sterilization, the heat makes the moisture in the nut to expand, detaching the kernel from the nut shell.

The sterilization process is the most important operation in the oil processing because ensures the success in other stages. It is important also because the incorrect operation will compromise considerably the product quality if air is not completely evacuated from the vessel.

3. **Bunch threshing**: Fruit removal is generally carried out in rotary drum threshers Figure 2.11. The rotating drum has rotary
beater bars that detach the fruit from the bunches, leaving the EFB soaked with a small amount of oil that if not extracted becomes a loss in the process.

Figure 2.11: Thresher Feeder Crane (Left); Thresher Rotating Drum (Right) (González & Tovar, 2008)

4. **Fruit digestion**: Cylindrical vertical tanks are used to digest the fruit by stirring the fruit at 100°C (Figure 2.12). During this step the pulp is separated from the nuts. In this step, the mashing of fruits takes place leading to the separation of pulp from the nuts. During digestion the palm oil is released through the rupture of the oil-bearings cells. Commonly the digester used in this process is a steam-heated isolated cylindrical vessel fitted with a rotating shaft, carrying a number of beater arms. The combination of the pounding action of the rotating arms and the high temperature reduces the oil viscosity. The outer covering (skin) is destroyed in this stage and which finalized the disruption of the oil cells that started in sterilization stage.

Figure 2.12: Fruit Digester Upper Manhole, Beater Arms Shaft (González & Tovar, 2008)

5. **Pulp pressing**: There are two methods for extracting oil from the digested material, mechanical method called “dry” and the
other that uses hot water and called “wet” method. In the dry method (more suitable for large productions), the oil is extracted from a mixture of fibers, nuts and moisture. There are two types of presses, batch or continuous operation. In the case of Colombia, the continuous operation presses are the most commonly used. In this type of presses the digested fruit is continuous feed to a cylindrical perforated cage through which runs a closely fitted screw. The cage is cone-shaped at the outlet causing the oil to flow through the perforations by increasing the pressure. In this type of digester, moderate metal wear occurs during operation. The rate of wear depends directly on the type of device, pressure and nut-to-fibre ratio. The corresponding effect of metal bits in the oil increases the risks of oxidation and oil rancidity.

6. **Oil clarification and drying:** The oil is separated from impurities through the clarification process. After the pulp pressing device, the fluid is a mixture of palm oil, water, cell debris, solids and fibrous material. Hot water is added to thin the mixture and to decant the heavy solids (water is added in a 3:1 ratio). This mixture is then passed through a screen to remove coarse fiber. Thereafter, it is boiled for one or two hours and allowed to settle by gravity. The clear oil (clarified oil) containing still some traces of moisture and impurities and it is reheated until the moisture content is reduced to 0.15-0.25 %. An extra centrifugal process can be applied to remove the residual dirt and moisture. The effluent, Palm Oil Mill Effluent (POME), is then anaerobically digested in ponds (see Figure 2.8).

7. **Kernel recovery:** As shown in Figure 2.13 the nuts are recovered. At this stage the nuts are separated from the fiber (which follows another drying process until it is suitable for combustion in the steam boilers) by the use of a depericarper. This device uses an air flow column to separate the denser nut from the fiber. Once the nuts have been separated, they are centrifugally cracked, and then the kernel is separated from the shells in cyclones. As it is shown in Figure 2.13 the kernel recovery can be done on site, in large scale facilities or it can be processed in a different plant. The advantage of processing the palm nut on site is that the dried shells provide a good fuel for the steam generation boilers.
8. **Steam boilers:** The steam required by the mills is proportional to the amount of oil produced in the plant. Determining the amount of steam required is of paramount importance for managing the process properly. In a typical mid-size installation, steam is used primarily for direct heating (sterilizers and digesters), indirect heating (oil management in different stages) or drying processes. Typical values of steam consumption are presented in Table 2.1.

Given that most of POM has an excess of fuel for the process, steam management is not given the required importance for the stages that require superheated steam. It is clear that steam management does not seem important, but if the losses due to supply pressure drops are considered, this will become a critical aspect in POM operation. More importantly if a power cycle based on a steam turbine is supposed to operate in conjunction with the POM, steady stream flow is necessary in order to operate the turbine under satisfactory conditions. In this regard a steam accumulator should be considered after the turbine, and before supplying steam to the process.
Table 2.1: Indirect Heating Steam Requirement of a Typical POM  
(FEDEPALMA, 1996)

<table>
<thead>
<tr>
<th>Process stage/equipment</th>
<th>Steam requirement (kg/ton FFB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digesters</td>
<td>35</td>
</tr>
<tr>
<td>Fiber transport</td>
<td>10</td>
</tr>
<tr>
<td>Nut drying silo</td>
<td>65</td>
</tr>
<tr>
<td>Crude oil heaters</td>
<td>22</td>
</tr>
<tr>
<td>Oil heaters</td>
<td>22</td>
</tr>
<tr>
<td>Clarifiers</td>
<td>10</td>
</tr>
<tr>
<td>Water heater</td>
<td>40</td>
</tr>
<tr>
<td>Storage and grease traps</td>
<td>21</td>
</tr>
<tr>
<td>Boiler feedwater preheater</td>
<td>25</td>
</tr>
<tr>
<td>Total</td>
<td>250</td>
</tr>
</tbody>
</table>

2.2.2 Palm Oil Mills in Colombia

The milling process is distributed along 51 POMs in the territory, with a total installed capacity of 1249 tons FFB per hour. The POM’s are grouped according to the region in which they are located (Figure 2.14) and their installed capacity (Table 2.2). There has been a dramatic increase in the installed capacity in the last 10 years which has been mainly driven by internal market factors including the biodiesel initiative (B20 mixture) approved by the Colombian government.
The increase in the processing capacity in existing large mills as shown in Table 2.2 as an answer to the increase in the internal demand. One of the objectives of FEDEPALMA is to increase the yield from 3.9 tons palm oil/ha in 1999 to 5.5 tons palm oil/ha in 2020 (FEDEPALMA, 2013a).

**Table 2.2: Distribution of Palm Oil Mills by Size (FEDEPALMA, 2013b)**

<table>
<thead>
<tr>
<th>Size range (ton FFB/h)</th>
<th>Number of mills</th>
<th>Aggregate installed capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>6-10</td>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>11-15</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>16-25</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>more than 25</td>
<td>10</td>
<td>11</td>
</tr>
</tbody>
</table>
The demand in Colombia has been further increased by the use of palm oil for biodiesel production. The worldwide increase in the palm oil consumption has created additional pressures in this sector which had different effects in the society and environment including deforestation, environmental degradation, negative social impacts as well as a competition between palm oil final uses (i.e. fostering the debate of fuel vs. food). All these factors have contributed with the debate about palm oil sustainability. However, the palm oil industry in different countries has benefited of the possibility that it has of reducing its environmental footprint by proposing Clean Development Mechanism (CDM) projects fulfilling the imperatives of the Kyoto Protocol. Most CDM projects in palm oil mills are on waste-to-energy, co-composting, and methane recovery from open POME ponds with the latter being the most common.

The most important products of the process are crude palm oil (CPO) and palm kernel oil (PKO). Palm oil is obtained from processing the FFB which normally weights between 23 and 27 kg (Poku, 2002) and its composition is shown in Table 2.3. However, plenty of biomass waste is also generated in the process accounting for around 42% of the FFB.

Table 2.3: Biomass production in the palm oil extraction process (Yáñez Angarita, 2008)

<table>
<thead>
<tr>
<th>% FFB</th>
<th>% dry biomass</th>
<th>Production (kg/ha y)</th>
<th>Energy potential (GJ/ha y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude palm oil</td>
<td>19 – 21</td>
<td>4000</td>
<td>158.4</td>
</tr>
<tr>
<td>Palm kernel oil</td>
<td>2 – 2.5</td>
<td>400</td>
<td>15.84</td>
</tr>
<tr>
<td>EFB</td>
<td>20 – 25</td>
<td>53.2</td>
<td>4380</td>
</tr>
<tr>
<td>Fiber</td>
<td>11 – 14.5</td>
<td>32.3</td>
<td>2660</td>
</tr>
<tr>
<td>Shell</td>
<td>5 - 7</td>
<td>14.6</td>
<td>1200</td>
</tr>
<tr>
<td>*Biogas</td>
<td>15 – 21</td>
<td>392</td>
<td>12.24</td>
</tr>
</tbody>
</table>

There are two main types of wastes from POMs: solid wastes (fibers, shells, EFB) and liquid waste (POME). In the case of Colombia, shells and fibers are burned to generate steam and EFB is partly used for fertilization while the remaining EFB is left to decay. POME is a wastewater generated from palm oil milling activities (see Figure 2.8)
which characterized by having highly polluting properties. POME is treated through anaerobic digestion open ponds. Recent efforts supported by CDM mechanisms have focused on biogas recovery from these ponds. At the moment the biogas is flared and no energy recovery is performed. Figure 2.15 shows a simplified POM process highlighting the different effluents and solid waste streams.

![Diagram of POM waste source scheme](image)

Figure 2.15: Simplified waste source scheme in a POM (adapted from ADB, 2006)

Most of the POMs in Colombia are connected to the national grid for covering the electrical demand of the process (FEDEPALMA, 2009). Those POMs not connected to the grid used diesel generators for generating the electricity required. The heat demand is commonly covered by burning fibres. Thus, there is an untapped potential for supplying the energy needs of the POMs with its own waste. The possibilities of using solid wastes for energy purposes in the mills is the objective of the study and are analysed in detail and presented in this thesis in chapter 4 and in papers I-III. Furthermore, the option to also provide excess of electricity to the national grid is investigated in the aforementioned papers considering the legislative aspects presented in the next section.
2.3 The Oil-Palm Internal Market Perspectives

The vision of the palm oil sector is to expand by increasing the annual production and export capabilities. This is an ambitious goal as a palm tree takes between three to five years to become productive. In spite of the time required for the plant to growth, policies incentives for biodiesel production as well as tax exemptions for palm growers approved in 2004 have helped to increase the production of palm oil as shown in Figure 2.14 and Figure 2.16. The projections from FEDEPALMA show a sharp increase from 2013 to 2020 based on its vision. This vision includes a higher biodiesel production and an increased export capacity which was reduced significantly when the national biodiesel policy was enforced.

![Graph showing Colombian palm oil market (FEDEPALMA, 2011)]

The declared tax exemption for palm growers had the intention to provide the means of covering a future local demand based on biodiesel and encourage exports thus consolidation FEDEPALMA’s envisioned goals for 2020. In parallel an ethanol program was also introduced to achieve E10 blends in all major cities in Colombia.

The Biodiesel Program is based on three main issues: the diversification of the national energy mix, environmental improvement and development of the agricultural sector (which has an important impact in rural job opportunities). The program was conceived to be B5 in the early stages and slowly become a B10 blend for all the Colombian territory. The implementation started early 2008 within the city of Bogotá. The coverage and details of the blends used in Colombia is shown in Figure 2.17. This figure shows that biodiesel was used
commercially at least in a B7 blend in Colombia in 2011. The biodiesel used in the national blends comes solely from palm oil.

The implementation of B10 blends in the whole territory is still cause of national debate as it includes issues such as fuel vs. food, effect on the biodiversity and the impact on the national diesel fleet with more than 15 years in service (50% of the total diesel fleet).

Based on the scenario shown above, the palm oil market will be ruled by several factors, i.e. the price of biodiesel (regulated by the government), the internal demand and national process as well as the international palm oil price. However, the internal demand is enough to drive further developments in the palm oil sector and new plantations are developed as well as new plants are being commissioned.

2.4 Power Generation Regulation and Legislative Framework

The framework of the power generation sector has suffered some substantial structural changes regarding the trade of energy, the energy spot price in the market, and the role of the players in the grid. All these changes had given a new deregulated market. The wholesale electricity market became deregulated when the law of public utilities, became operational with the MEM (acronym for “Mercado de Energía Mayorista”) in 1995, as a model of competitive market for the provision of public utilities in Colombia.
After ten years under the deregulated scheme utilizing an income stabilization instrument known as Capacity Charge, the commission in charge (CREG), considered appropriate to replace it with a market scheme. This new mechanism is focused on promoting new investments in generation resources in Colombia in a long term perspective, to guarantee the availability of electricity at efficient prices in periods of scarcity. Several concepts and mechanisms required for cogeneration schemes will be explained in the following sections.

2.4.1 Cogeneration and polygeneration alternatives

In 1994, the operational model for residential public services was deregulated, i.e. it went from being state owned and operated to work as an open and competitive market, remaining for the state certain functions of planning, control and regulation. The law 143/94 defined the four main activities in the electrical sector, namely, generation, transmission, distribution and commercialization. Regarding the generation activity the Commission of Regulation of Energy and Gas (CREG), has defined 4 categories, each of them with different conditions for operation, these categories are shown in Table 2.4. Under the conditions described in Table 2.4 auto generation and cogeneration activities are regulated for the national interconnected zones (NIS).

<table>
<thead>
<tr>
<th>Category</th>
<th>Power</th>
<th>Interconnection NIS</th>
<th>Selling</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generators</td>
<td>≥ 20 MW</td>
<td>Mandatory</td>
<td>Energy market</td>
<td></td>
</tr>
<tr>
<td>Minor plants</td>
<td>&lt; 20 MW</td>
<td>Optional</td>
<td>EM and others</td>
<td>If &lt; 10 MW no interconnection</td>
</tr>
<tr>
<td>Auto generators</td>
<td>No limit</td>
<td>Optional</td>
<td>No selling</td>
<td>Connection to grid just as backup</td>
</tr>
<tr>
<td>Cogenerators</td>
<td>No limit</td>
<td>Optional</td>
<td>EM and others</td>
<td>Can sell energy if:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Electricity from thermal energy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;5% of total energy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Thermal energy from electrical</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>generation &gt;15% of total energy</td>
</tr>
</tbody>
</table>

Table 2.4: Categorization of energy generators (CREG, 1996)
Under the actual model the electricity sales can be done in two main ways:

- under offer and demand laws operated by open market concepts, where the plant offering the best price will get dispatched first then the following ones until the demand is reached and the last price dispatched will define the spot electricity price for a specific hour of the day

- by an agreement made between the generators and the retailers where certain amount of energy is bought during certain time, usually long term periods, an average of this price

These two methods result in different prices, with the spot market price being more volatile than the contract’s price (see Figure 2.18).

In Colombia, the final users of energy are divided according to the amount of energy they consume in regulated and non-regulated users. The first ones are mainly residential, small commercial and industrial users whose average consumption in a six month period is below 0.1 MW of power or 55 MWh of energy (CREG, 1996). For the non-regulated users, there is no set equation for determining price, but they are free to find their own supplier or to buy directly on the spot market if they own the appropriate infrastructure, in other words to negotiate their own electricity. In order to qualify as a non-regulated user the power consumption must be above the mentioned limit. However there is an
exception for agro-industrial clients that have a seasonal consumption, in which case the average period reduces from six to three months.

The CREG defined cogenerator as a natural or juridical person that produces electricity through the process of combined heat and power and that contributes to a productive activity. The products can be consumed by the producer or by third parties and can be used for industrial or commercial purposes. It is also established that cogeneration saves primary energy, contribute to reduction of losses in generation and transmission and therefore it is important to promote this activity for its effects in the energy balance and the environment (CREG, 1996).

Based on this concept, there should be strong programs to promote cogeneration, however this has not been the case. The regulation is not clear enough in some aspects, and in others it does not consider some of the specific characteristics of cogeneration, creating rules that do not help it to be competitive. For co-generators in Colombia there are four main regulations that define and control their activity and they are: CREG 085/96 (CREG, 1996), CREG 107/98 (CREG, 1998), CREG 039/01 (CREG, 2001) and CREG 5/2010 (CREG, 2010). In those regulations cogeneration is defined and some important concepts are as well specified, the most relevant ones are the following:

- Additional demand: the maximum extra demand (MW) that a co-generator connected to the NIS requires covering 100% of its needs.

- Excess of energy with guaranteed power: the extra energy produced by cogeneration that is associated with a constant power guaranteed by certain amount of time, which could be sold and maintained in the long term, and that will not be used for own consumption at any time, therefore can be registered in the energy market as a generator.

- Excess of energy without guaranteed power: the extra energy produced by a cogenerator that is not associated to a constant power and is just the result of the variation in the own consumption.

- Inflexibility of cogeneration systems: condition due to the technical characteristics of these systems that results in the production of more energy that the required for the own consumption during one hour (or more).
The regulation also determines some of the conditions to sell this excess of energy (electricity or heat) produced based on the categories described in Table 2.4. Regarding the connection of cogeneration plants to the NIS, the rules that apply are the same that for any other plant i.e. mandatory for capacities higher than 20 MW and optional from 10-20 MW, the plants with capacity lower than 10 MW can be connected to the system but the energy produced will not be centrally dispatched, and will not be part of the spot market.

Most of the regulation about selling electricity concerns plants that are connected to the NIS. However, the regulation is not completely clear about the plants that are not connected as they operated under what is called a special regime, particularly in the non-interconnected zones (NIZ). If the co-generator fulfills the conditions expressed in Table 2.4 under the column titled "Others", then there are four different options to sell the electricity (CREG, 2010), as summarized below:

1) Cogeneration with excess of energy with guaranteed power < 20 MW:
   a) Option 1: it is not connected to the central dispatch and thus, is not part of the spot market. For these plants it is possible to:
      i) Sell the energy to another retail company at the spot market price minus 1 COP/kWh according to the resolution CREG-005 of 2001. This fee will be indexed yearly.
      ii) Offer the energy to a retail companies that provide regulated users. This is done by participating in the retailers open bids and the winner is defined by price competition.
      iii) Freely sell energy and arrange prices with other retailers that serve non-regulated users.
   b) Option 2: the plant has access to the central dispatch and thus, participates in the spot market. In order to be part of this category, the excess of energy with guaranteed power has to be declared inflexible (in the same way as generators will do). Then:
      i) The energy can be sold in the spot market
      ii) The energy can be sold following the guidelines explained in option 1

2) Cogeneration with excess of energy with guaranteed power = 20 MW: the cogenerators will be part of the central dispatch and will offer the energy in the spot market. The excess of energy with guaranteed power should be declared inflexible and the respective regulations will apply. The excess of energy will be traded based on
the same principles explained in option 2 of the section for cogeneration with excess of energy with guaranteed power < 20 MW.

3) Cogeneration with excess of energy without guaranteed power:
   
a) Option 1: the plant does not have access to the spot market and central dispatch. The excess of energy can be sold freely and prices arranged within the parties involved. The energy can be sold to generators or retail companies dealing with non-regulated users.

b) Option 2: Can sell in the spot market and it will be part of the central dispatch. The same conditions as for inflexible generation will apply to this category.

2.4.2 Renewable sources and efficient use of energy

Regarding renewable energies, the country is relative immature in the topic, even though some technologies have been used. The regulations have not been clear and the government had not paid enough attention to this aspect. However, in the year 2001 with the law 697 the country took an important step toward sustainability in the energy field. Although this law is very basic, it gave the initial tools to establish a stronger legislation that promotes these technologies and resources that will benefit in the long term the energy balance, competitiveness, and sustainability of the country.

2.4.3 Biodiesel and pellets markets

The biofuels sector has presented the fastest development of all the renewable sources in the country. This situation is the consequence of many factors like international tendencies in the development of alternative fuels and the high oil prices. In the past years some changes have been introduced in this sector and since then the legislation concerning biofuels and particularly biodiesel has affected directly the palm oil industry.

According with the MME, the biofuels program seeks for diversification of energy sources, environmental sustainability, development and preservation of the agricultural activity, energy self-sufficiency, agro industrial development and improvement in the air quality as a result of the mix of fuels.

The first step to develop the biofuels in the country was the law 693 of 2001 that basically established the following: gasoline used in the urban
centres of more than 500'000 inhabitants, should include oxygenated compounds beginning from 2005. The percentages of the mix are to be defined by the MME. It also changed the article 11 of the law 83/25 by which the production of alcohols was a departmental monopoly by letting it operate as an open activity where any private or public company can participate. Later in the law 788 of 2002 it was included the exemption of VAT and other taxes for fuel alcohol. By means of different decrees in the past 7 years the regulation of the percentage, quality, mixing conditions, selling, distribution and so on have been defined, as result in the present there is clear policy regarding the mix of gasoline and ethanol. The main consequence of this has been the increase of ethanol production for fuel use. It went from 11 million litres per month in 2005 to 34 million litres per month in 2013 (FEDEBIOCOMBUSTIBLES, 2012).

The MME developed and implemented a program that began in November 2005, when the larger cities in the southwest of the country and some in the central part of the country started using gasoline mixed with 10% ethanol. In January 2006 the capital city, Bogota, began to sell the oxygenated gasoline and by June 2007 with the participation of the departments of Santander and North of Santander, 71% of the big urban areas were covered (Londoño, 2007). The implementation was done in steps in order to allow the production and distribution to adapt to the new demand. The production of ethanol comes mainly from sugar cane. Nonetheless, there are other feedstocks like cassava, potatoes, corn, or beet that are being considered for this purpose.

The other important legislation to promote biofuels is the law 939 of 2004 whose main objective is to stimulate the production and commercialization of biofuels from vegetal or animal origin to be used in diesel engines. The main points of the law are:

- to exempt of income taxes the plantations that are suitable for those fuels such as palm oil,
- to allow the mix of suitable biofuels with diesel to be fuelled in engines
- to exempt of VAT and extra taxes the biofuels produced to be mixed with diesel

This law does not have clear goals like the bioethanol law but it is the first step made by the government in order to promote the industry of biodiesel. The law started the introduction of a mix of 5% of biodiesel with regular diesel for transport in the main cities.
Preliminary studies for production of pellets from palm oil residues have shown the potential of these resources. There are several niche markets for palm oil pellets in Colombia (e.g. co-firing with brown coal, rural supply of electricity). However, no commercial production exists in the country.

Pellets are starting to become an international commodity with the expected demand increasing from 13.5 million tons in 2010 to 20 million tons by 2020 (IEA Bioenergy, 2011).
3 Forest-based fuels in Sweden

This chapter describes the forest biomass sector in Sweden. It describes briefly the forest biomass characteristics as well as the operations for forest fuel harvesting and transport in Sweden. The chapter also highlights their importance of forest-based industries in the country and discussed their energy use from a general perspective.

In contrast to a tropical country like Colombia, whose climate allows the cultivation of a wide variety of crops and plantations, a temperate country like Sweden is largely dominated by conifer and deciduous forest only (less than 10% of the country is arable). Residues from forest-based industries have evolved from being a disposal problem to become an important source in the Swedish energy mix. In this regard, biomass forest residues have a prominent position in the Swedish energy supply, particularly for heating applications. They also have an important position in the renewable electricity sector as biomass plants have been granted more electricity certificates than any other renewable sources since the implementation of this scheme. The utilization of these resources can be further optimized by fostering synergies between wood-based industries, energy industries and energy consumers.

Different components of a tree can be used for energy production (see Figure 3.1). While the crown mass includes living and dead branches and leaves, the stump-root system includes all wood and bark below the stump section. Usually, the fellings are composed of stem wood removals which are recovered, and stem wood losses which are left in the forest. If the removals fulfil specific parameters of quality and size, they are considered as industrial wood. On the other hand, if the removals do not fulfil quality requirements, they are considered as fuel wood (Röser, et al., 2008). The traditional forest practices give value just to stem wood (Hakkila, 2004). However, the increased need for bioenergy has resulted in more intensive use of the forests and whole tree harvesting. Thus, besides the stem wood which has been traditionally harvested, most branches and needles are also removed from a harvesting site (Lairo, et al., 2009).
Before the final felling, a number of pre-commercial thinnings are conducted in order to improve the growth rate and health of the remaining trees. The present study considers forest residues as all biomass residues left on site after timber harvesting operations. Residues resulting from pre-commercial thinnings of young stands are not included. It is recommended not to use all forest residues as fuels. According to Luiro et al. (2009), removing logging residues increases the loss of nutrients from the forest and might impact the site nutrient status and productivity, particularly after thinning. Hakkila (2004) suggests that about 30% of these residues are left on site. The Swedish National Board of Forestry has also made a number of recommendations in order to avoid negative impacts of wood fuel harvesting on the nutritional balance of the soil, the biological diversity of national forests and the water quality (National Board of Forestry, 2002).

As described in Pulkii (2013), there are various harvesting methods and handling practices: (i) cut-to-length, in which trees are cut-off above the stump, delimbed and bucked to various assortments such as pulpwood or sawlogs directly in the stump area. (ii) tree-length, in which trees are felled, delimbed and topped. Delimming and topping could be done directly at the site or at a point before roadside and, (iii) full tree, in
which the complete trees are felled and transported to the roadside. The trees, with tops and branches, are processed at roadside or hauled completely to central processing yards or the mill.

Forest fuels are limited resources and their amount is determined by the availability of clear-cut residues and thinnings (Eriksson, 2008). Depending on the species and the type of thinning and final cut, the obtained residues vary. Hakkila (2004) has estimated the distribution of biomass between stem, crown and stump-root system in final fellings for spruce and pine stands, two common species in Sweden. The proportion of residues of stem wood left at site as residue in commercial logging operations is higher in the first commercial thinning (20-30%) than in the final cut (4-5%) (Hakkila, 2004). We have considered only the final felling for the purpose of this study.

Table 3.1: Distribution of biomass between stem, crown and stump-root system in final fellings (%)

<table>
<thead>
<tr>
<th></th>
<th>Scots Pine</th>
<th>Norway Spruce</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stem</td>
<td>69</td>
<td>59</td>
</tr>
<tr>
<td>Crown</td>
<td>16</td>
<td>27</td>
</tr>
<tr>
<td>Stump and root</td>
<td>15</td>
<td>14</td>
</tr>
</tbody>
</table>

In Sweden, the total land area corresponds to 41.3 million hectares, of which 23 million hectares correspond to forest landwood (Swedish Forestry Agency, 2013). The total standing volume on productive forest land is about 2.9 billion m$^3$, of which 39 % is Scots pine, 42 % Norway spruce and 12 % birch m$^3$ standing volume/ha/year. The average annual productivity of forest land is 5.3 m$^3$/ha. However, it differs among the national regions and it is possible to find places such as Skåne, where the average productivity of forest is 11 m$^3$/ha (Swedish Forest Agency, 2011). This implies a potential for forest fuels in Sweden of about 0.85 billion m$^3$ if only Scots Pine and Norway Spruce species are considered.

In general, forest fuels (e.g. logging residues, small round wood and stump) are characterized by low density and homogeneity (Johansson, et al., 2006). This creates challenges for efficient transportation. Also, the energy content of these residues is very low, if compared to that of fossil fuels. Thus, low density, low homogeneity and low energy density turn harvesting and transporting into critical stages for the profitability of
forest fuels. Johansson et al. (2006) summarizes information on the energy content of the forest residues considered under this study.

Table 3.2: Definition and energy content of forest fuels

<table>
<thead>
<tr>
<th></th>
<th>Loose material</th>
<th>Small roundwood</th>
<th>Stump</th>
</tr>
</thead>
<tbody>
<tr>
<td>Definition</td>
<td>Unbundled forest residues including branches and alive and dead leaves</td>
<td>Forest residues that do not fulfil size requirements.</td>
<td>Rooted remains of a felled tree below the stump cross-section (Johansson 2006)</td>
</tr>
<tr>
<td>Energy content</td>
<td>5.3 – 6.2 MWh/t (Richardson, et al., 2002)</td>
<td>2.6 MWh/t (Moisture 45%) (Eriksson, 2008)</td>
<td>3.8 MWh/t (Moisture 25%) (Eriksson, 2008)</td>
</tr>
</tbody>
</table>

3.1 Forestry operations

Forestry operations are fully mechanized in Sweden. They usually include a harvester and a forwarder. The harvester cuts down and processes the trees and the forwarder transports the logs or the forest fuels to the roadside. Logging residues from final felling are the most important source of forest fuel in the Nordic countries (Richardson, et al., 2002) besides the bark and other wood residues from industrial processing. Potential sources of forest fuels are residues from forestry operations: loose material, stumps and the roundwood part, consisting of the stem wood, the crown and stump wood.

The scope of this analysis is given by the activities at the forest site, once the final felling is performed. This has been a common practice in Sweden and Finland despite a growing interest in harvesting of fuel wood in the form of whole-trees or tree-sections (Richardson, et al., 2002). The term logging is hereby used to describe a range of forestry or activities from cutting to loading of trees or logs onto purpose-built trucks. The objective of forest fuel harvesting is to obtain high-quality raw material to produce heating or power. The term forest fuel harvesting is used to describe the activities from cutting to loading logging residues onto road vehicles, including on-site processing such as cutting or bundling. Sweden has a gentle terrain in which harvesters and forwarders can operate not only for felling but also for collecting and hauling logging residues. Usually, a single-grip harvester is used for felling and a forwarder operates in a sequential manner (Talbot, et al.,
2003; KLVAC, et al., 2003). Forwarders extract the timber and haul it to the roadside. Finally, most of the timber, about 75%, is transported on roads (Berg, 2003). In Sweden, the most widely used chain for logging residues from final fellings includes felling/cutting by harvester, forwarding/skidding by forwarder, chipping/crushing at the road-side and transportation by truck (Díaz-Yáñez, et al., 2013, p. 567). According to Alakangas & Flyktman (2001), logging residues can be harvested immediately after felling or after summer, when they are dried. They can be harvested, stored and handled in several ways with different implications in terms of logistics. Logging residues can be harvested by: (i) pilling of residues and chipping at stand, at roadside or at particular terminal, (ii) compacting the residues into bundles and chipping at final user facilities, and (iii) pilling of residues at stand, transport them as loosing material and chipping at final user facilities. In Sweden, logging residues are rarely transported to final user facilities by road (Alakangas & Flyktman, 2001). Instead, they are chipped at stand and the chips are usually transported in road transport bins (Johansson, et al., 2006).

In Nordic countries, factors influencing fuel harvesting techniques include: (i) a high demand for timber (ii) dominant use of cut-to-length logging system, (iii) harvesting by clear-cutting at the end of each rotation of large timber volumes, (iv) existence of few tree species with relatively uniform growth in the forests, (v) forest soils are geologically young and most of the nutrients are in the mineral soil (Richardson, et al., 2002).

The studied harvesting-transport system for fuel wood considers logging residues that are either processed on-site or directly forwarded to the roadside following the routes indicated in Figure 3.2. On-site and roadside operations include compressing of the residues to bundles, cutting small roundwood, chipping and extraction of stumps. Forest residues are piled after harvesting, usually on the logging site. The idea is to locate fuel wood to promote natural drying of the residues.
3.1.1 Forwarding - Transport

In Sweden, forest residues are usually extracted of the piles at the site after logging and transported to the road side where chipping and bundling can also take place. Forwarding should be developed at the end of summer or in early autumn, after residues have dried. Finally, the residues are hauled to the end users. Transport is a key element of forest activities as the low bulk density of forest fuels increases significantly transportation costs. For Nordic countries in general, half of the costs of the wood residues delivered at district heating plants is related to transportation which is in average 60 km. (Richardson, et al., 2002). Though most forest fuel systems in Sweden concern chips utilization; the use of bundles to transport forest fuels could also be an alternative. Bundles increase the load capacity and allow a more efficient handling in loading and storing of the wood fuel (Johansson, et al., 2006).

3.1.2 Compressing of the residues to bundles

Bundles are compressed and uniform handling units that are produced from logging residues and other small size energy wood (Johansson, et al., 2006). In this way, a uniform handling unit, easier to transport and store is produced. The compressing operation includes the use of
different equipment to compact logging residues and can be performed either in a batch wise operation or following a continuous scheme. Two technology developers in Scandinavia, Wood Pac and Fiberpac, have developed machinery that compress loose material into bundles which can be easily transported by forwarders and conventional hauling. In the first case a bundler compacts logging residues into cylindrical bundles. Bundles can then be collected and transported in the same way as logs. In the second case a bundler uses two compression arms and four feeding roller which work continuously to produce bundles that can be cut to desired length (Johansson, et al., 2006; Yoshioka, 2011). Thus, while the Wood Pac bundler produces bundles with a fixed length of approx. 3 m, the Fiberpac bundler (Timberjack, 1490 D) produces 70–75 cm thick bundles with the length chosen by the operator through a continuous process. More recent technologies are the Pika RS 2000 and the Valmet WoodPac bundlers (Kärhä & Vartiamäki, 2006).

3.1.3 Reduction of size – cutting and chipping

The size reduction of forest residues should be delayed as long as possible to limit chip storage time and reduce the risk of biomass losses. Small roundwood from thinnings stumps and loose material can be cut, if needed, chipped at the roadside and transported by a purpose-built vehicle. It can also be chipped at the plant after transportation in a truck. If chipping is done at the roadside, the chippers are commonly mounted on forwarders, while if chipping is done at the plant the chippers are mounted on trucks. Hammer mills are frequently used at landings, terminals and industrial sites. They are more tolerant to contaminants but also less productive (Richardson, et al., 2002).

3.1.4 Extraction of stumps

Stump lifting for bioenergy started in Sweden in 2000. According to Richardson et al, (2002), the stump-root system could offer an additional 20 per cent gain beyond that obtainable from the stem (Richardson, et al., 2002). If the energy content of stumps is greater than 200 MWh/ha, the process of extracting stumps and use them as energy sources becomes cost-effective (Eriksson & Gustavsson, 2008). However, it is important to recognize that recovering stumps implies various environmental impacts such as removal of soil organic matter, increased soil compaction and erosion among others (Walmsley & Goldbold, 2010).
3.2 Biomass-based processes in Sweden

Sweden is large dominated by forest and thus, forestry is fundamental for the national economy. Sweden provides 10% of the world’s sawn timber and pulp and paper from just below 1% of the world’s commercial forest area (Skogsindustrierna, 2010). Figure 3.3 shows the industrial wood consumption in Sweden. This figure shows the major consumers of wood (sawn timber industry and pulp and paper industry) and also displays the interrelations between them. Fuel wood represents only around 8% of the total wood consumption.

A combination of industrial and policy actions has led to a high degree of biomass utilization in Sweden. The sustainable use of this resource requires a new generation of biomass plants and their effective integration into already existing industrial processes. One of the objectives of this thesis was to develop an optimization methodology using genetic algorithms in conjunction with energy simulation software to find the best alternatives in order to reach higher biomass usage as shown in papers V and VI. It also considered producing high-value energy commodities such as electricity and pellets by analysing different technologies and configurations from a source-to-product viewpoint as it is shown in chapter 5 and paper V and VI.

Figure 3.4 shows a simplified view of the possible integration of biomass CHP plants with other biomass-based industries which will be used for identifying the different optimization cases and also defining the boundaries of the system considered.
3.2.1 Pulp and paper industry

Sweden was the largest producer of pulp and the third largest producer of paper in Europe in 2010 (Swedish Forest Agency, 2010). The production in 2010 amounted to 11.9 Mtonne of pulp and 11.4 Mtonne of paper and paperboard, which corresponded to 7% of the global pulp production and around 3% of the world’s paper production. According to the Confederation of European Paper Industries (CEPI1), about 11.8 million tons of Mechanical and Semi-Chemical Pulp and about 26.8 million tons of Chemical Pulp were produced by the confederation members. Contributions from Sweden and Finland were the most relevant with 30.6% and 26.7% respectively (CEPI, 2012).

In Sweden, the production of pulp increased from 8.4 Mtonne in 2008 to 11.7 Mtonne in 2009 and 11.9 Mtonne in 2010 and 2011 (Swedish Forest Agency, 2010). The production of paper decreased from 12.4 Mtonne in 2008 to 11 Mtonne in 2009 and then increased slightly to 11.4 Mtonne in 2010 (Swedish Forest Agency, 2010). The number of pulp and paper mills decreased 30% (to 45 mills) between 1998 and 2008 in spite of the

1 Members of CEPI in 2011: Austria, Belgium, Czech Republic, Finland, France, Germany, Hungary, Italy, Norway, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, The Netherlands, United Kingdom

Figure 3.4: Industrial use of wood in Sweden
growth in production according to Ericsson (Ericsson, et al., 2011). These remaining mills are owned by companies also involved in sawmill activities and pelletization activities (Ericsson, et al., 2011).

Pulping commercial processes are generally classified as mechanical, chemical, or semi-chemical. In mechanical pulping, the wood fibers are usually torn out of the wood, abraded, and removed using a rough, revolving grinding stone (Figure 3.6). In this type of pulping electricity is used mainly for wood grinders. According to the Swedish Forest Industries Federation, the mechanical pulping processes are: groundwood pulp (SGW), thermo-mechanical pulp (TMP), chemothermomechanical pulp (CTMP) and semi-chemical pulp (referring to various combinations of chemical and mechanical processes).

Figure 3.5: Swedish production of wood pulp by grade (Swedish Forest Agency, 2012)

Figure 3.6: Mechanical pulping process
In chemical pulping, the wood fibers are separated by dissolving the lignin component. Among the chemical process the sulphite and sulphate processes are used in Sweden. The Kraft (sulphate) process is by far the largest in terms of production volume not only within CEPI but also globally (Jönsson, 2012).

In 2011, the Swedish pulp industry produced 3.6 Mtonne of pulp using mechanical pulping, 0.3 Mtonne using semi-chemical pulping, 7.4 Mtonne using sulphate pulping and 0.6 using sulphite pulping (Figure 3.5). In this year, there were 51 pulp and paper mills in Sweden (5 mills were closed during the period 2007-2011 and 4 more during 2000-2007) (Wiberg & Forslund, 2012).

Table 3.3 shows the pulp production in Sweden in 2011. Production of pulp is divided in market pulp, which is dried, and the mass integrated paper production, which is directly used in paper production without being dried, and so-called pump mass.

Table 3.3: Pulp production volumes (in 1000 ton) in Sweden (Wiberg & Forslund, 2012)

<table>
<thead>
<tr>
<th>(*1000 ton)</th>
<th>Sulphate Mills</th>
<th>Sulphite Mills</th>
<th>Mechanical Pulp</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Market Pulp</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bleached (dried)</td>
<td>3372 3715</td>
<td>240 227</td>
<td></td>
</tr>
<tr>
<td>Unbleached (dried)</td>
<td>94 101</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groundwood pulp</td>
<td></td>
<td>0 155</td>
<td></td>
</tr>
<tr>
<td>TMP</td>
<td></td>
<td>153 417</td>
<td></td>
</tr>
<tr>
<td><strong>Pump pulp</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bleached</td>
<td>2036 1986</td>
<td>332 371</td>
<td></td>
</tr>
<tr>
<td>Unbleached</td>
<td>1987 2035</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groundwood pulp</td>
<td></td>
<td>327 380</td>
<td></td>
</tr>
<tr>
<td>TMP</td>
<td></td>
<td>2912 2834</td>
<td></td>
</tr>
</tbody>
</table>
3.2.1.1 Energy use in the pulp and paper industry

In Europe, about 48% of the primary energy used in the pulp and paper industry comes from fossil fuels and 52% from the combustion of biofuels (Coakley, et al., 2010). In particular mechanical pulping is electricity intensive and the produced paper is characterized by a lower strength compared to paper produced using chemical pulping (Coakley, et al., 2010).

In 2010, the industry sector was the largest user of energy and accounted for 37% of the final energy use in Sweden (Energimyndigheten, 2012). Regarding the energy use in the industrial sector, the pulp and paper industry accounted for 52% of the energy use (Figure 3.7) and 42% of the electricity use (Figure 3.8) in 2010 (Energimyndigheten, 2011). The total energy use in the pulp and paper industry comes primarily as electricity or from black liquors. Black liquors are a by-product of pulp production which contains energy and chemicals that could be used and recovered. Thus, possible energy efficiency measures in this sector are of interest for achieving the national environmental goals.

Figure 3.7: Energy use in industry per sector, 1990–2010, in TWh
In average the electricity consumed in Swedish pulp and paper mills was 321 GWh compared to 93 GWh for European mills mainly due to the share of mechanical pulp production (Blomberg, et al., 2012).

In Sweden, a CO\textsubscript{2} tax was implemented in 1991 which depended on the amount of carbon dioxide emitted by the fuels except biofuels (including waste) and peat; it was also applied for heat production in boilers or CHP plants. This triggered the switch from fossil fuels to biomass in the district heating sector and created a market for biofuels (Ericsson, et al., 2011). The pulp and paper industry also started to phase out fossil fuels and use more biomass. Figure 3.9 shows the decrease in the use of fossil fuels in the industry as a result of the policy measures.
The industry also started organizational and operational and started to deliver wood chips and pellets to customers outside the pulp market. The Swedish energy policies created the framework for cooperation between different sectors and currently pulp and paper mills are delivering district heat to other companies/communities and producing wood chips and pellets as shown in Figure 3.10 and discussed by (Ericsson, et al., 2011). For example, between 2000 and 2007, the contribution from pulp and paper mills to district heating increased from 639 GWh to 1495 GWh (coming from 22 pulp and paper mills from a total of 41 existing mills according to (Ericsson, et al., 2011)). This further increased to 2170 GWh during 2011, as shown in Figure 3.10.

Figure 3.10: Fuel and electricity balance in the pulp and paper industry during 2011 in GWh (Wiberg & Forslund, 2012).
Table 3.4: Average heat and electricity consumption in different pulp and paper processes in Sweden (Wiberg, 2007)

<table>
<thead>
<tr>
<th>Production Process</th>
<th>Energy Carrier</th>
<th>Unit</th>
<th>Average Consumption (2007)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical market pulp</td>
<td>Heat</td>
<td>GJ/ton pulp</td>
<td>18</td>
</tr>
<tr>
<td>Chemical market pulp</td>
<td>Electricity</td>
<td>kWh/ton pulp</td>
<td>821</td>
</tr>
<tr>
<td>Integrated production of pulp and paper</td>
<td>Heat</td>
<td>GJ/ton paper ind. pulp</td>
<td>16</td>
</tr>
<tr>
<td>Mechanical pulp</td>
<td>Heat</td>
<td>GJ/ton pulp</td>
<td>0.9</td>
</tr>
<tr>
<td>Mechanical pulp</td>
<td>Electricity</td>
<td>kWh/ton pulp</td>
<td>2256</td>
</tr>
<tr>
<td>Paper</td>
<td>Heat</td>
<td>GJ/ton pulp</td>
<td>4.9</td>
</tr>
<tr>
<td>Paper</td>
<td>Electricity</td>
<td>kWh/ton paper</td>
<td>697</td>
</tr>
</tbody>
</table>

Table 3.4 shows the average heat and electricity consumption of different pulp and paper production processes in 2007 according to Wiberg (Wiberg, 2007).

3.2.2 Sawn timber industry

Sweden is the third largest exporter of sawn timber in the world, after Canada and Russia, and the largest exporter of soft sawn wood in Europe. In 2011, Sweden produced about 16.8 million m$^3$ of wood products, 11.6 of which were exported, representing a value of about 22.4 SEK billion. Sawn products were mainly exported to countries such as Great Britain, Germany and Egypt among others. The sawn timber is mainly softwood, Norwegian spruce, and Scots pine. Leading producers of sawn wood products in Sweden are Setra Trävaror, SCA timber, Södra Timber, Vida, Moelven, Stora Enso Timber among others. They have specialized sawmills that deliver a wide range of products from standard timber, to finished products such as flooring and furniture materials (Skogsindustrierna, 2012).
The number of sawmills has significantly decreased during the last decades despite an increasing production (see Table 3.5). Today, the 20 largest producers in the Swedish sawmilling industry account for about 70% of production. With few exceptions, the sawmills are Swedish-owned.

Table 3.5: Sawmills and sawn products in Sweden (Skogsindustrierna, 2012)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of sawmills &gt;</td>
<td>283</td>
<td>260</td>
<td>207</td>
<td>150</td>
<td>140</td>
</tr>
<tr>
<td>10 000 m³/year</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production per</td>
<td>35</td>
<td>40</td>
<td>75</td>
<td>110</td>
<td>120</td>
</tr>
<tr>
<td>sawmill, 1 000 m³</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>approx.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total production,</td>
<td>11.2</td>
<td>12</td>
<td>16.4</td>
<td>17</td>
<td>16.8</td>
</tr>
<tr>
<td>million m³</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The sawmill production process includes removing bark from the incoming timber, sawing timber into planks and boards, and drying the sawn wood. Drying can be done with kilns or using air. Often, the production process is fully automatized and in many cases, sawmills include further processing to upgrade the sawn wood. Typically, a sawmill with a capacity of 150'000 m³/y of sawn wood transforms 50% the incoming wood into timber products (Vidlund, 2004). The remaining 50% is transformed into residues in the form of bark, sawdust and wood chips, as shown in Figure 3.11.

![Material flow in a sawmill](image_url)

Figure 3.11: Material flow in a sawmill (Adapted from (Vidlund, 2004))
3.2.3 Cogeneration plants and district heating

Sweden has a well-developed district heating network mostly using renewable sources. In 2011, biomass and waste represented 61% of the total fuel use for district heating production. In 2011, biofuels accounted for 47% of the energy input for district heating production in Sweden, waste for 20%, peat for 4%, oil for 4%, natural gas for 5%, coal for 5%, heat pumps for 9% and waste heat for 6% (see Figure 3.12). The use of waste has increased over the last decade, to the extent that the heat from refuse incineration now provides the base output for district heating. The district heating production in Sweden was 50.8 TWh in 2011 (Statistiska Centralbyrån, 2012). From this total, electric boilers produced 0.095 TWh, heat pumps produced 5.1 TWh, flue gas condensing units produced 4.4 TWh and thermal plants produced the remaining 41.3 TWh (Statistiska Centralbyrån, 2012). District heating is widely used and it is the most common carrier for space heating and hot water in apartment buildings and commercial premises followed by electricity. For detached houses, electricity is the most common carrier used for space heating and hot water (Energimyndigheten, 2013).

Figure 3.12: Energy sources for district heating, 1970–2011

District heat originating from CHP plants was about 40% of the total district heat produced in 2010 (Energimyndigheten, 2013). Lately, there has been a renewed interest in CHP plants using biomass due to the subsidies from electricity certificates (Energimyndigheten, 2013). In fact, the bioenergy sector has been leading the use of electricity certificates followed by wind power. Further to the effects of the electricity certificates, the CO₂ tax rate on heat produced in CHP plants was
reduced from 15% to 7% (Energimyndigheten, 2013) of the price base and was decided to be entirely removed from January 1st, 2013 (Energimyndigheten, 2013). This gives CHP plants certain advantage over heating plants that have to pay a CO$_2$ tax rate of 94% of the price base.

In terms of electricity, CHP plants contributed with approximately 11% of the total electricity production in Sweden in 2011 (Energimyndigheten, 2011). From this share 10.4 TWh of electricity were produced in combined heat and power plants (CHP) and 5.9 TWh in industrial back pressure facilities.

3.2.4 Small-scale biomass CHP plants in Sweden

Most CHP production in Sweden today is large-scale cogeneration however, some small-scale CHP units exist. Small-scale CHP plants have a relatively small market share in Sweden. The major reason for this is the large contribution of hydropower and nuclear power and historically low electricity prices. However, the economic conditions are changing rapidly as a result of policy measures like the electricity certificates and tax relief on heat produced in CHP plants. In cold or low-precipitation years the electricity price tend to increase and Sweden imports more electricity to cover the internal demand. All these factors could impact the economic feasibility of small-scale CHP plants considering that up to now, there has been essentially no market for small-scale biomass cogeneration in Sweden as explained by Salomón et al. (2011), Kjellström (2012), and Sundberg et al. (2011).

Although CHP plants do not represent an important share of electricity production in Sweden, the political goals to decrease nuclear power production and to not extend hydropower production are important factors driving the development of CHP plants forward. Renewable energy sources are one important alternative to reach these goals. CHP plants using biofuels are supported by the Swedish government through electricity certificates and tax relief on the heat produced. Also the converting of existing heat or power generating plants into biofuel CHP plants is an interesting possibility.

Currently the market for small-scale CHP plants is very limited in Sweden. Some already built CHP units have been taken out of operation due to economic reasons. However, there is a potential to replace small district heating units with CHP if the economic conditions improve, for example, due to favourable energy taxation system and investment
subsidies. There is also some potential to connect more single houses into small-scale district heating networks (Salomón, et al., 2011).

An increase in the electricity prices and the promotion of biomass-based CHP plants could help the development of the market for small-scale CHP units. The future potential of CHP in Sweden is judged to be in the order of 10-20 TWh\textsubscript{e} per year. From this amount the small-scale CHP plants might stand for 20%.

### 3.2.5 Pelletization plants

Electricity is one of the most important energy carriers for space heating and hot water in detached houses. During 2010, electricity delivered 16 TWh to the residential sector (Energimyndigheten, 2013). After electricity, biofuels are the most important energy carriers. Around 12 TWh of biofuels (wood chips, sawdust, pellets and wood logs) were used in 2010.

The production and use of pellets has been increasing throughout the years as shown in Figure 3.13. At the beginning of the 1990s the available of surplus (and thus, cheap) residues for wood manufacturing industries helped to establish a market. This together with the increase in oil price and the implementation of the CO\textsubscript{2} tax has contributed to an increase in the demand of biofuels.

![Figure 3.13: Swedish pellets delivery (Swedish Association of Pellet Producers, 2013)](image-url)
Several pelletization plants have been installed in Sweden as a result of the increasing demand fuelled by the governmental policies implemented. From the 1990s, Sweden became a leading manufacturer of pellets mainly focused to cover the demand of a well-developed national pellet market. Pelletization plants have been installed as part of already existing CHP plants, sawmills, etc., as well as stand-alone facilities around the country.

The pelletization process is relatively straightforward as shown in Figure 3.14. Biomass residues (sawdust, shavings, etc.) are conveyed to a hammermill as shown in Figure 3.14 to achieve a uniform particle distribution. The milled product is dried down to a moisture content of 15%-20% (Klass, 1998). The dried product is fed to a pellet press where a ring shaped die generating a pressure between 5.5 and 27.5 bar (Klass, 1998). The pressure exerted should be high enough to raise the temperature of the biomass between 160 °C and 180°C (Klass, 1998). The lignin migrates to the pellet surface and creates a protective film that reduced the risk of the pellet to be affected by changes in the moisture content. The sieve cuts the pellet to the required length and then the pellet is ready to be packed.

![Figure 3.14: Wood pellet mill schematic (FFS Pellet Mill, u.d.)](image)

Pellets have seen an increase in the price throughout the years as shown in Figure 3.15. The price of wood fuels remained unchanged until the 2000s when the increased demand fostered and increase in competition for byproducts from the forest industry that were not used fully before.
The pellet market is divided in three sectors:

- **Large-scale**: this market is comprised of CHP plants mostly (boiler capacity > 5 MW). The possible use of other cheaper biofuels has become a reason of a decrease in the demand of pellets in this market but also the import of pellets from outside the EU. In 2005, 600,000 tons were delivered by Swedish producers to the large scale market. In comparison, during 2010 only 360,000 tons were delivered (PELLCERT, 2012).

- **Medium scale**: this market includes apartment buildings, small industries and small heating plants. The deliveries from Swedish pellet producers to this market was about 500,000 tons in 2010. The imported pellets mainly go to the large-scale market. Thus, this sector is currently the most interesting for Swedish pellet producers.

- **Small-scale**: this market is mostly comprised of detached houses. The increase in the use of pellets in this sector has been fostered by incentives to convert existing oil boilers to pellets. This market expanded significantly in the period 2004-2007 (PELLCERT, 2012). The cold winter of 2010, increased the deliveries of this sector for about 100,000 ton (PELLCERT, 2012).
4 Technical Assessment of Palm Oil Based Polygeneration Plants in Colombia (Papers I, II, III)

This chapter summarizes the main results presented in Papers I – III, which considered the use of palm oil solid residues for energy applications. The papers focused on a case study representative of the palm oil processing sector in Colombia and the most relevant results are presented in this chapter.

The solid waste from the palm oil extraction process could represent an important resource for the production of industrial heat, cooling, heating, biodiesel, densified biofuels and electricity as discussed in Chapter 2. The papers analysed the technical feasibility of different solutions to sustainable manage the solid waste from a typical palm oil mill in Colombia. The utilization of palm oil solid residues and its potential was analysed by considering different conversion technologies and different products, namely electricity, process heat, biodiesel and pellets. Different conversion technologies and schemes were simulated and analysed with emphasis in the use of solid residues and electricity generation. So far the polygeneration possibilities in the Colombian palm oil industry have not being investigated, particularly the production of densified biofuels for the solid residues generated on site. Furthermore, the conversion of palm oil into biodiesel has not been integrated so far in the palm oil processing mills and thus, it offers a unique possibility to increase the use of the solid residues and also the efficiency of the plants.

This study focuses on these new areas by using a selected case study representative of the Colombian palm oil industry. Through this analysis, the opportunities of increasing energy efficiency in the agroindustrial sector in Colombia by using onsite generated residues are highlighted. The alternatives proposed in this chapter and Papers I - III could help in the reduction of the industry’s greenhouse gas emissions by fostering energy savings in the sector thus, helping to reduce the environmental footprint of this industry.
4.1 Palm Oil Mill Process Analysis

The technical analysis was done in a palm oil mill with a processing capacity of 30 ton FFB/h located in Colombia. According to Colombian National Federation of Oil Palm Growers (FEDEPALMA) this capacity is representative of the Colombian industry (Yáñez Angarita, 2008).

The plant produces about 10.5 ton of solid residues per hour. The POM uses the fibers to produce saturated steam for the extraction of palm oil. Shells are sold to a nearby industry, part of the EFB is used form mulching in the plantation and the rest is left to decay (see Figure 4.1). Currently, the electricity required for the palm oil extraction is provided by the national grid. Thus, there is a wasted energy potential in the process that can be efficiently used through different polygeneration configurations.

![Figure 4.1: POM current configuration](image)

The mill was analysed in terms of energy consumption, current production methods and fuel consumption. Currently, the electricity required for the palm oil extraction is provided by the national grid. Thus, there is a wasted energy potential in the process that can be efficiently used through different polygeneration configurations. Some of the most important POM characteristics used in this study are shown in Table 4.1. Based on the needs and residues available different alternative configurations were considered and evaluated in terms of improved energy efficiency in the system, reduction and possible delivery of excess electricity to the grid and reduction of CO$_2$ emissions related to electricity consumption.
4.2 Energy models

The assessment of the polygeneration possibilities from palm oil residues was evaluated under different conditions and it was also considered establishing a priority in one of the main products (e.g. electricity, biodiesel). The analysis was done using Aspen Utilities Planner®. For that purpose, different configurations were considered as shown in Figure 4.2. In this figure the different paths for fuel utilization are shown as well as possible variations in the equipment to be selected as prime movers to enable a more robust analysis. Further details are available in papers I-III including assumptions and other considerations.
Table 4.2 summarizes the alternatives analysed considering different degrees of integration and residue utilization in the chosen POM. The first five alternatives deal with pelletization and the remaining alternatives (highlighted in grey) include biodiesel production. Additional generation of electricity using biodiesel was also considered in this analysis keeping in mind the contribution that this industry could have in the development of regions not connected to the national electricity grid and also the possible replacement of fossil diesel with biodiesel in these regions.

A complete description of the different alternatives considered for the use of solid residues for energy purposes are available in papers I and II.
Table 4.2: Summary of the configurations considered

<table>
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<tr>
<th>Case study</th>
<th>Back-pressure steam turbine</th>
<th>Extraction steam turbine</th>
<th>Backpressure-condensing steam turbine</th>
<th>EFB Pelletization</th>
<th>Fibers and shells</th>
<th>Treated EFB fuelling steam cycle</th>
<th>EFB gasification + electricity generation</th>
<th>Biodiesel</th>
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<td>2: 50% of the biodiesel is used for electricity production, 50% of the biodiesel is sold</td>
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For the proposed case studies, a classical thermodynamic assessment was performed to analyse the alternatives in order to reduce the solid wastes from the oil extraction process. For this analysis it was assumed that:

- Drying is included in the pelletization plant as a complete pretreatment process.
- The gasifier model is a downdraft type.
- The net electricity generation, $E_{el,net}$, is given by:

$$E_{el,net} = E_{el,ICE} + E_{el,steam \, turbine} - E_{fw,pump} - E_{el,gran} - E_{el,ham} - E_{el,pelt} - E_{el,POM} - E_{el,md} \quad (4.1)$$

Where $E_{el,ICE}$ is the internal combustion engine power output, $E_{el,steam \, turbine}$ is the steam turbine power output, $E_{fw,pump}$ is the feedwater pump power consumption, $E_{el,gran}$ is the granulator power consumption, $E_{el,ham}$ is the hammermill power consumption, $E_{el,pelt}$ is the pelletizer power consumption, $E_{el,POM}$ is the POM power consumption and $E_{el,md}$, is the biodiesel plant power consumption.

- The net electrical efficiency, $\eta_{el,net}$, is defined as

$$\eta_{el,net} = \frac{E_{el,net}}{(m_{EFB,61\%}LHV_{EFB,61\%}) + (m_{fib,32\%}LHV_{fib,32\%}) + (m_{shell,11\%}LHV_{shell,11\%}) + (m_{bd,el}LHV_{bd})} \quad (4.2)$$

Where $m_{EFB,61\%}$, $m_{fib,32\%}$, $m_{shell,11\%}$ and $m_{bd,el}$ are the mass flow of EFB, fibers, shells and biodiesel respectively. $LHV_{EFB,61\%}$, $LHV_{fib,32\%}$, $LHV_{shell,11\%}$ and the $LHV_{bd}$ are the low heating value of the EFB, fibers, shells and biodiesel respectively.

- The thermal efficiency, $\eta_{th}$ is given by

$$\eta_{th} = \frac{Q_u}{(m_{EFB,61\%}LHV_{EFB,61\%}) + (m_{fib,32\%}LHV_{fib,32\%}) + (m_{shell,11\%}LHV_{shell,11\%}) + (m_{bd,el}LHV_{bd})} \quad (4.3)$$

Where $Q_u$ is the useful heat.
• The energy utilization factor, $EUF$, is defined as

$$EUF = \eta_{th} + \eta_{el} \quad (4.4)$$

• The power-to-heat ratio, $\alpha$, is as follows

$$\alpha = \frac{E_{el,net}}{Q_u} \quad (4.5)$$

• The moisture content in the EFB, $MC_{EFB, out}$, after the steam dryer depends on the EFB mass flow, $m_{EFB, in}$; its moisture content, $MC_{EFB, in}$ and the water removed from the EFB, $m_{wat, EFB}$ as follows

$$MC_{EFB, out} = \frac{m_{EFB, in} MC_{EFB, in} m_{wat, EFB}}{m_{EFB, in} m_{wat, EFB}} \quad (4.6)$$

• The emissions are calculated based on the emissions avoided due to the displacement of grid power in Colombia, $E_{el, net}$ and the associated reduction credits for displacement of grid power, $R_{CO2}$. In this term

$$CO_2 \text{ emissions} = E_{el, net} \times R_{CO2} - E_{methanol} - \cdots \quad (4.7)$$

$$\cdots + E_{biodiesel}$$

4.3 Case studies and selected results (Papers I and II)

The results from the analysis show that palm oil residues can contribute significantly in the production of electricity and process heat. They can also be used as fuel in a compact form like pellets which allows easy distribution and storage or support the production of biodiesel from palm oil. In most of the cases, the POM becomes completely self-sufficient in terms of energy requirements. Only when just a pelletization plant is added (and no other modifications) as well as when all EFB is pelletized and a palm oil is converted to diesel the plant will not be self-sufficient as shown in Figure 4.3. Otherwise the suggested configurations could contribute with up to 8 MW of electricity to the grid from palm oil residues. If the biodiesel produced is also used for electricity production then the contribution to the national grid is higher.
The Colombian regulations for cogeneration, defined in the Resolution CREG005-2010 (CREG, 2010), state that equivalent electrical performance, \( \text{REE} \), should be higher than those specified in Table 4.3.

<table>
<thead>
<tr>
<th>Fuel Used</th>
<th>REE [%]</th>
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<tbody>
<tr>
<td>Natural Gas</td>
<td>53.5</td>
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<tr>
<td>Coal</td>
<td>39.5</td>
</tr>
<tr>
<td>Fuel Oil API &lt; 30</td>
<td>30.0</td>
</tr>
<tr>
<td>Fuel Oil API &gt; 30</td>
<td>51.0</td>
</tr>
<tr>
<td>Bagasse and other sugarcane residues</td>
<td>20.0</td>
</tr>
<tr>
<td>Other agricultural fuels</td>
<td>30.0</td>
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</tbody>
</table>

The equivalent electrical performance should be calculated according to the following expression:

\[
\text{REE} = \frac{E_{\text{gross}}}{E_{\text{fuel}} - \frac{Q_{u}}{\text{ref,CL}}} \times 100 \quad (4.8)
\]

Where:

- \( E_{\text{gross}} \) is the gross electricity produced by the plant in kWh
- \( E_{\text{fuel}} \) is the energy from the fuel expressed in kWh and calculated
using the low heating value

\( Q_u \) is the useful heat employed in the process, expressed in kWh

\( \eta_{\text{ref},\text{CU}} \) is the reference value for the useful heat given by the CREG as 0.9

Based on this definition, the different alternatives were evaluated and as it can be seen from Figure 4.4 only seven of them comply with the specifications included in the resolution by CREG. Three cases are independent of this regulation as they require power from the grid (pelletization cases 3 and 4 and biodiesel case 4a). From the purely industrial cogeneration alternatives (biodiesel cases 1 a-c) only the option with an extraction turbine is more close to the 30% REE limit.

![Figure 4.4: REE of the palm oil case studies](image)

In terms of greenhouse gas emission reductions, although not all components are accounted for (e.g. methane emissions from EFB decay, emissions from palm oil plantations, etc.); the purpose was to have an estimate the amount that could be saved by direct substitution of electricity and diesel. Figure 4.5 shows the reduction in emissions for the different alternatives considered. The greatest reduction is achieved when using biodiesel for electricity production or diesel substitution. However, the most effective case is when all the mill waste outputs (fibers, shells, EFB and biogas) are used to replace fossil energy coming to the mill or used outside the mill.
Figure 4.5: CO$_2$ emissions reductions of the different polygeneration alternatives
This chapter summarizes the main results of papers IV through VI which considers the possible upgrade and optimization of existing biomass district heating plants and other wood-based industries to produce electricity, process heat, district heating and other biomass products.

When dealing with biomass-based energy systems, several aspects have to be taken into account simultaneously to analyse possible alternatives and implementation scenarios. Conflicting aspects such as cost, performance and resource availability are commonly included in the analysis. Biomass is considered as a CO$_2$ neutral resource and thus, the emissions aspect is not included directly in the analysis. In the Swedish case, the implementation of emission taxes since 1991 has helped to switch from fossil fuel to biomass in the district heating sector and also in the cogeneration sector. This has been further reinforced with the introduction of electricity certificates in 2003. Thus, a thermoeconomic optimization considering cost, performance, resource availability and market incentives is very valuable. As explained by Li et al. (2006) there is no single optimum point for all objectives and thus, a trade-off between different optimization objectives needs to be considered.

The core of the optimization is the objective function. Pelster et al. (Pelster, et al., 2000) used a single environomic function that included economic parameters as well as environmental parameters.

However, the possibility to evaluate the trade-off between different economic parameters or objective functions using multiobjective optimization gives a better understanding to decision makers and allows them to choose the most suitable design under certain constrains. The multiobjective optimization provides the required number of Pareto points for selection resulting in decision variable values. The decision maker then is presented with a set of optimum designs for the given
optimization problem and constraints, represented by the Pareto front. The solutions on the Pareto optimal front represent optimal solutions in the sense trying to improve the value of one of the objective functions will not lead to an improvement of the value of the other objective functions. Thus, identifying a set of Pareto optimal solutions is the key for the decision maker selection of a compromise solution satisfying the conflicting objectives as “best” possible. In the case of multiobjective optimization, evolutionary algorithms are appropriate as solving methods they deal simultaneously with a set of possible solutions (the so-called population). This methodology has several advantages including the evaluation of the population in a single run including the identification of several Pareto optimal points. Also, genetic algorithms are not influenced in a large extent by the shape or continuity of the Pareto front.

In energy optimization problems, the cost aspect plays the deciding role in determining systems for electricity generation as well as in the choice of the primary energy.

For integrating technical and economic considerations, the costs of investment and operation can be modelled simultaneously with the thermodynamic system model. Environmental considerations could be integrated through the concept of external pollution costs or other policy mechanisms (e.g. electricity certificates, environmental taxes, etc.). Integrating them into a model as additional cost factors is a form of internalization. For the simultaneous modelling and optimization of energy system configuration and design, the options are modelled in a so-called superconfiguration that combines different configurations into a single model in which different cycle/component alternatives can be considered.

This gave as a result a global optimum for a specific configuration. However, this limited the possibilities of choosing different design conditions. Thus, a multiobjective optimization algorithm was used. This allowed to compare a cost objective function (e.g. levelised electricity cost) against an environmental performance function (e.g. avoided CO\textsubscript{2} emissions) and allows decision makers to have a better perspective of the effects of the different design configurations. The cost and environmental objective functions are optimized using genetic algorithms with respect to a set of independent variables and subject to a set of equality and inequality constraints. The use of multiobjective optimization with genetic algorithms is especially attractive, since this approach allows for a handful of optimal solutions to be identified from a very large set of possible alternatives. This methodology offers to the technical decision-maker a tool for system development and operation
that simultaneously determines the optimum system configuration, design and operational mode for the system.

5.1 Optimization model

The thermodynamic analysis used in the multi-objective optimization was performed using Aspen Utilities®. Aspen Utilities® is a utility system management tools that rigorous process simulation and includes a library of models that has been developed for utility consuming systems.

The designs generated by the evolutionary algorithm in MATLAB were evaluated thermodynamically using Aspen Utilities® which returns the required parameters for the economic evaluation (see Figure 5.1). It was not possible to perform this evaluation directly as it is not possible to integrate directly ASPEN Utilities® and MATLAB. Thus, a modified ActiveX component and a Visual Basic macro were used in order to enable the interaction of both programs through Microsoft Excel. For this methodology, Microsoft Excel was used as a communication bridge between both programs facilitating the thermodynamic evaluation of the population created by MATLAB.

![Figure 5.1: Optimization methodology](image)
The size and the operating conditions of selected equipment are optimized in this step. These variations and results are integrated in the genetic algorithm based multi-objective optimizer in MATLAB highlighting Pareto-optimal power plant configurations and facilitating trade-off studies considering the performance indicators selected for the optimization. The genetic algorithm optimization in Matlab deals with the minimization of multiple objectives functions given a set of linear or nonlinear constrains. The solver identifies a Pareto front that describes the trade-off between the objective functions (e.g. levelised electricity cost, CO2 emissions, etc.). Each point in the Pareto front corresponds to an optimal configuration and it gives the optimal design parameters. This offers certain flexibility to the decision maker or designer to help the assessment and decision making under certain economic and environmental constrains. This method when used to assess a large number of options, can also be used by to identify the most efficient use of a renewable resource or the most cost-effective measures to promote efficient and environmentally sound energy solutions. Evolutionary algorithms are used to solve multiobjective problems mainly due to the population-based nature of the algorithm itself that allows the generation of several Pareto optimal solutions in a single run. Additionally, the complexity of some multiobjective optimization problems makes difficult the use of other techniques.

The objective functions are decided based on the assessment to be performed. The main goal of these models is to evaluate the effects that the thermodynamic conditions and the size of the equipment could have on the proposed configuration, including possible benefits of including additional refined products.

5.1.1 Performance indicators

There are several indicators used to quantify the performance of the alternatives assessed. In the performance evaluation of the different designs technical, economic and environmental performance indicators are used. As part of the technical performance indicators the net power output, thermal and electrical efficiency and power-to-heat ratio, are among the most commonly used. In several cases they might be selected as one of the objective functions.

Among the economic performance indicators the investment cost, levelised electricity cost and net present value are commonly used. The investment cost required to build the plant is a key economic indicator used to calculate other economic indicators. Mathematical functions
have been proposed to calculate approximately the cost of the different plant components as suggested by Pelster (Pelster, 1998), Sicilia and Keppler (Sicilia & Keppler, 2010), Bejan (Bejan, et al., 1995) and Uslua et al (Uslua, et al., 2008). The Levelised Electricity Cost (LEC) on the other hand is a function of the investment cost (C_{inv}), the fuel cost (C_{fuel}), the operation and maintenance cost (C_{O&M}) and the net annual electricity production (E_{el,net}*t_{op})

\[
LEC = \frac{(f_{cr}C_{inv})+C_{fuel}+C_{O&M}}{(E_{el,net}*t_{op})} \tag{5.1}
\]

Where f_{cr}, the annuity factor, depends on the lifetime of the plant (n), the interest rate (i) and the annual insurance rate (k_i) is 1%.

\[
f_{cr} = \frac{i(1+i)^n}{(1+i)^{n-1} + k_i} \tag{5.2}
\]

However, cogeneration plants and polygeneration plant do not just meet the electrical demand but also supply district heat and other products. In that case, the Levelised district Heating Cost (LHC) is defined in the same way as the LEC with the difference that the net electricity production is replaced by the heat load, Q_{u,PG} in the equation.

\[
LHC = \frac{(f_{cr}C_{inv})+C_{fuel}+C_{O&M}}{(Q_{u,PG}*t_{op})} \tag{5.3}
\]

5.2 Energy models analysis and system boundaries

System component efficiencies are usually controlled at industrial level but measuring and controlling the installed system efficiency is less frequent, even though it might have a greater impact on emissions reduction. As a result, the definition of the boundaries plays a critical role (Tanaka, 2008).

The scope of this analysis is given by the activities at the forest site, once the final felling is performed. This has been a common practice in Sweden and Finland despite a growing interest in harvesting of fuel wood in the form of whole-trees or tree-sections (Richardson, et al., 2002). The analysis starts with forest products (pulp wood and timber) and residues (fuel wood) at a clear-cut and ends with final products in the form of energy carriers (wood chips, ethanol, lignin, heat, power and pellets) or materials (paper and timber) ready for its final use in diverse applications (Figure 5.2). The forest-fuel systems examined and compared by Eriksson (2008) were used for the purpose of this study.
according to the processes described below. The term logging is hereby used to describe a range of forestry or activities from cutting to loading of trees or logs onto purpose-built trucks.

Figure 5.2: Simplified biomass source-to-product chain
5.2.1 Superconfiguration model and reference plants

In order to simultaneously model and optimize the synthesis aspects of the cycles considered, the concept of a superconfiguration was used to allow the technoeconomic and environmental optimization of different schemes to be evaluated. The superconfiguration combines different configurations, into a single model. In order to analyse different alternatives two reference plants were used as validating the models in Aspen Utilities®. The two plants, Härnösand and Tranås, were identified in Paper IV (Salomón et al. (2011)). They were selected based on the different performance characteristics (e.g. boiler fuel input, flue gas condensing) and their characteristics are listed in the following sections.

5.2.1.1 Härnösand CHP Plant

Härnösand combined heat and power plant was taken into operation on the beginning of the year 2002 and it produces district heat and power for the town of Härnösand. The CHP plant in Härnösand produces 11.7 MW\textsubscript{e} electricity and 26 MW district heat. In addition to this the flue gas condensing in the power plant produces about 7.3 MW heat. The fuels used at Härnösand are wood fuels (forest residues, bark, sawdust) and peat. Oil is used as a startup fuel.

The boiler in Härnösand is a BFB type (Fortum) with a sand bed. The average bed temperature is 870°C. During the start up the bed sand is heated with oil firing to 350°C before the fuel feeding can be started. When the bed temperature has reached 600°C the oil firing is shut down. The oil firing cannot be used during normal operation e.g. to upgrade steam values.

Air is fed into the boiler as fluidization air from the bottom of the boiler and as secondary and tertiary air from the upper parts of the boiler. NO\textsubscript{x} emissions are controlled with SNCR. The NaOH can be injected to the boiler with two different injection stages but these stages are never used simultaneously. The higher stage is used during the high boiler loads and the lower one during low loads. With this SNCR the NO\textsubscript{x} emissions can be kept under the required 50 mg/MJ. The estimated NH\textsubscript{3} slip from the SNCR is 12 ppm.

The boiler produces high-pressure steam (90 bar, 510°C and 14 kg/s) which is injected to a back pressure turbine (Ahlstom). The pressure between the two stages of the turbine is 10 bars and the back pressure is 0.4 bars. After the turbine the steam is condensed with a district heating
heat exchanger. The temperature of the district heating water coming from district heating network is > 50°C and the temperature of the water leaving to the network is 75-120°C. The accumulator at the power plant can store heating water for two hours’ demand.

The condensed steam from the district heating heat exchanger is injected into a feedwater boiler. The pump after the feedwater boiler rises the water temperature above 90 bars (approx. 96 bars) to ensure a good injection through two economizers and into the boiler.

After the BFB boiler the flue gases are cooled down with superheaters, economizers and air preheaters. The flue gas temperature after the heat exchangers is around 130-140°C. In this temperature the flue gases are cleaned first in multicyclone and then in a fabric filter. After the dust removal the flue gases are condensed with flue gas condensing (Fagersta Energetics) and an additional 7.3 MW heat is produced for district heating. The flue gas temperature before the stack is then around 126°C. The minimum load allowed in the power plant is around 7 MW heat. A summary of the plant main characteristics is shown in Table 5.1.

| Table 5.1: Härnösand CHP plant characteristics used for the reference model |
|--------------------------|--------|
| Electricity generation (MW<sub>e</sub>) | 11.7   |
| District heating production (MW<sub>th</sub>) | 26     |
| Electrical efficiency (%) | 28     |
| Fuel input (MW) | 42     |
| Total efficiency (%) | 90     |
| Fuel used | wood and peat |
| Boiler type | BFB |
| Steam values | 14 kg/s, 510°C, 90 bar |
| Flue gas condensation | 1-stage |
| Emission control | SNCR, multicyclone, fabric filter |
| Emissions | NO<sub>x</sub> < 50 mg/MJ<sub>fuel</sub>, particles 35 mg/m<sup>3</sup>n(11%CO<sub>2</sub>), SO<sub>2</sub> < 100 mg/MJ, CO < 90 mg/MJ, N<sub>2</sub>O < 20 mg/MJ |
| Start up year | 2002 |

5.2.1.2 Tranås CHP Plant

Tranås CHP plant is a small-scale CHP plant that delivers the required heat to the district heating system in Tranås. The plant uses a BioGrate boiler which is characterized by its fuel flexibility. The BioGrate is a rotating grate with a conical primary combustion chamber. The fuel is fed from underneath which is dried in the middle of the grate. After the
fuel is burned the ashes are collected at the edge of the grate in a space filled with quenching water. The plant operational conditions during the year are shown in Table 5.2 and the main design characteristics are shown in Table 5.3.

Table 5.2: Tranås CHP plant seasonal operation parameters

<table>
<thead>
<tr>
<th></th>
<th>Summer</th>
<th>Summer/Autumn</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler (MW)</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Flue gas condensing (MW)</td>
<td>3.1</td>
<td>2.7</td>
<td>1.6</td>
</tr>
<tr>
<td>District Heating (MW)</td>
<td>8.2</td>
<td>8.3</td>
<td>8.5</td>
</tr>
<tr>
<td>Turbine (MW)</td>
<td>1.7</td>
<td>1.6</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Table 5.3: Tranås CHP plant characteristics used for the reference model

| Fuel Input: MW       | 11.7   |
| Fuels used:          | sawdust, bark and other residues from the sawmills |
| Heat:                | 10.5 MW |
| Power:               | 1.7 MW |
| Electrical efficiency:| 14.5%   |
| Total efficiency:    | 104%   |
| Steam values         | 16 bar, 345 C, 3.4 kg/s |
| Startup year         | 2002   |

5.3 Case studies and selected results

Two case studies in Sweden were selected to be optimized. The first case was a sawmill considering possible expansions and diversification of its business by supplying district heat to a nearby community and by manufacturing wood pellets. The second case study selected was a district heating plant considering expanding its district heating network.
and also interested in the evaluation of additional products, namely electricity and pellets. The power plant models discussed and validated in the previous section were used in these two cases as based for the multiobjective optimization. For the sawmill plant, the Tranås plant model was used as a base for the modelling considering its characteristics and size. For the district heating plant case, the Härnösand plant was selected based on its size, operational characteristics and flue gas condensing availability (already existing in the district heating plant).

5.3.1 Optimization of a sawmill-based polygeneration plant (paper IV)

This case study considers the upgrading of a sawmill in Sweden to produce electricity/heat/pellets. The sawmill analysed has an annual capacity of 130’000 m³ of sawn wood. Different options for generating electricity and process heat (for the sawmill and for a district heating network) as well as densified biofuels were considered. For that, a unified modelling approach taking into account thermodynamic as well as economic and environmental aspects was used. The analysis was done using ASPEN Utilities and the MATLAB optimization toolbox.

In this case study the boundaries are set around the sawmill, pelletizer and CHP plant studied as shown in Figure 5.3. The biomass extraction and transportation stages were not included in the analysis and they have been suggested as part of the future work in chapter 7.

Figure 5.3: Sawmill polygeneration system boundaries
The Levelised Electricity Cost (LEC) was calculated as a function of the investment cost ($C_{inv}$), the biomass cost ($C_{bio}$), the maintenance cost ($C_{maint}$), the net annual electricity production and annuity factor ($f_{cr}$).

The lifetime of the plant ($n$) is assumed to be 25 years, the interest rate ($i$) is 7%, and the annual insurance rate ($k_i$) is 1%.

$$LEC = \frac{(f_{cr}C_{inv})+C_{bio}+C_{maint}}{(F_{el.net+t_{op}})}$$  \hspace{1cm} (5.4)

$$f_{cr} = \frac{i(1+i)^n}{(1+i)^n-1} + k_i$$  \hspace{1cm} (5.5)

The objective functions used in the optimization were the LEC and the use of raw forest biomass per year. The purpose was to minimize both objective functions and find a set of possible solutions from which decision makers can choose and which evaluates the economic and environmental performance of the solutions proposed. The LEC was selected to evaluate whether electricity produced was competitive in the Nordic electricity market. The biomass use on the other hand, was selected as one of the main objectives is to minimize the amount of virgin biomass so the different wood-related industries could be provided with this indigenous resource and avoid/minimize importing. The LEC calculated for the different cases considered in paper IV, was penalized by including the complete investment cost, fuel cost and maintenance cost. These were the most disadvantageous conditions to evaluate such performance and the outcome of this assumption is clearly shown in the results obtained. However, a cogeneration/polygeneration plant is doing more than covering an electrical demand. In this case, the plant is producing district heat which otherwise needs to be supplied by an additional source. Thus, the appropriate method for calculating the LEC is considering what will be the cost of an auxiliary unit supplying the district heating load for the particular case. This means that the investment cost, fuel cost and maintenance cost should include this consideration. It has been suggested as future work to refine the objective function by subtracting the costs of an auxiliary unit.

The Pareto-optimal trade-off curve shown in Figure 5.4 considers the LEC and forest biomass use for case 1. This case is based on a business-as-usual model. In this case the sawdust and wood chips from the sawmill are sold to the market (current operation). The bark is used for the CHP plant as well as additional forest residues. The CHP plant also supports a pelletization unit that uses forest biomass to produce pellets.
The configurations located on the Pareto front in Figure 5.4 are the optimal selection for achieving the lowest LEC and at the same time avoid using unnecessary resource use. In particular, LEC depends on several factors namely the investment cost, net electricity production and biomass cost. Thus, a plant with lower steam data might have a lower investment cost but demands more fuel to cover the same demands and thus, the biomass cost will increase. This helps to choose the optimal configurations considering the variations specified for the decision variables. All these variations are included in the optimization process and only the best combinations are represented by the Pareto front.

![Figure 5.4: LEC and Forest Biomass Use - Case 1](image)

As shown in figure above the levelised electricity cost is relatively high and it is difficult to compete in an electricity market dominated by relative cheap energy sources such as hydropower and nuclear. The average electricity price in the NordPool during 2011 was 300 SEK/MWh (43.5 USD/MWh).

Another possibility considered was the use sawdust and wood chips from the sawmill in the pelletization process. Thus, no wood chips and sawdust are sold to the market. The Pareto-optimal trade-off curve for this case is shown in Figure 5.5.
In this second case, the tendencies are similar to case 1 as the only difference is whether the sawmill’s byproducts, namely sawdust and wood chips, are used in the pelletization process or sold to the market. The use of biomass is significantly decreased compared to case 1.

However, the levelised electricity cost is higher than the electricity price in the common Nordic electricity market and thus, it becomes difficult to compete. In spite of this, biomass polygeneration is still attractive for covering the internal electrical demand of the sawmill and pelletization plant.

The results shown that the sawmill has the capability to (i) supply its own energy needs; (ii) export between 0.4 and 1 MW of electricity to the grid; (iii) contribute with 5 to 6 MWth district heating and, (iv) produce 20,000 ton/y pellets.

5.3.2 Upgrade of a district heating plant into a polygeneration plant (paper V)

A possible upgrade of a municipal district heating plant to a polygeneration plant producing electricity, pellets, DH and process heat) was evaluated. The system boundaries (Figure 5.6) were set around the plant itself and thus, no analysis related with the forest area required as well as energy consumed and emissions generated during the extraction and transportation was included.
The objective functions used in the optimization were LEC and $C_{\text{inv}}$. The optimization algorithm was set to minimize both objective functions and find the possible optimum solutions in the form of a Pareto front which decision makers can evaluate. The optimum alternatives shown in the Pareto front include the technical, economic and environmental evaluation of the solutions proposed providing a thorough analysis. The investment cost was selected as a key objective for the decision makers.

The LEC was calculated as a function of the investment cost ($C_{\text{inv}}$), the biomass cost for electricity production ($C_{\text{bio}}$), the maintenance cost ($C_{\text{maint}}$), the net annual electricity production and annuity factor ($f_{\text{cr}}$).

The lifetime of the plant ($n$) is assumed to be 25 years, the interest rate ($i$) is 7%, and the annual insurance rate ($k_i$) is 1%.

$$\text{LEC} = \frac{(f_{\text{cr}} \cdot C_{\text{inv}}) + C_{\text{bio}} + C_{\text{maint}}}{(E_{\text{el,net}} \cdot t_{\text{op}})}$$ (5.6)

In the case of a CHP or polygeneration, the plant is supplying additional products besides electricity as explained by Horlock (Horlock, 1987). The biomass cost ($C_{\text{bio}}$) then should consider the cost of the fuel used in the cogeneration plant and the cost of the fuel used in the original DH plant. Thus the LEC for a polygeneration plant as the one proposed is defined as,
In the investment cost is included the cost of the boiler (Sicilia & Keppler, 2010), the cost of the steam turbine, the cost of the deaerator, the cost of the heat exchangers for the district heating as well as the cost of the pelletizer (Uslua, et al., 2008). The flue gas condensing unit and the heat exchanger used to preheat the DH water using the industrial process heat are assumed to be the already existing ones. The installation cost (20% of the equipment cost) and the contingency cost (10% of the equipment cost) were also added to the investment cost.

\[
LEC_{PG} = \left[ f_{cr} (C_{inv,PG} - C_{inv,DH} - C_{inv,pell}) + (C_{bio,PG} - C_{bio,DH} - C_{bio,pell}) + (C_{maint,PG} - C_{maint,DH} - C_{maint,pell}) \right] \ast \left( E_{el,net} \ast t_{op} \right)^{-1} \tag{5.7}
\]

The flue gas condensing unit and the heat exchanger used to preheat the DH water using the industrial process heat are assumed to be the already existing ones. The installation cost (20% of the equipment cost) and the contingency cost (10% of the equipment cost) were also added to the investment cost.

\[
C_{equip} = C_{boiler} + C_{turbine} + C_{DH} + C_{deaer} + C_{pell} \tag{5.8}
\]

\[
C_{inv} = C_{equip} + C_{install} + C_{cont} \tag{5.9}
\]

The investment cost for the different equipment has been transformed to 2011 USD using the Marshall and Swift cost index (Sinnott, 2005). Maintenance costs \(C_{maint}\) were assumed as 2% of the equipment cost (Kehlhofer, et al., 2009) and the insurance cost \(C_{ins}\) as 1% of the total investment cost. Other economic parameters that were considered are listed in Table 5.4.

<table>
<thead>
<tr>
<th>Economic parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity price (Energimyndigheten, 2012)</td>
<td>300 SEK/MWh</td>
</tr>
<tr>
<td>Electricity certificate (Statens energimyndighet, 2012-06-01.)</td>
<td>250 SEK/MWh</td>
</tr>
<tr>
<td>District heating price (Statens energimyndighet, 2012-06-01.)</td>
<td>800 SEK/MWh</td>
</tr>
<tr>
<td>Pellets market price (Statens energimyndighet, 2012-06-01.)</td>
<td>300 SEK/MWh</td>
</tr>
<tr>
<td>Return wood price</td>
<td>100 SEK/MWh</td>
</tr>
<tr>
<td>Wood chips price (Statens energimyndighet, 2012-06-01.)</td>
<td>200 SEK/MWh</td>
</tr>
<tr>
<td>Sawdust price (Uslua, et al., 2008)</td>
<td>45.9 SEK/m³</td>
</tr>
<tr>
<td>Bark price (Klugman, et al., 2009)</td>
<td>126 SEK/MWh</td>
</tr>
<tr>
<td>Exchange rate (SEK-EUR)</td>
<td>9 SEK/EUR</td>
</tr>
<tr>
<td>Exchange rate (SEK-USD)</td>
<td>6.7 SEK/USD</td>
</tr>
<tr>
<td>Plant life time (n)</td>
<td>25 years</td>
</tr>
<tr>
<td>Debt interest rate (i)</td>
<td>7 %</td>
</tr>
</tbody>
</table>
The production cost of district heat in a polygeneration plant could be expressed in the same way as the LEC.

\[
LHC_{PG} = \left[ f_{cr} (C_{inv,PG} - C_{inv,DH} - C_{inv,pell}) + (C_{bio,PG} - C_{bio,DH} - C_{bio,DH}) + (C_{maint,PG} - C_{maint,DH} - C_{maint,pell}) \right] \times (Q_{u,PG} \times t_{op})^{-1} \quad (5.10)
\]

The NPV was also calculated as another performance parameter for easier comparison of the different cases.

\[
NPV = \sum_{k=0}^{n} \frac{R_{el} + R_{DH} + R_{ind} + R_{pell} - C_{bio} - C_{main} - C_{ins}}{(1+t)^k} \quad (5.11)
\]

Where \( R_{el} \) are the electricity revenues, \( R_{DH} \) are the district heating revenues, \( R_{ind} \) are the industrial heat revenues and \( R_{pell} \) are the pellets revenues.

5.3.2.1 Electricity production

One of the alternatives analysed included only cogeneration with a possible increase in the DH capacity. The Pareto curve considering the investment cost and the LEC is shown in Figure 5.7.

![Figure 5.7: LEC, Cinv and NPV - Case 1](image)
The Pareto front in Figure 5.7 shows that the LEC is close to the electricity price in the market (without considering the electricity certificates). This CHP plant could compete in the Nordic electricity market considering the average electricity price of 300 SEK/MWh during 2011 with the additional benefits of the electricity certificates of approximately 250 SEK/MWh (see Table 5.4).

In the case that additional process steam is also produced in the plant then the results of the optimization are shown in Figure 5.8.

The main difference between case 1 and 2 is that additional steam is extracted from the turbine for industrial purposes (pelletization is not in the system boundaries considered). The relation between the two objective functions (i.e. LEC and Cinv) has the same tendency as for case 1.

It is important to mention that the original power plant used for this model does not have a high electrical efficiency and thus, an electrical efficiency ranging from 13% to 20% is expected considering the draw of useful steam from the turbine to the pelletization unit. Also, electricity production is limited by the fixed demand of district heating and process steam which makes difficult to increase production to larger plant sizes.

For the third case, a pelletization plant was suggested to be included to increase the operational hours of the plant with increased power
production for a restricted heat load. As more steam is drawn from the turbine this is directly reflected in the LEC and the electrical efficiency as shown in Figure 5.9. However, additional benefits such a producing other market valued products such as pellets are not shown directly in the figure.

As in case 1, for configurations with an LEC between 330 and 350 SEK/MWh the LEC, investment cost and electrical efficiency have the best trade-off. In this range the NPV does not varies considerably.
6 Discussion and Concluding Remarks

This chapter summarizes the potential of biomass residues for generating electricity, process heat, district heating and/or pellets. This has been done by covering various industries in different locations. The potential for polygeneration using solid residues from the palm oil industry in Colombia was assessed based on a specific case study. The selected palm oil mill is representative of the capacity in the Colombian national palm oil industry and thus, the results can be extended to the whole local industry. Also, the use of biomass residues in Sweden for polygeneration purposes was analysed through two case studies. The discussion and conclusions are summarized below.

6.1 Use of solid residues in the palm oil industry

The possibilities of improving the energy efficiency of palm oil mills that today operate based on electricity from the grid in Colombia have been investigated. The analysis was based on the use of solid residues for energy purposes. For that, different technology configurations were proposed based on the case of a small-scale palm oil mill in Colombia processing 30 ton FFB/h. The technology configurations include steam cycles using backpressure turbines, condensing-extraction turbines and gasification-gas engine cycles in hybrid configurations. The possibilities to produce pellets from the residues from palm oil were also analysed. All the analyses performed included a maximum of 60% of the EFB (empty fruit bunch) produced in the POM for energy purposes due to its value as natural fertilizer in the palm oil plantations. It was shown that palm oil solid residues have the possibility to supply the heat and power requirements of a standard Colombian mill. The residues can even support other processes such as pellet or biodiesel production as well as supply electricity to the national grid which has not been analysed previously for this industry in Colombia.

Different alternatives for the use of solid residues were considered based on the interest of the POM studied. The main objective was to cover the internal energy demand of the POM by utilizing the available residues. Gasification of pelletized residues was considered as well as conventional combustion. The use of the solid residues could deliver up to 9 MWe to
the national grid and cover the POMs internal demand. It could also save up to 30,000 tons CO$_2$/year of grid-related emissions.

If biodiesel is produced and used then the possible contribution to the national electricity grid and savings of greenhouse gas emissions is much higher. Although, POM’s prefer to stay in the main core of business, the incentives for biodiesel production have become very attractive and several of them are investigating the possibility of allocating part of the palm oil for biodiesel production. Biodiesel could be used either in the transportation sector (for B5 or B10) or for decentralized electricity generation. The latter could play an important role in rural development in sites near POMs with no access to the electricity grid (especially in the south part of the country). These POMs could supply the required biodiesel to replace costly diesel transported over long distances and at the same time helped with the reductions of emissions from burning fossil fuels.

This study showed the feasibility of producing EFB pellets and the possible integration of this manufacturing process in the already existing POM activities. This can open a new market for the POMs in Colombia which could support further energy efficiency projects. These options have not been considered previously for the palm oil industry in Colombia but have been proved to be technically feasible in this thesis. The final decision of implementing the alternatives considered will depend of the economic feasibility, national policies and international financing schemes.

Preliminary studies have shown that the suggested technical options might be associated to a significant capital investment with low returns. However, these options need to be considered in the specific context of Colombia. For example, the POM under study can become a cogenerator and could sell the electricity to any retail company. In addition, given the prominence of the palm oil industry in Colombia, environmental and social impacts are relevant and thus, any improvement in the use of the resources will have strong effect at national levels.

The manufacturing of different energy products in an integrated scheme has not been considered previously for Colombian palm oil mills thus offering a unique possibility for the implementation of energy saving measures in a growing industry. Previous studies have been focused on ethanol and biodiesel production, their potential, possibilities for expansion and environmental impacts however, they have not analysed the possibilities that solid residues could have in a more efficient palm oil industry and how they can contribute to provide the required energy for
this expansion in a more dynamic biodiesel market. Furthermore, the pelletization of EFB has not been considered so far in Colombia and as shown in Paper I and II it could have a strong impact in the plant economic performance.

6.2 Multiobjective optimization of biomass plants in Sweden

For the specific case of a sawmill in Sweden, different options for generating electricity and process heat (for the sawmill and for a district heating network) as well as densified biofuels were considered. For that, a unified modelling approach taking into account thermodynamic as well as economic and environmental aspects was used. The analysis was done using ASPEN Utilities and MATLAB optimization toolbox. The results shown that the sawmill has the capability to: (i) supply its own energy needs; (ii) export between 0.4 and 1MW of electricity to the grid; (iii) contribute with 5 to 6 MWth district heating and, (iv) produce 20,000 ton/y pellets.

The production of pellets helps to maintain the electricity production throughout the year when the district heating demand is lower. However, the LEC is higher than the electricity price in the common Nordic electricity market and thus, it becomes difficult to compete with low-cost electricity sources. Also the Swedish government has been trying to promote the replacement of fossil fuels in the transport sector which is the only sector solely dependent on oil. This has been done by promoting the use of ethanol, biogas and hybrid vehicles. Considering the scenario above certain industries have started to investigate the possibilities to use byproducts for energy purposes and to diversify their core business.

In addition to this the electricity production is limited by the fixed district heating demand which makes difficult to increase the generating capacity.

A CHP plant with flue gas condensing might perform better from the thermoeconomic viewpoint considering that it will have a higher alpha value. This case could be considered in an additional evaluation in future works.

The results are representative for sawmills in Sweden considering expanding the business. The focus of these industries has been until now in providing district heating to nearby communities or manufacturing pellets. The analysis done provides an insight of the opportunities and
limitations of an integration of all these processes in the framework set by the government of reducing the energy use of sawmills by 20%.

In the case of the district heating plant, it was considered the production of electricity and pellets. The evaluation is carried out by optimizing the alternatives from the economic, thermodynamic and environmental point of view. A detailed model of the process based on a genetic algorithm optimization was developed using ASPEN Utilities and MATLAB optimization toolbox. The main advantage of the methodology involving ASPEN and MATLAB is that employs two widely used and robust commercial software that allow the representation of the total industrial system. Also, the use of genetic algorithms to perform multiobjective optimization of non-linear problems include certain advantages such as finding multiple solutions in a single run, finding different Pareto-optimal solutions and solving the complexity of some multiobjective optimization problems.

The results showed that a modification of the current district heating plant could: (i) generate between 18 and 25 MWe, (ii) supply the steam demand of the 2 existing industries; (iii) cover an increase in the demand of up to 25 ton/h of district heating water and, (iv) produce 6500 ton/y pellets.

The production of pellets helps to maintain the electricity production throughout the year when the district heating demand is lower. The electricity production is limited by the fixed district heating and process steam demand which makes difficult to increase the power generating capacity even further.

The LEC in all the cases is competitive in the Nordic electricity market when the electricity certificates are considered. Since the LEC is focused on the cost side, it is not enough to make a decision as the average annual electricity price in the Nordic market can vary quite significantly. However, the electricity certificates help to harmonize the market conditions for renewable energy technologies and thus, it creates a competitive atmosphere for this type of investment. This assessment (also applied to the sawmill case previously discussed) has proven to be convenient while evaluating the feasibility of a new polygeneration plant by offering the possibility of comparing competing criteria and thus, providing a set of optimum solutions that allows investors or decision-makers to choose the best option considering the entire source-to-product chain. Furthermore, as all the designs considered are optimal, relevant design suggestions can be established for upgraded biomass power plants, specially district heating plants. The use of multiobjective optimisation to study possible upgrades to existing plants has been
revealed as a valuable and powerful approach. By analysing a Pareto optimal set of power plant designs, as opposed to a single configuration, the trade-offs between economic costs and environmental performance can be determined. The results also highlight the potential regarding industrial integration.

In summary, the case studies in Colombia and Sweden highlight the possible measures that could be considered to improve the industrial energy use, especially considering that industrial energy efficiency is one of the most important means of reducing the emissions of greenhouse gases. Higher energy prices are also an important factor in favor of energy efficiency measures as higher energy costs could affect negatively certain industries. In this case, savings measures could represent an important aspect for these industries to remain competitive. Of great importance are thus different means to promote energy efficiency in industries including technical and energy policy measures. However, cost-effective energy efficiency measures are not always undertaken and careful consideration is required before implementing them.

This thesis highlighted the potential that polygeneration solutions can have at industrial level both in high income and medium income countries. It considered what will be the outcome of the implementation of polygeneration schemes and use of solid residues from the industrial processes studied. It was shown that additional high-value products could be manufactured and thus, the competitiveness of these industries could be increased as well as the reduction of their greenhouse gas emissions. Thus, it was an important to identify the requirements of the industries and possibilities to become a net energy exporter. In the Colombian case, the effects from the implementation of polygeneration schemes using the processes’ solid residues could be quantified in terms of net energy exports and reduction of emissions. However, clear policies and complete economic analysis are required in order to consider the options proposed. In the case of the Swedish wood-based industries it is shown the advantages that energy policy and energy efficiency measures could have in the feasibility of such projects. Even though these industries have been improved and optimized throughout the years, it has shown in this thesis that there are still possibilities to become more efficient as long as the energy policy measures to encourage this are established.
7 Future Work

The work presented here has shown the potential of solid palm oil residues for electricity and process heat generation to support the palm oil extraction process as well as biodiesel conversion. The densification of some of the residues (i.e. pellets) as a value added product was also analysed and proven to be feasible from the technical point of view. However, a complete financial analysis is required before considering the alternatives proposed in this thesis as viable solutions. The effect that carbon certificates could have in the economic feasibility of the selected alternatives must be included and a sensitivity analysis considering both, the carbon certificates price as well as the electricity price should be performed.

Furthermore, the use of POME for electricity generation should be studied considering that the biogas is already being captured in palm oil processing plants. The use of this biogas for electricity generation, instead of being flared, could have a positive impact in the processing plant economy. In this analysis it should be considered that the most expensive work, covering the ponds and installing biogas extraction system, has been already performed in the Colombian mills. This analysis could serve to compare the economic performance of the alternatives for using solid residues and the biogas from POME. In consequence, this will allow deciding the best solution for electricity and process steam generation and also suggesting the best way to utilize the residues from the palm oil extraction process. A complete analysis of the energy needs and possible use of the residues generated by the plant will help in a long-term perspective to use more efficiently these underutilized resources by integrating different production processes and optimizing them.

The analysis done for the case studies in Sweden using forest residues considered the generation of additional heat, electricity or processed wood fuels under the current conditions. The results showed that it was possible to generate different products. However, the variable price of electricity in the Nordic market needs to be considered more in detail. As mentioned in the previous section, the average annual electricity price in the Nordic market can vary quite significantly and thus, a sensitivity analysis should be performed to account for these variations and realize
their effects. Even though, the electricity certificates help the financial performance of renewable energy technologies, the variation of electricity price can have a considerable impact in the feasibility of any plant or plant upgrade. Also, depending on the case considered, the biomass extraction and transportation stages should be considered as can have an important impact in the proposed solutions. Plant load variation throughout the year and optimized operational schemes depending on the season and market development should also be considered.

The use of the multiobjective methodology considered in this thesis for other biomass processes (e.g. pulp and paper, biogas, ethanol production, etc.) could show some potential niche activities that could help increasing the competitiveness of these industries. Thus, further analyses using this methodology are recommended as the whole source-to-product chain could be included.
8 References


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