Mittuniversitetet
MID SWEDEN UNIVERSITY

Thesis for the degree of Doctor of technology
Sundsvall 2014

GASIFICATION-BASED BIOREFINERY FOR MECHANICAL PULP MILLS

Jie He

Supervisors:
Prof. Per Engstrand
Asso. Prof. Wennan Zhang
Dr. Olof Björkqvist

FSCN - Fibre Science and Communication Network
Faculty of Science, Technology and Media
Mid Sweden University, SE-851 70 Sundsvall, Sweden

ISSN 1652-893X,
Mid Sweden University Doctoral Thesis 188
ISBN 978-91-87557-60-6

FSCN
PART OF MID SWEDEN UNIVERSITY

Akademisk avhandling som med tillstånd av Mittuniversitetet i Sundsvall framläggs till offentlig granskning för avläggande av teknologie doktorsexamen i kemiteknik, tisdagen den 20 maj 2014 klockan 09:15 i sal N109 Fälldinsalen, Mittuniversitetet, Sundsvall.
Seminariet kommer att hållas på engelska.

GASIFICATION-BASED BIOREFINERY FOR MECHANICAL PULP MILLS

Jie He

© Jie He, 2014

FSCN - Fibre Science and Communication Network
Faculty of Science, Technology and Media
Mid Sweden University, SE-851 70 Sundsvall, Sweden

Telephone: +46 (0)771-975 000

Printed by Service and Maintenance Office, Mid Sweden University, Sundsvall, Sweden, 2014

GASIFICATION-BASED BIOREFINERY FOR MECHANICAL PULP MILLS

Jie He

FSCN - Fibre Science and Communication Network
Department of Chemical Engineering
Mid Sweden University, SE-51 70 Sundsvall, Sweden
ISSN 1652-893X, Mid Sweden University Doctoral Thesis 188;
ISBN 978-91-87557-60-6

ABSTRACT

The modern concept of "biorefinery" is dominantly based on chemical pulp mills to create more value than cellulose pulp fibres, and energy from the dissolved lignins and hemicelluloses. This concept is characterized by the conversion of biomass into various bio-based products. It includes thermochemical processes such as gasification and fast pyrolysis. In thermo-mechanical pulp (TMP) mills, the feedstock available to the gasification-based biorefinery is significant, including logging residues, bark, fibre material rejects, bio-sludges and other available fuels such as peat, recycled wood and paper products. On the other hand, mechanical pulping processes consume a great amount of electricity, which may account for up to 40% of the total pulp production cost. The huge amount of purchased electricity can be compensated for by self-production of electricity from gasification, or the involved cost can be compensated for by extra revenue from bio-transport fuel production. This work is to study co-production of bio-automotive fuels, bio-power, and steam via gasification of the waste biomass streams in the context of the mechanical pulp industry. Ethanol and substitute natural gas (SNG) are chosen to be the bio-transport fuels in the study. The production processes of biomass-to-ethanol, SNG, together with heat and power, are simulated with Aspen Plus. Based on the model, the techno-economic analysis is made to evaluate the profitability of bio-transport fuel production when the process is integrated into a TMP mill.

The mathematical modelling starts from biomass gasification. Dual fluidized bed gasifier (DFBG) is chosen for syngas production. From the model, the yield and composition of the syngas and the contents of tar and char can be calculated. The model has been evaluated against the experimental results measured on a 150

KWth *Mid Sweden University* (MIUN) DFBG. As a reasonable result, the tar content in the syngas decreases with the gasification temperature and the steam to biomass (S/B) ratio. The biomass moisture content is a key parameter for a DFBG to be operated and maintained at a high gasification temperature. The model suggests that it is difficult to keep the gasification temperature above 850 ℃ when the biomass moisture content is higher than 15.0 wt.%. Thus, a certain amount of biomass or product gas needs to be added in the combustor to provide sufficient heat for biomass devolatilization and steam reforming.

For ethanol production, a stand-alone thermo-chemical process is designed and simulated. The techno-economic assessment is made in terms of ethanol yield, synthesis selectivity, carbon and CO conversion efficiencies, and ethanol production cost. The calculated results show that major contributions to the production cost are from biomass feedstock and syngas cleaning. A biomass-to-ethanol plant should be built over 200 MW.

In TMP mills, wood and biomass residues are commonly utilized for electricity and steam production through an associated CHP plant. This CHP plant is here designed to be replaced by a biomass-integrated gasification combined cycle (BIGCC) plant or a biomass-to-SNG (BtSNG) plant including an associated heat & power centre. Implementing BIGCC/BtSNG in a mechanical pulp production line might improve the profitability of a TMP mill and also help to commercialize the BIGCC/BtSNG technologies by taking into account of some key issues such as, biomass availability, heat utilization etc.. In this work, the mathematical models of TMP+BIGCC and TMP+BtSNG are respectively built up to study three cases:

1) scaling of the TMP+BtSNG mill (or adding more forest biomass logging residues in the gasifier for TMP+BIGCC);
2) adding the reject fibres in the gasifier;
3) decreasing the TMP SEC by up to 50%.

The profitability from the TMP+BtSNG mill is analyzed in comparison with the TMP+BIGCC mill. As a major conclusion, the scale of the TMP+BIGCC/BtSNG mill, the prices of electricity and SNG are three strong factors for the implementation of BIGCC/BtSNG in a TMP mill. A BtSNG plant associated to a TMP mill should be built in a scale above 100 MW in biomass thermal input. Comparing to the case of TMP+BIGCC, the NR and IRR of TMP+BtSNG are much lower. Political instruments to support commercialization of bio-transport fuel are necessary.

Keywords: Gasification, Mechanical Pulping, Biofuels, Power Generation, Biomass Residues, ASPEN Plus

TABLE OF CONTENTS

ABSTRACT ..... **II**

TABLE OF CONTENTS ..... **IV**

LIST OF PAPERS ..... **VI**

AUTHOR'S CONTRIBUTIONS ..... **VII**

ABBREVIATIONS ..... **VIII**

1 INTRODUCTION **1**

1.1 OBJECTIVES 3
1.2 CONTENT DESCRIPTION 5

2 BACKGROUND **6**

2.1 DFBG 6
2.2 BIOMASS-TO-ETHANOL 9
2.3 TMP+BIGCC 11
2.4 TMP+BTSNG 13

3 PROCESS AND MODELING **15**

3.1 DFBG 15
3.1.1 DFBG *15*
3.1.2 Simulation *17*
3.2 BIOMASS-TO-ETHANOL 19
3.2.1 Process *19*
3.2.2 Evaluation *20*
3.3 TMP+PM 21
3.4 TMP+BIGCC 23
3.4.1 BIGCC *23*
3.4.2 Simulation *25*
3.4.3 Economic evaluation *26*
3.5 TMP+BTSNG 28
3.5.1 BtSNG *28*
3.5.2 Simulation *31*

3.5.3 Economic Evaluation *33*

4 RESULT AND DISCUSSION **35**

4.1 DFBG 35
4.1.1 Effect of temperature *35*
4.1.2 Effect of S/B *36*
4.1.3 Effect of biomass moisture content *37*
4.1.4 Effect of residence time *38*
4.2 BIOMASS-TO-ETHANOL 39
4.2.1 Ethanol production cost vs. plant scale *39*
4.2.2 Capital Investment *40*
4.2.3 Production cost contribution *40*
4.3 TMP+BIGCC 42
4.3.1 Implementation of BIGCC in a TMP mill *42*
4.3.2 Additional biomass *43*
4.3.3 Reject fibres to gasifier *44*
4.3.4 Improved electric energy efficiency of the TMP-line *46*
4.4 TMP+BTSNG 48
4.4.1 Implementation of BtSNG in a TMP mill *48*
4.4.2 Economics of scale *50*
4.4.3 Reject fibres to gasifier *51*
4.4.4 Improved electric energy efficiency of the TMP-line *53*

5 CONCLUSIONS **55**

6 FUTURE RESEARCH **58**

7 ACKNOWLEDGEMENTS **59**

8 REFERENCES **60**

LIST OF PAPERS

This thesis is mainly based on the following five papers, herein referred to by their Roman numerals:

Paper I Simulation of Biomass Gasification in a Dual Fluidized Bed Gasifier
J. He, K. Göransson, U. Söderlind and W. Zhang.
Biomass Conversion and Biorefinery 2 (2012), 1–10.

Paper II Review of Syngas Production via Biomass DFBGs
Göransson, U. Söderlind, J. He and W. Zhang.
Renew Sust Energ Rev 15(1) (2011), 482–92.

Paper III Techno-economic Evaluation of Thermo-chemical Biomass-to-Ethanol
J. He and W.N. Zhang.
Applied Energy 88 (2011), 1224–32.

Paper IV Techno-economic Evaluation of a Mechanical Pulp Mill with Gasification
J. He, P. Engstrand, O. Björkqvist and W. Zhang.
Nord Pulp Pap Res J 28(3) (2013), 349–57.

Paper V Bio-SNG Production in a TMP Mill in Comparison with BIGCC
J. He, P. Engstrand, O. Björkqvist and W. Zhang.
To be submitted to Applied Energy.

AUTHOR'S CONTRIBUTIONS

The author's contributions to the papers in the thesis are as follows:

Paper I Author's entire modelling work. The experimental measurement data to evaluate author's mathematic model were obtained by Kristina Göransson and Ulf Söderlind.

Paper II Author has provided some information on the syngas cleaning-applied catalytic materials.

Paper III Author's entire modelling work.

Paper IV Author's entire modelling work. Supervisors provided the required operation data both on biomass gasification and on mechanical pulping.

Paper V Author's entire modelling work. Supervisors provided some required data both on biomass gasification and on mechanical pulping.

ABBREVIATIONS

bdt	bone dry tonne
BFB	Bubbling Fluidized Bed
BIGCC	Biomass Integrated Gasification Combined Cycle
bio-SNG	SNG produced from biomass
BtDME	Biomass to DME
BtSNG	Biomass to SNG
BTL	Biomass to Liquid Fuels
CFB	Circulating Fluidized Bed
CHP	Combined Heat and Power
CIGCC	Coal Integrated Gasification Combined Cycle
CNG	Compressed Natural Gas
CPD	Chemical Percolation Devolatilization
CTMP	Chemithermomechanical Pulp
CTU	Clean Technology Universe
daf	dried and ash free
DD	Double Disc
DDB	Double Declining Balance Depreciation Method
DFBG	Dual Fluidized Bed Gasifier
DH	District Heating
DME	Dimethyl Ether
ESP	Electrostatic Precipitators
FB	Fluidized Bed
FSCN	Fibre Science and Communication Network
FT	Fischer-Tropsch
GHG	Greenhouse Gas
H&P	Heat and Power
HTDD	High Temperature Double Disc Refiner
IGCC	Integrated Gasification Combined Cycle
IGHATC	Integrated Gasification Humid Air Turbine Cycle
IRR	Internal Rate of Return
LC	Low Consistency
LHV	Lower Heating Value
MIUN	Mid Sweden University
MTBE	Methyl Tertiary-butyl Ether
NR	Net Revenue

O&M	Operation and Maintenance Cost
PFI	Pulp and Paper Research Institute
PGW	Pressurized Groundwood
PM	Papermaking
PSA	Pressure Swing Adsorption
PSI	Paul Scherrer Institute
RME	Rapeseed Methyl Ester
ROR	Rate of Return
RTS	High Temperature Refiner, High rpm R—Lower Retention T—Higher Temperature S—Higher Refiner Disc Speed
SD	Single Disc Refiner
SEC	Specific Electricity Consumption
SECR	Reduction of SEC, %
SGW	Stone Groundwood
SNG	Substitute Natural Gas
TMP	Thermomechanical Pulp
tpy	tonne per year
VOC	Volatile Organic Carbon
WH	Waste Heat

T	gasification temperature
S/B	steam to biomass mass ratio
M	biomass moisture content
τ	gasification residence time
d_P	biomass/char particle size
t	tonne
yr	year
hr	hour
Nm^3	normal cubic meter (0 ℃, 1.0 atm)

1 INTRODUCTION

TMP refining is a very energy-intensive process. Substantial improvement of electric energy efficiency in refining is needed in order to secure a long term operation of many TMP mills. With rapidly growing energy costs the problem of high energy demand has become acute in recent years.

The present transport biofuels in the market are produced mainly from food crops, referred to as the 1st generation biofuels, which are not encouraged any longer. From the viewpoint of economics, environment, land use, water use, chemical fertilizer use, etc., however, there is a strong preference for the 2nd generation biofuels that are produced from woody, grassy materials as well as agricultural residues, municipal wastes and industrial wastes as the feedstock. Thus, the production of the synthetic transport fuels such as methanol, ethanol, dimethyl-ether (DME), Fischer-Tropsch (FT) fuel and SNG via gasification and synthesis is promising (Zhang 2010).

The *Fibre Science and Communication Network* (FSCN) is a multi-disciplinary research centre at *Mid Sweden University* (MIUN). FSCN is aiming for the improved profitability of mechanical paper and pulp industry and to find new ways to use the forest as a resource. An EU research project, *Forest as a Resource* (FORE), runs from 2011-01 to 2013-12 in FSCN, which deals with production of fibre-based products in synergy with extraction of materials, chemicals and bio-energy. The principle structure of the FORE concept is shown in Fig. 1.1.

Fig. 1.1: The concept of Forest as a Resource (FORE) with the role of biomass gasification

The work is included in the FORE-subproject *Gasification-based Biorefinery for Mechanical Pulp Mills*, where the bio-energy research group focuses on synthesis gas production for bio-automotive fuels. The group consists of Wennan Zhang, asso. Prof., Ulf Söderlind, Ph.D. student and research engineer, Kristina Göransson, Ph.D. student, Till Henschel, master student, and Jie He. The project has two tasks, 1) development of biomass to liquid (BTL) pilot plant and experimental test, 2) mathematic simulation of the BTL system and its application to the pulp industry. The author, Jie He, undertakes the 2nd task.

The bio-energy research group is included in Swedish Gasification Centre (SFC), a research centre with academic and industry cooperation supported by Swedish Energy Agency from 2011 to 2020. The research in SFC supports the Swedish industry for commercialization of bio-transport fuel production.

1.1 Objectives

International Energy Agency defines biorefinery as "the sustainable processing of biomass into a spectrum of marketable products (food, feed, materials and chemicals) and energy (fuels, power, heat)". The modern concept of "biorefinery" in the forest industry is dominantly based on chemical pulp mills to create more value than pulp fibres, and energy from the dissolved lignins and hemicelluloses. This concept is characterized by the conversion of biomass into various bio-based products. It includes thermochemical processes such as gasification and fast pyrolysis.

In mechanical pulp mills, the feedstock available to the gasification-based biorefinery is significant, and can be classified into five categories: 1) residues from the thinning and logging such as tree tops and branches (about 30% of the harvested trees); 2) bark, taking up 10–13% of the pulp wood flow; 3) reject fibres (deteriorate paper properties; 10–20% of the total pulp fibres); 4) wastewater treatment sludge from sedimentation or primary clarification operations and secondary/biological treatment operations; 5) other available fuels such as peat, the recycled wood, and paper products. This work is to study co-production of bio-automotive fuels, chemicals, bio-power, and steam via gasification in the context of the mechanical pulp industry. In particular, the aim is to study the possibility of commercializing conversion of the above-mentioned biomass residues into ethanol and SNG plus electricity and steam.

The production of various fuels and chemicals from biomass through the syngas platform in a biorefinery concept is illustrated in Fig. 1.2.

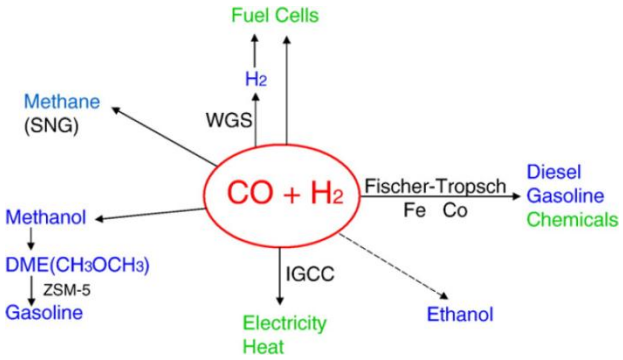


Fig. 1.2: Products from syngas

The indirect gasification technology has seen a rapid development in the last decade and several commercial plants for CHP production have been built. This technology can use inhomogeneous and moist biomass as a source for gasification. This means that this technology is a good candidate to be integrated into a mechanical pulping mill where the gasifier can utilize low quality fiber material and wood residuals from the pulp and paper production process. The specific objective in this study is to develop a set of mathematical models reliable for evaluating and optimizing the production lines from biomass to electricity and transport fuels. *The work includes:*

1. Developing a mathematic model to predict the performance of an indirect biomass gasifier. Tar evolution during gasification is taken into account. It is also significant to estimate how much extra biomass is needed to feed in the combustor to hold a normal gasification temperature level against the biomass moisture content;
2. Developing a mathematic model to evaluate a case in which BIGCC with efficiency close to 50% will be introduced into a TMP mill for electricity production, instead of CHP, with efficiency less than 30%, being introduced. An economic analysis will be conducted in 3 cases: 1) adding more forest biomass logging residues in the gasifier, 2) adding the reject fibres in the gasifier, and 3) decreasing the TMP-specific electricity consumption (SEC) by up to 50%;
3. Developing a mathematic model to perform a techno-economic evaluation of a process producing bio-ethanol from biomass via a gasification-synthesis pathway. Heat integration will be paid attention to;
4. Developing a mathematic model applied to evaluate a case in which a Biomass-to-SNG route via a gasification-synthesis pathway will be implemented in a TMP mill. The implementation of BtSNG will be compared with that of BIGCC. The reciprocal utilization of energy will be investigated.

1.2 Content description

Chapter 2 presents the background of DFBG (*Paper I*), syngas preparation (*Paper II*), biomass-to-ethanol (*Paper III*), TMP+BIGCC (*Paper IV*) and TMP+BtSNG (*Paper V*);

Chapter 3 describes the biomass conversion processes and the evaluation methods. Section 3.1 describes the MIUN DFBG system (*Paper I*). Section 3.2 describes a biomass-to-ethanol process and the techno-economic evaluation method (*Paper III*). Section 3.3 describes a TMP+PM process. Section 3.4 describes a TMP+BIGCC process and the techno-economic evaluation method (*Paper IV*). Section 3.5 describes a TMP+BtSNG process and the techno-economic evaluation method (*Paper V*);

Chapter 4 presents a review of the main results presented in papers I–V. Section 4.1 presents the predicted performance of a DFBG gasifier (*Paper I*). Section 4.2 presents the results of a techno-economic evaluation of a biomass-to-ethanol process (*Paper III*). Section 4.3 presents the results of a techno-economic evaluation of a TMP+BIGCC process (*Paper IV*). Section 4.4 presents the results of a techno-economic evaluation of a TMP+BtSNG process (*Paper V*);

Chapter 5 presents the main conclusions from this thesis;

Chapter 6 suggests future work about fuel cell and DME.

2 BACKGROUND

This chapter presents the background of DFBG (Paper I), syngas preparation (Paper II), biomass-to-ethanol (Paper III), TMP+BIGCC (Paper IV) and TMP+BtSNG (Paper V).

2.1 DFBG

The DFBG (also referred to as indirect or allothermal gasifier), with steam as the gasification agent, can be used to produce a syngas of 12–20 MJ/Nm^3 (LHV), which is the appropriate syngas for the downstream synthesis of transportation fuels and chemicals. The gasifier consists of two separate reactors: a steam gasifier used to convert biomass into syngas, and an air combustor used to burn the char and to provide the necessary heat for biomass steam gasification. A typical DFBG is composed of a BFB (bubbling fluidized bed) and a CFB (circulating fluidized bed). In comparison with auto-thermal pressurised gasifiers, the advantages of DFBGs are (Zhang 2010):

- no oxygen demand to obtain nitrogen-free syngas;
- low temperature operation;
- low investment cost;
- no or simple pre-treatment of biomass;
- easy feeding of biomass;
- suitable for the biomass-based S/M scale bio-automotive fuel plants.

For biomass, a small or medium scale bio-automotive fuel plant close to the feedstock resources is preferable as this kind of feedstock is widely sparse and has relatively low density, low heating value and high moisture content (Zhang W, Forsman B et al. 2005). An oxygen production system costs about the same as the gasification system, and is too expensive for a small biomass-based plant. For a DFB gasifier, no oxygen and pressurization are required, which makes the gasifier robust and cost-efficient for small-scale.

Syngas mainly consists of CO and H_2. In addition, it contains CO_2, CH_4, H_2O, trace amounts of higher hydrocarbons (tars), and possible inert gases. An expensive cleaning process is generally required for syngas production towards automotive fuels synthesis. Reduction of tar/CH_4 in the syngas is a major challenge to the commercialization of DFBGs for synthetic fuels production. Tar condenses with temperature (below 400 ℃), which leads to knotty problems to the downstream processes. The problems are e.g., fouling and blocking of filters and pipeline passages, dirty working environment, heavy waste water treatment, poisoning of

catalyst in synthesis reactors, etc. Moreover, tar results in a part of energy lost from the syngas.

Reduction of tars and CH_4 to an acceptable low level is usually achieved by thermal cracking with or without catalyst, or physical tar treatment like water or oil scrubbing. Catalysts can be used directly inside a gasifier. An internal reforming method is more cost-effective than a secondary downstream method (Göransson 2014). Tar/CH_4 catalytic reforming performance might be improved by more intensive contact between the gases and catalytic bed material.

Göransson et al. (**Göransson**, **Söderlind** et al. 2011; **Göransson** 2014) have being conducting a research in syngas cleaning, especially, the reforming of tars and CH_4. The work investigates catalytic bed material and an internal reformer in the MIUN gasifier.

The main function of bed material in a DFBG is to supply the gasification zone with energy for conversion of biomass (Göransson 2014). Reactive bed materials can be applied to improve agglomeration behaviour, to enhance tar cracking, and to increase H_2 content. Catalytic reforming can be performed either with catalytic bed material during gasification or after gasification by using a separate, downstream catalytic reactor. There is a great interest in using in-bed additives since complex downstream cleaning methods can be simplified.

For bed materials used in DFBGs, examples of natural minerals are dolomite, limestone, olivine and iron ores, and examples of synthetic minerals are Ni-supported olivine, Fe-supported olivine, alkali metal-based materials, and char (Pfeifer, Rauch et al. 2004; Göransson 2014). Sulphur substances (H_2S, COS, etc.) can be retained (up to 90%) by sorbents such as limestone (Zhang, Söderlind et al. 2007).

For the R&D of DFBG technology, a great deal of effort has been contributed to the experimental study. Very little work can be found on the mathematic simulation, especially, the simulation on tar evolution in biomass gasification.

In coal industry, a chemical percolation devolatilization (CPD) model was developed to model coal devolatilization based on characteristics of the chemical structure of the parent coal. The direct use of chemical structure data as a function of coal properties is useful to justify the model on a theoretical basis rather than an empirical basis. Fletcher (Fletcher) made a contribution to the CPD model development. The predictions of the amount and characteristics of syngas and tar

fit well with available measurement data. The application of CPD model to biomass has not been seen to a certain extent.

ASPEN Plus is often used to simulate the coal/biomass conversion processes. Sotudeh-Gharebaagh et al. (Sotudeh-Gharebaagh, Legros et al. 1998) used it to predict coal combustion in a CFB combustor regarding combustion efficiency, emission levels of CO, SO_2, and NOx, as well as concentration profiles of O_2 and CO. Lee et al. (Lee, Kim et al. 1998) presented the kinetic expressions for steam–char and oxygen–char reactions in the atmospheric coal gasification in a fluidized bed reactor. These expressions were cited by Nikoo et al. (Nikoo and Mahinpey 2008) in the biomass gasification simulation with ASPEN Plus. Doherty et al. (Doherty, Reynolds et al. 2009) developed a simple model with ASPEN Plus for the simulation of biomass gasification with steam and air in a CFB gasifier. Parameter sensitivity analyses, especially the effect of air preheating on gasification, were performed. The result is plausible. Corella et al. (Corella and Sanz 2005) set up a model for atmospheric biomass gasification in a CFB gasifier. In this model, the hydrodynamics and reaction kinetics aspects were considered, and the issues on the tar formation and reduction were discussed. On the basis of this model, Corella et al. (Corella and Sanz 2005) investigated the axial profiles of temperature, and the concentrations of ten different substances (H_2, CO, CO_2, tar, char…). However, the details have not been presented.

In this work, biomass gasification with steam in a DFBG is simulated by taking care of the evolutions of tar and char. Some subroutines are designed based on relevant empirical equations from literature. The sub-models are set up based on the thermodynamics and reaction kinetics. The yield and composition of the syngas, and the contents of tar and char can be calculated from the model. The concerned variables are: structure of the gasifier, gasification temperature (T), steam to biomass mass ratio (S/B), and biomass moisture content (M), gasification residence time (τ) and biomass/char particle size (d_P). The model is evaluated against the experimental results measured on a 150 KWth MIUN DFBG.

2.2 Biomass-to-Ethanol

In the transport sector, energy consumption accounts for more than 30% of the total energy supply in developed countries, which is 98% dependent on fossil fuel and difficult to be replaced with sustainable and CO_2 neutral bio-automotive fuel in the transport fuel market. Bio-ethanol is the major bio-automotive fuel today, and is rapidly expanding as a fuel additive in addition to its use as a chemical raw material. It is already commonly used in gasoline blended with 10% ethanol, and can be blended up to 85% by flexible fuel technology (Piccolo and Bezzo 2009). Through on-board reforming to hydrogen, ethanol is also suitable to be applied in future fuel cell vehicles (Hamelinck, Hooijdonk et al. 2005). As an alternative to methyl tert-butyl ether (MTBE) which raises serious health risks, ethanol enhances octane rating of gasoline and reduces emissions of CO, VOC (volatile organic carbon) and particulates (Hamelinck, Hooijdonk et al. 2005).

Ethanol is commercially produced via two routes, hydrolysis-fermentation of sugars from corn or sugar cane and hydration of petroleum-based ethylene. The ethylene hydration route is unattractive for large-scale ethanol production, which is dependent on imported crude oil and the volatile price of crude oil. Bio-ethanol feedstock can be divided into two major groups, sugar/starch materials and lignocellulosic biomass. Ethanol produced from sugar/starch materials is referred to as the 1st generation bio-automotive fuel (Zhang 2010). However, with regard to raw material potential, sustainability, fossil fuel consumption, farmland occupation, conflict with productions of food and high value chemicals, as well as net CO_2 emission, bio-ethanol produced from lignocellulosic biomass is more attractive, which is referred to as the 2nd generation bio-automotive fuel. Production of the 2nd generation bio-automotive fuels is too expensive at present due to complex conversion process and its demands on large scale and big investment. However, the production cost is expected to drop down as the lignocellulosic biomass feedstock is cheap, abundant, and does not compete with food production. Lignocellulosic biomass is envisaged to provide a significant portion of the raw materials for bio-ethanol production in the medium and long-term.

Lignocellulosic biomass can be converted into bio-ethanol by gasification-synthesis, gasification-fermentation, and hydrolysis-fermentation. In the hydrolysis-fermentation route, the biomass-to-ethanol conversion efficiency is fairly low since 25--30 wt % biomass as lignin cannot be broken down, and hydrolysis of cellulose and hemicellulose is difficult. A significant portion of 5-carbon sugars from hemicellulose hydrolysis cannot be completely metabolized into alcohol. Further achievements strongly depend on the development of cheaper and more efficient enzymes and microorganisms (Rajagopalan, P Datar et al. 2002; Younesi,

Najafpour et al. 2005; Sassner, Galbe et al. 2008; Zheng, Pan et al. 2009). The techno-economic assessment of production of ethanol (hydrolysis-fermentation) from lignocellulosic biomass has been made (Murphy and McCarthy 2005; Balat and Balat 2009; Yu and Tao 2009; Eriksson and Kjellström 2010; Qiu, Huang et al. 2010; Starfelt, Thorin et al. 2010; Naqvi, Yan et al. 2012).

In the gasification-synthesis route, biomass is gasified into raw syngas which is further reformed, cleaned, compressed, heated and converted into mixed alcohols from which ethanol and higher alcohols are obtained through a series of separation and purification treatments. This route has the following advantages — short reaction time, inexpensive and abundant raw materials, nearly complete biomass conversion and so on. However, commercialization of catalytic synthesis of ethanol from syngas is under development (Subramani and Gangwal 2008).

On the other hand, catalytic synthesis of methanol from H_2 + CO is an existing commercially available technology. It is evaluated (Kumabe, Fujimoto et al. 2008) that MeOH yield is 0.31 Kg MeOH per Kg dry biomass (Japanese cedar 400 t dry/d), the production cost lies between 12.8 and 78.0 U/m^3 MeOH, and the energy recovery rate is 31% (higher than the wood-to-power generation efficiency 22%). The lowest production cost is achieved when the shortfall of heat and power is compensated by an auxiliary CHP plant fed with biomass, char, off-gas, etc.

The present work aims at commercial ethanol production via thermo-chemical route in the near future. The thermo-chemical process is designed, simulated and optimized. Techno-economic evaluation is conducted in terms of ethanol yield, synthesis selectivity, carbon and CO conversion efficiencies, and ethanol production cost. Sensitivity of the important techno-economic parameters is also analyzed.

2.3 TMP+BIGCC

Paper mill with thermomechanical pulp (TMP) process has a very high wood-to-pulp/wood-to-paper yield (> 95%), but consumes a large amount of electricity (about 2.5 MWh per tonne of pulp). As a TMP-process normally is integrated with paper production, and electricity consumed in the refining process is simultaneously utilized to obtain steam and hot water, one can say that the electric power is used twice, first to produce the pulp and then to produce steam for drying paper. Chemical pulp mill producing bleached softwood Kraft can be self-sufficient in both heat and electric energy use, but has a low wood-to-pulp yield (45%). Lignin, extractives, and most of the hemicellulose, which make up about half of the pulp wood, are dissolved to become black liquor, which is incinerated to produce steam and electricity. This way, black liquor has become the most important bioenergy source in the pulp and paper industry and also the largest bioenergy source presently in Sweden. A focus has been on the technology development on black liquor gasification for the cogeneration of heat and power (Berglin and Berntsson 1998; Eriksson and Harvey 2004; Harvey and Facchini 2004; Holmberg and Gustavsson 2007; Naqvi, Yan et al. 2010; Naqvi, Yan et al. 2012). On the other hand, very little development has been accomplished for gasification-based cogeneration of heat and power in the context of a TMP mill.

The pulp quality possible to achieve by means of mechanical pulping processes is a prerequisite for producing printing paper and paperboard, especially due to their important functional properties of these products, such as printability and stiffness. In the Nordic countries, a larger share of paper production uses mechanical pulp than anywhere else in the world (Ruohonen and Ahtila 2011). Energy-efficient refining has been an important research subject for a long period of time (Engstrand, Hammar et al. 1991; Baeck, Danielsson et al. 1994; Sabourin 1999; Engstrand, Jonsson et al. 2002; Norgren and Höglund 2009; Gorski, Hill et al. 2010; Muhic, Sundström et al. 2010). The institute of Fibre Science and Communication Network (FSCN) at Mid Sweden University, together with Scandinavian forest and supplier companies, the Pulp and Paper Research Institute (PFI), and other Scandinavian universities, is working with a large research program with the goal of showing how to design the TMP and chemithermomechanical pulp (CTMP) mills of the future. It is possible to reduce 50% of the specific electricity consumption (SECR). Today, a large part of biomass such as the logging residues (branches and tree tops), is normally not utilized as a source of bioenergy. Furthermore, the possibility of utilizing the fibre material that has negative influence on the final product properties as a source of bioenergy has not been evaluated. Normally, only the bark, shavings, and bio-sludge are utilized in present bark boilers of CHP systems of mechanical pulp mills. It is also important

to explore the potential of achieving cost-effective and energy-efficient heat and power production from those biomass residues, especially for a TMP mill.

The back-pressure system with a steam turbine is popular in TMP mills. This system has low electricity generation efficiency less than 30%. In comparison, a gas turbine system has the efficiency up to 40%; while a biomass integrated gasification combined cycle (BIGCC) may reach the efficiency up to 50%. Implementing BIGCC to a TMP mill may create significant potential for self-sufficient electricity and for more economic benefit to the mill.

Ong'iro, et al. (Ong'iro, Ugursal et al. 1995; Ong'iro, Ugursal et al. 1996) developed several models to study the effects of design and operation parameters on the energy efficiency of a coal-based integrated gasification combined cycle (CIGCC) and on the efficiency of an integrated gasification humid air turbine cycle, respectively. A thermodynamic model of a combustion power plant was also developed with ASPEN Plus to evaluate the thermodynamic feasibility of the cogeneration with a higher ratio of electricity to heat. Using ASPEN Plus, Emun et al. (Emun, Gadalla et al. 2010) simulated a CIGCC, and pointed out that the overall energy efficiency can approach to 45%. Eriksson and Kjellström (Eriksson and Kjellström 2010) performed a techno-economic analysis over a CHP plant process integrated into a wood-based ethanol production process. They claimed that the utilization of the residues from an ethanol production plant process through a CHP system was the most promising of all. For a CHP process, the annual fixed operation cost was assumed to be 2% of the total investment, and the capital investment was only about 10% of the total cost of a wood-based ethanol production process (Eriksson and Kjellström 2010).

In the present study, a BIGCC model, special for a combined TMP+BIGCC system, is set up with ASPEN Plus. The syngas is produced from the biomass residues, collected at a pulpwood logging site, and the rejects from a TMP mill, by means of a dual fluidized bed gasifier (DFBG) system. A BIGCC system consists of a gas- and steam-turbine cycles. The obtained syngas will fuel the gas-turbine cycle, while the steam used in a papermaking (PM) process is withdrawn from the coupled steam cycle.

A techno-economic analysis is performed on the basis of this modelling. *Three cases are studied:*

1) adding more forest biomass logging residues in the gasifier;
2) adding the reject fibres in the gasifier;
3) decreasing the TMP-specific electricity consumption (SEC) by up to 50%.

The production profits are evaluated. The economic benefit from a TMP+BIGCC mill is compared with that from a TMP+CHP mill.

2.4 TMP+BtSNG

The possibility of producing transportation fuels from biomass and wastes has been a more and more important issue with regard to the challenges of energy security and climate change.

The present transport biofuels in the market are produced mainly from food crops, referred to as the 1st generation biofuels, which are not encouraged any longer. From the viewpoint of economics, environment, land use, water use, chemical fertilizer use, etc., however, there is a strong preference for the 2nd generation biofuels that are produced from woody, grassy materials as well as agricultural residues, municipal wastes and industrial wastes as the feedstock. Thus, the production of the synthetic transport fuels such as methanol, ethanol, dimethyl-ether (DME), Fischer-Tropsch (FT) fuel and SNG via gasification and synthesis is promising (Zhang 2010). Production of these fuels from coal and natural gas has been well commercialized e.g., by Sasol and Mobil (Dry 2002). For biomass, however, the technology has not been established mainly due to the high production cost against a limited scale of biomass-based plant.

Among the above mentioned fuels, Bio-SNG can be produced easily since the once through methanation conversion efficiency is high even at a moderate condition, and a sophisticated upgrading of products is not needed. Thus, Biomass to SNG (BtSNG) can be realized commercially with a small & medium scale of around 100 MW.

For an extremely small scale, the German company, Agnion, offers bio-SNG plants based on a heat-pipe reformer concept with a capacity of approximate 3 MW bio-SNG (Held 2013). The isothermal fluidized bed methanation developed at Paul Scherrer Institute (PSI) and commercialized by Clean Technology Universe (CTU) was demonstrated with a scale of 1 MW in Güssing in 2009. A larger scale demonstration plant of 20 MW bio-SNG output has been put into operation at the beginning of 2014 in Gothenburg as the GoBiGas project, which is scheduled to scale up to 100 MW bio-SNG plant. A bio-SNG plant of 200 MW is planned in the

E.ON Bio2G project. Depending on technology, scale, and energy prices, the most economic configuration may provide a net SNG yield of 66 to 75% from wood (based on LHV of the dry substance) at 50 wt.% moisture content, and the poly-generation of fuel, heat, and power allows for a total useful energy yield ranging from 71 to 91% (Gassner and Marechal 2012).

Bio-SNG can be used in a variety of applications:

- Grid injection;
- Vehicle fuel;
- Chemical feedstock;
- Fuel for electricity or heat production.

In Sweden, biogas produced from waste treatment through digestion has been used as vehicle fuel in the market. The scale expands rapidly up to about 1 TWh in recent years. This provides an excellent opportunity for cost-effective co-production of biogas and bio-SNG with respect to the gaseous fuel infrastructure and the synergy in the gas cleaning and upgrading processes.

In the present study, the feasibility of biomass gasification-based technology to produce CH_4, in a TMP mill is evaluated and compared with TMP+BIGCC in terms of the technical and economic aspects. Fig. 2.1 schematically shows two designed systems integrated with a TMP mill.

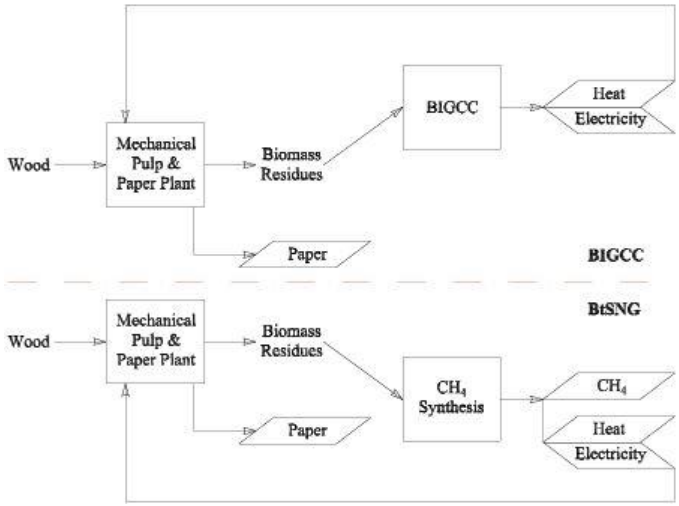


Fig. 2.1: Two designed systems integrated with a TMP mill respectively

3 PROCESS AND MODELING

This chapter describes the biomass conversion processes and the evaluation methods. Section 3.1 describes the MIUN DFBG system (Paper I). Section 3.2 describes a biomass-to-ethanol process and the techno-economic evaluation method (Paper III). ***Section*** *3.3 describes a TMP+PM process. Section 3.4 describes a TMP+BIGCC process and the techno-economic evaluation method (Paper IV).* ***Section*** *3.5 describes a TMP+BtSNG process and the techno-economic evaluation method (Paper V).*

3.1 DFBG

3.1.1 DFBG

A DFBG consists of two beds (Fig. 3.1). One is blown with steam to gasify biomass and to produce syngas. The other is blown with air to burn char to produce heat. Bed material is circulated to transfer heat from combustion bed to gasification bed. Flue gas is prevented from mixing with the produced syngas. Since air is not injected into the gasifier directly, N_2-free syngas can be obtained. The temperatures in the reactors are maintained by the char combustion and bed material recirculation. Some options for DFBG technology are possible from different combinations of the BFB and the CFB. So far, the most attractive design is supposed to have biomass gasification in the BFB and char combustion in the CFB from the viewpoints of particle circulation, fuel conversion, tar cracking, etc. Some typical combination (gasifier/combustor) examples are BFB/CFB (Güssing (Hofbauer, Veronik et al. 1997; Fercher, Hofbauer et al. 1998; Pfeifer, Rauch et al. 2004), Trisaia (Foscolo 2007), CAPE (Brown 2006), Chalmers (Seemann and Thunman 2009; Heyne 2010), MIUN (Zhang 2010; Göransson, Söderlind et al. 2011; Göransson, Söderlind et al. 2011)), CFB/BFB (MILENA (van der Meijden, Bergman et al. 2010; Zwart, van der Heijden et al. 2010)), and CFB/CFB (SilvaGas (Paisley, Corley et al. 2007; Tarka, Wimer et al. 2009), Taylor (Paisley, Corley et al. 2007)). The measured H_2/CO ratios range from 0.45 (SilvaGas) to 3.5. The CH_4 concentration is generally around 10.0 vol. %. The tar contents range from 0.5 g/Nm^3 (Trisaia, Güssing) to 32.0 g/Nm^3 (MIUN, Milena). The measurement data are scattering in a wide range. Similar summaries can be found (Göransson, Söderlind et al. 2011; Göransson, Söderlind et al. 2011; He, Göransson et al. 2012).

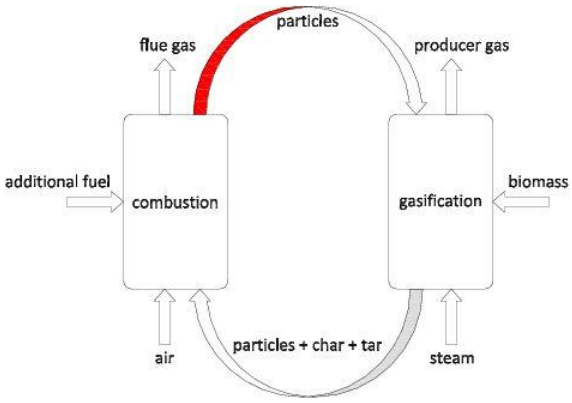


Fig. 3.1: Concept of a DFBG system

MIUN DFBG

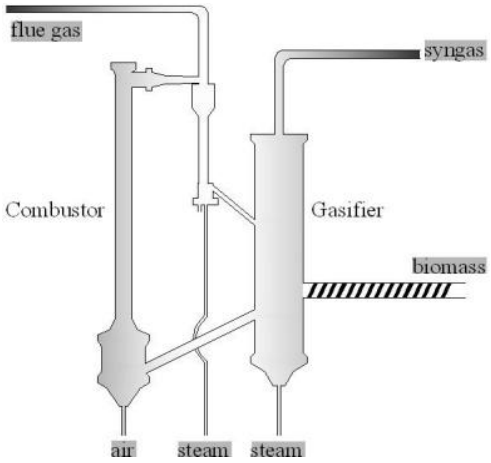


Fig. 3.2: A MIUN DFBG

The MIUN gasifier is schematically shown in Fig. 3.2. The gasifier consists of an endothermic steam-fluidized bed gasifier and an exothermal CFB combustor. The biomass treatment capacity is 150 KWth, that is, approx. 30 kg/h. The heat carrier is silica sand (150 μm, in diameter). The bed material circulation is controlled with the air velocity in the combustor, the steam velocity in the gasifier, the total solids inventory, and the aeration in a tube connecting the gasifier and the combustor at the bottom. The Process Logic Controller-operated feeding system is designed for constant biomass feeding. The biomass is fed into a pneumatic oscillatory vane feeder to achieve high precision. The fluidization agent in the gasifier is steam, and

the syngas is drawn off from the top of the gasifier. The residual biomass char is transferred along with bed material into the combustor through the lower pressure lock. In the combustor, the fluidization agent is air participating in the char combustion (950–1050 ℃). The hot bed material is separated from the flue gas through a cyclone and recycled into the gasifier through the upper pressure lock (loop seal pot) which is designed to prevent gas leakage. The heights of the gasifier and combustor are 2.5 m and 3.1 m, and the inner diameters are 300 and 90 mm, respectively. It is 0.7 m from the surface of bed material to the distributor, and about 0.2 m to the feeding point. The experiments were carried out at 750 ℃, 800 ℃, and 850 ℃, respectively. The steam input into the gasifier was held at 4.0 kg/h. Wood pellets are from SCA BioNorr AB. The S/B ratios are 0.3, 0.6, and 0.9, respectively. The details on experiments have been reported elsewhere (Göransson, Söderlind et al. 2011; He, Göransson et al. 2012).

3.1.2 Simulation

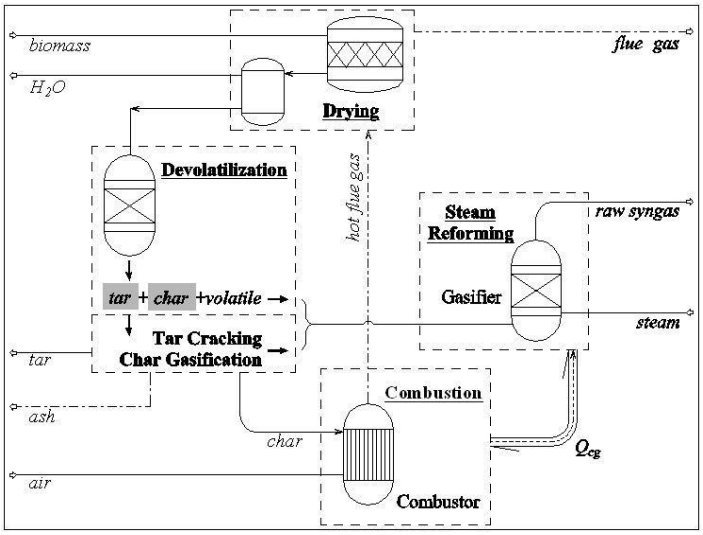


Fig. 3.3: Flowsheet of a DFBG biomass gasification model

ASPEN Plus consists of various sub-models simulating various unit operations. It can be used to model complicated chemical engineering systems. Equations and data for the calculations are accessed from ASPEN Plus databases. Customized models can be created to extend the capability of ASPEN Plus. Here, the RGibbs module was mainly adopted. The RGibbs module performs calculations according to the Gibbs free energy theory. Some subroutines are integrated for simulating biomass devolatilization and the evolutions of tar and char. Relevant empirical

correlations (Lee, Kim et al. 1998; Fagbemi, Khezami et al. 2001; Kiel, Van Paasen et al. 2004; Corella and Sanz 2005; Nikoo and Mahinpey 2008) are adapted and employed in the subroutines. As illustrated in Fig. 3.3, this model consists of four sections. The bed materials are not considered in the phase and chemical equilibria calculations. Q_{cg} denotes a stream of heat carried by bed material. With respect to tar and char, as nonconventional components, the calculations will be conducted independently from using the database in ASPEN Plus. S/B is calculated according to:

$$S/B = \frac{\dot{M}_{steam} + \dot{M}_{H_2O \text{ in biomass}}}{\dot{M}_{dry \text{ biomass}}} \quad (3\text{-}1)$$

where, $\dot{M}$ denotes the mass flow (kg/s). A number of hypotheses for the model are listed:

- the process is of steady state;
- the biomass feedstock and bed materials are fed at an uniform temperature;
- ash as well as bed materials are inert;
- the char particles are spherical and of uniform size;
- the mixing of solid particles is perfect;
- the combustion and gasification of biomass are described by the shrinking core model.

3.2 Biomass-to-Ethanol

3.2.1 Process

In the gasification–synthesis route, biomass is gasified into raw syngas which is further reformed, cleaned, compressed, heated and converted into mixed alcohols from which ethanol and higher alcohols are obtained through a series of separation and purification treatments. Advantages of this route include a short reaction time, inexpensive and abundant raw materials, high conversion rate, etc (Kumabe, Fujimoto et al. 2008; Subramani and Gangwal 2008).

The process consists of five steps: biomass pre-treatment, gasification, syngas cleaning and conditioning, alcohols synthesis, and separation. Fresh biomass needs pre-treatment. Weighed wood chips are screened. Metal debris is removed using a magnetic separator. Particles larger than 10 mm are conveyed to a hammer mill for further size reduction. By direct contact with the hot flue gas, wet biomass is dried. Gasification is carried out in DFBG. Particles from raw syngas are separated. A small amount of MgO is added to raise the ash melting point and to avoid the agglomeration that would result from the interaction of biomass potassium with silicate compounds. The composition and quality of syngas from the biomass gasifier are dependent on a number of factors. Syngas with H_2/CO molar ratio of 1–2 is suitable for ethanol synthesis. Raw syngas contains various impurities which are potential threats to ethanol synthesis catalysts. Tars are cracked. Additional CO and H_2 are formed. Additional cooling is done via water scrubbing, and impurities such as particulates, residual tars, and ammonia are further reduced. Subsequently, in a five-stage compressor, the syngas is compressed to 29 bar. NH_3 and H_2O are condensed. Afterwards, acid gases (CO_2 and H_2S) removal is carried out in an amine system. Other sulphurous compounds—if contained in raw syngas, will be converted into H_2S. The presence of some CO_2 (about 5.0 vol.%) is necessary for the function of a methanol synthesis catalyst, and may also be advantageous for ethanol synthesis. After cleaning, syngas is compressed and pre-heated to the synthesis conditions of 100 bar and 300 ℃. Synthesis is completed in seconds or minutes, and the product is cooled and initially purified to separate out the unconverted syngas. Mixed alcohols are de-gassed, dried, and separated into ethanol and higher alcohols. In a flash separator, alcohols are separated from off-gas, and off-gas is diverted to a gas cleaning section. Since the recycled gas is at high pressure, it is further heated and applied to generate extra electricity. The depressurized alcohols stream is dehydrated with a molecular sieve and then sent to the main distillation column. The overhead is further processed in the second column to get high-purity ethanol. The obtained methanol/water mixture is

recycled for alcohols synthesis. The biomass-to-ethanol process is designed to be energy self-sufficient.

3.2.2 Evaluation

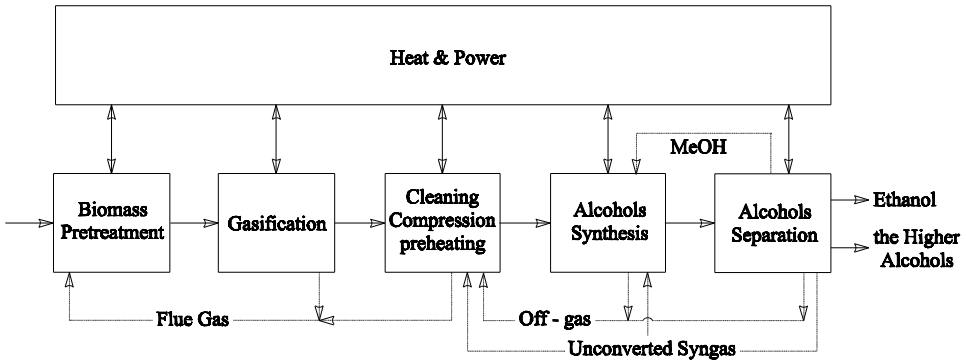


Fig. 3.4: Block flow diagram of a biomass-to-ethanol process

Before setting up the model, an optimal thermo-chemical biomass-to-ethanol process is designed (Fig. 3.4). In the process, off-gas and MeOH from ethanol synthesis and separation steps are recycled to increase conversion efficiency. A CHP plant is integrated from economic and environmental points of view.

The cost of equipment can be estimated by:

$$\mathbf{I_1 = I_2 \times \left(\frac{Q_1}{Q_2}\right)^n} \quad \textbf{(3-2)}$$

$$\mathbf{I_1 = I_2 \times \frac{CI_1}{CI_2}} \quad \textbf{(3-3)}$$

Here, "n" denotes the characteristic scaling exponent of either the overall plant or a single piece of equipment. Typically, "n" equals 0.6, that is, "0.6 exponent method". "n" has different referential values for different processes and types of equipment. Equipment installation cost is estimated to be 1.45 times equipment purchase cost. Operation cost consists of fixed and variable operation costs. Labour cost equals national per capita income multiplied by a factor of 1.2. Variable operation cost is calculated according to the stream flow rate. Price of cost item equals the temporal market price at the time when economic analysis is performed. Biomass procurement cost is set as 60 €/dry tonne. The fixed operation cost is supposed to stay invariable within a certain range, while variable operation cost is varied with the production scales. Since capital recovery charge is related to capital investment, "0.6 exponent method" is adopted to calculate the charge. Once total capital and operation costs are determined, ethanol production cost is calculated by "discounted cash flow analysis" when the NPV is zero.

3.3 TMP+PM

A typical flowsheet of TMP process (Fig. 3.5) can be found in the literature (Sundholm, Yhdistys et al. 1999). Some of the input data to this model are from a TMP+PM mill, Hallsta, Holmen Paper (Pettersson 2005). Biomass residues from a TMP+PM mill are traditionally utilized through a CHP plant to supply the mill electricity and steam. The original CHP plant is intended to be replaced by a BIGCC plant.

Available biomass residues from a TMP plant are significant and include: 1) logging residues, amounting to 30% of the tree; 2) bark, 12% of the stem, 3) bio-sludge, 2% of the pulpwood, and 4) reject fibres, 10% of the pulp. Fig. 3.5 implies that 0.7 tonne of biomass residues are available from the production of each tonne of pulp. Additional biomass (including peat) can be gained from other applications such as the production of chemical pulp, construction of woody structures, etc.

Table 3.1: Outline of a thermal mechanical pulping and paper-making line (Pettersson 2005)

		TMP	PM
Yield		230 000 t/yr	250 000 t/yr
Pulpwood with Bark		250 000 t/yr	
Pulpwood		220 000 t/yr	
Biomass Residues			3.9[a] MWh/bdt pulp
Electricity	consumption	2.5 MWh/bdt pulp	0.75 MWh/bdt pulp
Steam	production	1.2 MWh/bdt pulp	/
	consumption	0.03 MWh/bdt pulp	1.38[b] MWh/bdt pulp
Water	consumption	3.0 m^3/bdt pulp	10.4 m^3/bdt pulp
Effluent	fibre poor	3.8 m^3/bdt pulp	wastewater
	fibre rich	5.5 m^3/bdt pulp	2.5 m^3/bdt pulp

[a] including logging residues, bark, bio-sludge and reject fibres; see Fig. 3.5.

[b] in 1.38 (2.0 t/bdt pulp) = 1.32 (2.5 bar) + 0.06 (100 bar);
out 2.0 t/bdt pulp = 0.2 (to the air) + 1.8 (condensed).

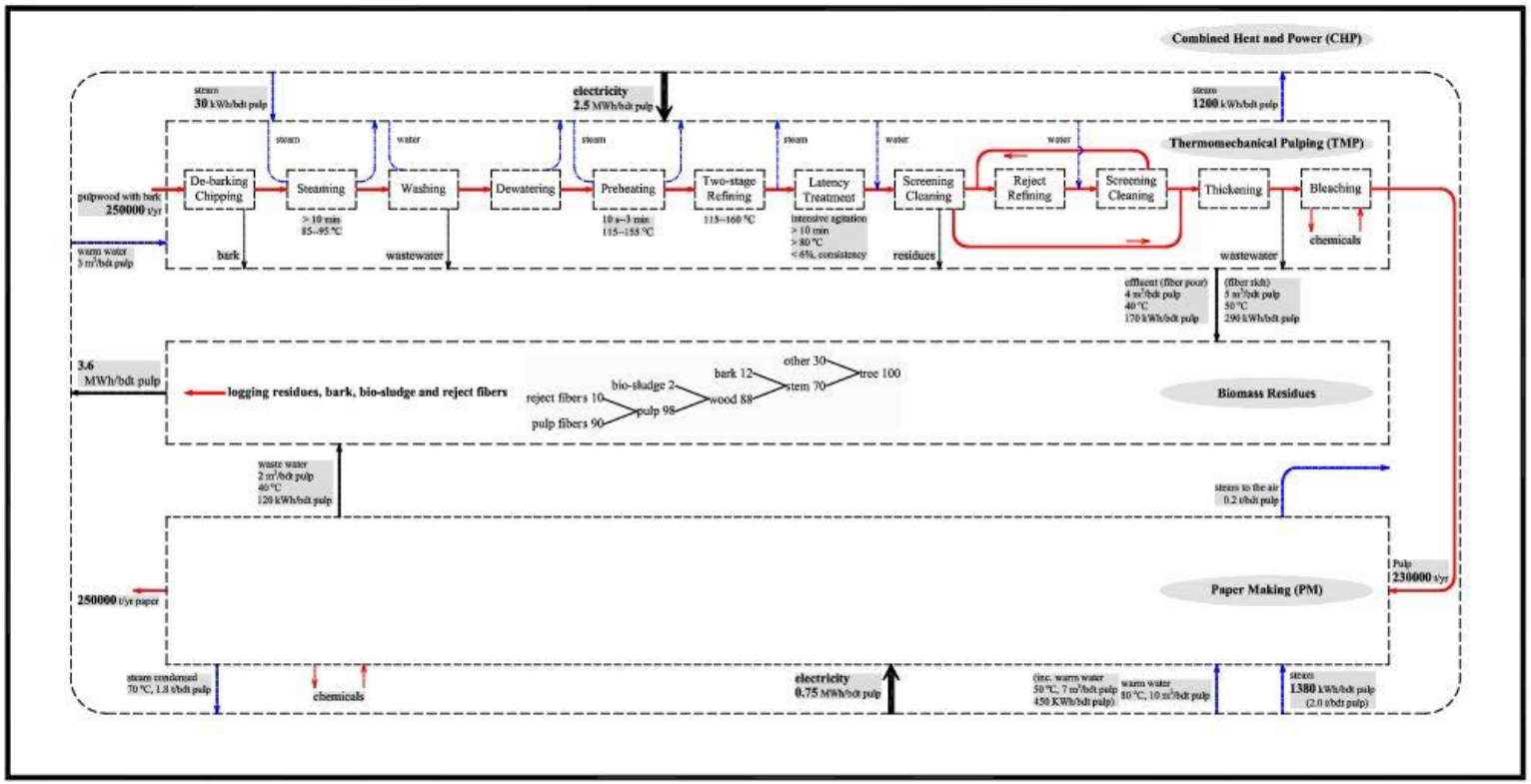


Fig. 3.5: Flowsheet of a typical TMP–PM process

3.4 TMP+BIGCC

In the present work, a BIGCC model is developed for a combined TMP+BIGCC system. The syngas is produced from the biomass residues collected at the pulpwood logging site, and the rejects from the TMP mill by means of a dual fluidized bed gasifier (DFBG) system. The obtained syngas will fuel the gas turbine cycle in the BIGCC system to generate electricity, while the steam used in the PM process is extracted from the steam cycle.

3.4.1 BIGCC

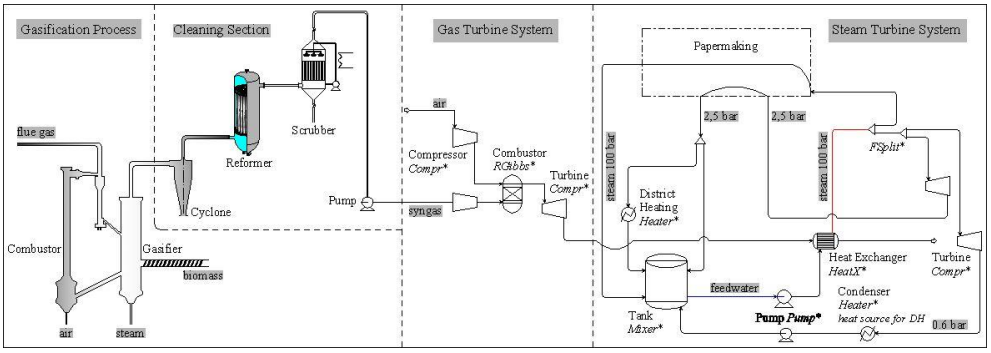


Fig. 3.6: Flowsheet of a BIGCC model

Coal-based IGCC technology has been effectively commercialized. Biomass-based IGCC technology, however, is at a pre-commercialization stage, with syngas cleaning as a key issue. In this study, DFBG, an indirect gasifier, is chosen for biomass gasification. It consists of a bubbling fluidized bed gasifier and a circulating fluidized bed combustor.

It is advantageous to apply the gasifier. The main advantages are that the gasifier can easily process various solid fuels, including high moisture biomass, and that the biomass pre-treatment is fairly simple (Zhang 2010). The details can be found in the literature (Göransson, Söderlind et al. 2011; He, Göransson et al. 2012).

A detailed study on syngas cleaning was made by by Göransson et al (Göransson, Söderlind et al. 2011). Eriksson and Kjellström (Eriksson and Kjellström 2010) suggested that the investment for a separate gasifier and gas cleaning unit amounts to about 25% of the CHP investment.

The cleaned syngas will be combusted to generate electricity through a gas turbine system. The exhausted high temperature flue gas flows through a heat exchanger. The steam (100 bar 565 C) can be therefore afforded, and expands through a steam turbine cycle from 100 bar to 0.6 bar to generate extra electricity. Simultaneously, a certain amount of 2.5 bar steam is withdrawn to PM. Besides, the 2.5 bar steam from TMP has been provided to PM.

For comparison, TMP+Boiler and TMP+CHP are also modelled, respectively. The available amount of heat energy for a district heating (DH) system is calculated with the model. Additionally, for the TMP+Boiler case, it is assumed that 50% of the energy after the production of steam is utilized in DH. Table 3.2 lists the model input data.

Table 3.2: Model input data (Göransson, Söderlind et al. 2011; He, Göransson et al. 2012)

LHV biomass		[MJ/kg]	18
efficiency	gasification combustion boiler DH	[%]	80 99 75 50[a]
syngas	yield	[m^3/kg daf biomass]	1.1
	composition	[vol.%]	H_2 37.5, CO 35.0, CO_2 15.0, CH_4 8.0, C_2H_4 0.5 and N_2 4.0
	LHV	[MJ/kg]	13.2
flue gas		[℃]	120[b]
working steam		[bar] [℃]	100 bar and 565 ℃ 100 bar to 0.6 bar (through a steam turbine cycle)
steam (in PM)		[bar]	2.5

a DH = (energy content of biomass - energy content of steam (steam from the boiler to TMP+PM))×0.5

b The hot inlet-cold outlet temperature difference is set as 209.6 ℃ for a sub-model of a heat exchanger connecting a gas- and steam-turbine cycles.

3.4.2 Simulation

The BIGCC model (Fig. 3.6) is set up with several ASPEN Plus modules. Each module simulates a unit process. The electricity generation efficiency of BIGCC depends on the efficiencies of gasification, compression, combustion, expansion, etc. The input data are collected from a variety of sources including experimental and literature data. The mass balance and energy balance are verified.

A compressor or a turbine is simulated with a module "Compr" which can calculate the power consumed or produced when the pressure ratio, isentropic, polytropic, and mechanical efficiencies, and clearance volume are given.

The combustor is modeled as a reactor in ASPEN Plus with the module "RGibbs" which executes equilibriums calculations by Gibbs free energy minimization. When a system does not reach a complete equilibrium state, "RGibbs" can also be used by additionally specifying an extent of equilibrium.

The heat exchanger is simulated with the module "Heatx", the pump with the module "Pump", and the flow splitter "FSplit".

The accessed equations and data are "packaged" in a specific Property Method set in ASPEN Plus. The involved substances and operation conditions are crucial in choosing a proper Property Method. In modelling the gas turbine system, the Property Method PR-BM is adopted, and for the steam turbine system, the Property Method STEAM-TA is employed.

The ASPEN Plus function block "Design Spec" is auxiliarily applied to predict how much steam can be produced from the heat exchanger. In essence, it is a multi-objective optimum design method adopted. The 100 bar, 565 ℃ steam is targeted to be produced. Simultaneously, the temperature of the flue gas is set to be 120 ℃. The manipulated variable is "MASS-FLOW" (flowrate, kg/s). Similarly, for simulating the distribution of steam (by "FSplit"), the function block is also employed. The original stream of steam will be divided into two parts. In optimization, the target value is the known amount of 2.5 bar steam used in PM. The manipulated variable is "FLOW/FRAC" (stream fraction). Some details of the model can be found elsewhere (He, Göransson et al. 2012).

3.4.3 Economic evaluation

The economic profitability of TMP+BIGCC is evaluated in terms of the net revenue (after subtracting the depreciation) and IRR. IRR is also called the discounted cash flow rate of return or the rate of return. IRR disregards the absolute amount of money to be gained, and is an indicator of the efficiency, quality, or yield of an investment. An investment is considered acceptable if its IRR is higher than an established minimum acceptable IRR, 0.1 for instance. Generally, the higher the IRR, the better the investment.

Table 3.3: Data for economic analysis (Pettersson 2005; Holmberg and Gustavsson 2007; Eriksson and Kjellström 2010; Stridsberg and Lindgren 2010)

operation time	8000 hr/yr
power generation efficiency	44% (calculated, BIGCC) 28% (calculated, CHP)
specific capital investment	3000 €/KWel (CHP) 2300 €/KWel (BIGCC) 1920 €/tpy (TMP+PM)
paper	710 €/t
heat	80 €/MWh
O & M cost	0.07 × the total capital investment
electricity price	50 €/MWh
electricity certificate	30 €/MWh
pulpwood	20 €/MWh
biomass to BIGCC	10 €/MWh (the logging residues) 0 €/MWh (the TMP residues)
plant lifespan	30 years
discounted payback period	10 years
annual depreciation	
the first 10 years	DDB (factor 1.5)
the next 20 years	Straight-line Depreciation
profit tax rate	0
discount factor	0.1

Table 3.3 lists the data on this economic evaluation. The electricity generation efficiency of BIGCC or CHP is calculated from the model. For a TMP+PM mill, its capital investment is about 1920 €/tpy in a given paper production capacity

(Holmberg and Gustavsson 2007). The capital investment for BIGCC is 2300 € /KWel (Wetterlund and Söderström 2010). The capacity of power generation is about 30 MWel. The prices for some facilities are referred to the literature (Phillips, Aden et al. 2007; Eriksson and Kjellström 2010). The operation and maintenance cost accounts for 7.0% of the capital investment of a combined TMP+BIGCC mill. Electricity is purchased at about 50 €/MWh. An electricity certificate credit of 30 € /MWh is taken into account. The price of pulpwood is 20 €/MWh. The discounted payback period is set as 10 years. Available raw biomass materials from a TMP mill are free of charge. The overall cost for the logging residues is 10 €/MWh in synergy with pulpwood harvesting. The heat is sold at 80 €/MWh for DH. The plant lifespan is anticipated to be 30 years. In sensitivity analysis, the pulpwood is priced at 20 or 40 €/MWh, and the electricity at, 50 or 100 €/MWh. The other values are unchanged.

Two depreciation methods are adopted: for the first 10 years the Double-Declining Balance method (DDB), and for the next years the Straight-line Depreciation Method. Tax is not added. The economic analysis routine is programmed with *Excel*.

3.5 TMP+BtSNG

3.5.1 BtSNG

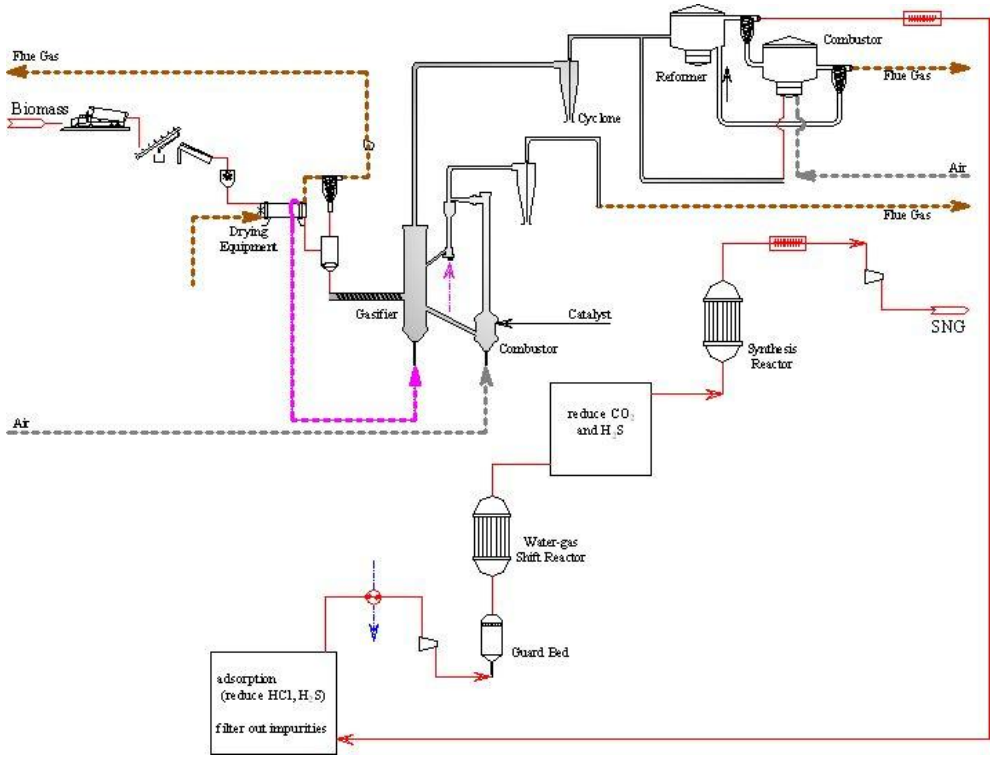


Fig. 3.7: Model of BtSNG with a fluidized-bed SNG synthesis system

Before setting up a mathematic model, an optimal BtSNG process flow diagram is designed as shown in Fig. 3.7. The process is established with five steps: biomass pretreatment, gasification, syngas cleaning and conditioning, SNG synthesis, and separation and purification. This system includes a steam turbine to utilize the waste heat from BtSNG to generate electricity and steam for the use in a TMP+PM mill.

Methanation can be either carried out in a series of adiabatic fixed bed reactors with inter-cooling and optional product recycle, or in a single fluidized bed reactor at isothermal conditions (Heyne 2013). The Ni-based catalysts are commonly used.

Methanation is highly exothermic (Tunå and Center 2008; Agersborg and Lingehed 2013). The temperature should be generally kept low to favor the equilibrium (Tunå and Center 2008). It should be considered that the temperature is limited by

the catalyst activation and carbon deposition problems (Heyne 2013). The operation is also limited by catalyst sintering problems at higher temperatures. The fixed bed methanation is operated at temperature around 650 ℃, whereas the fluidised bed methanation around 300 ℃.

A higher pressure is favorable for CH_4 formation, which increases methanation conversion efficiency and reduces the amount of catalyst required. For adiabatic fixed bed methanation, the pressure should be high, about 10 bar, corresponding to the high temperature. For fluidized bed methanation, on the other hand, the pressure should be low, about 4 bar, corresponding to its low temperature. A high conversion efficiency of methanation can also be achieved even at atmospheric pressures. A compression stage prior to the methanation stage ensures the necessary pressure for final SNG delivery to a local distribution network, otherwise, additional compression of final SNG is needed (Agersborg and Lingehed 2013; Heyne 2013).

Fluidized bed methanation is one key technology to unlock cost-effective bio-SNG production in a medium scale (Gassner and Marechal 2012; Held 2013). This reactor type is able to handle syngas with a wide range of CO/H_2-ratios, from 1:1 to 1:5 if water addition is optimized. The advantages of a fluidized bed methanation reactor compared to fixed bed methanation reactors are the isothermal operation, the easy controlling, the possibility for the in situ water gas shift reaction to adjust the H_2/CO ratio and the low risk of catalyst deactivation due to recirculation of the catalyst particles through the bed. There is a good synergy between DFBG and fluidized bed methanation as both have a moderate operation condition and make production cost reduction possible.

Since the methanation reaction equilibrium is reached in both fluidized and fixed bed reactors, the conversion efficiency to SNG is yet expected to be the same, and only the combined heat and power production might differ due to the respective dissimilar heat transfer profiles of the heat exchangers (Gassner and Marechal 2012). In present work, the fluidized bed methanation reactor is chosen for modeling BtSNG.

Methanation Reactions:

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O \qquad \Delta H^{\ominus}_{298} = -206\ \mathrm{kJ/mol} \qquad (3\text{-}4)$$

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \qquad \Delta H^{\ominus}_{298} = -165\ \mathrm{kJ/mol} \qquad (3\text{-}5)$$

$$C(s) + 2H_2 \leftrightarrow CH_4 \qquad \Delta H^{\ominus}_{298} = -\ 75\ \mathrm{kJ/mol} \qquad (3\text{-}6)$$

$$2CO \leftrightarrow C + CO_2 \qquad \Delta H^{\ominus}_{298} = -172\ \mathrm{kJ/mol} \qquad (3\text{-}7)$$

Water-gas shift reaction:

$$CO + 3H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H^{\ominus}_{298} = -\ 41\ \mathrm{kJ/mol} \qquad (3\text{-}8)$$

The upgrading of bio-SNG is simple comparing to other synthetic fuels. A minor part component of CO_2 in the product gas needs to be removed. MEA, pressure swing adsorption (PSA) and physical absorption with Selexol are suitable for CO_2-removal either up- or downstream of methanation, whereas membranes can only be applied downstream due to the fast permeation of H_2. Downstream to these CO_2-removal options, a final polysulfone membrane for H_2 removal and recycling to the CH_4 synthesis reactor has further proven useful to reach the required grid quality of 96 mol.% CH_4 (Gassner and Marechal 2012).

3.5.2 Simulation

Table 3.4: Model input data (Gassner and Marechal 2012; He, Göransson et al. 2012; He, Engstrand et al. 2013; Heyne 2013)

LHV biomass		[MJ/kg]	18
efficiency	gasification	[%]	80
	combustion		99
	boiler		75
drying	flue gas inlet	[℃]	550
	outlet		120
gasification		[℃]	850–900
syngas	yield	[m^3/kg daf biomass]	1.1
	composition	[vol.%]	H_2 37.5, CO 35.0, CO_2 15.0, CH_4 8.0, C_2H_4 0.5 and N_2 4.0
	LHV	[MJ/kg]	13.2
mathanation	internally cooled FB	[℃]	300
		[bar]	5–15
Purification PSA	CO_2 removal	[%]	95–99
	SNG recovery	[%]	95–99
	adsorption pressure	[bar]	5.5
steam	to turbine	[℃]	500
		[bar]	60
	in PM	[bar]	2.5

The BtSNG model is set up with several ASPEN Plus modules. Each module simulates a unit process. The input data were collected from a variety of sources including experimental and literature data. The overall mass and energy balance of the integrated mill is examined.

The gasifier and combustor were modelled with the module "RGibbs" which executes equilibriums calculations by Gibbs free energy minimization. When a system does not reach a complete equilibrium state, "RGibbs" can also be used by additionally specifying an extent of equilibrium.

The modelling of the shift reactor is done with an adiabatic Gibbs reactor where CH_4 is considered inert and therefore does not take part in the steam reformation (Agersborg and Lingehed 2013). The assumption is considered valid since the shift reactor utilizes a different type of catalyst than the methanation reactor and

therefore no methanation or steam reformation should occur in the reactor (Agersborg and Lingehed 2013).

An RGibbs module was used for methanation simulation (Porubova, Bazbauers et al. 2012; Heyne 2013). A temperature approach to equilibrium measure was adopted for the composition calculations in order to account for the deviation from the thermodynamic equilibrium in a real reactor (Heyne 2013). The ASPEN Plus function block "Design Spec" and in-built "Calculator" were auxiliarily applied for parameters adjustment and process control. In essence, it is a multi-objective optimum design method adopted.

This model is based on the following assumptions (Zwart, Boerrigter et al. 2006; Gassner and Marechal 2012; Agersborg and Lingehed 2013; Held 2013; Heyne 2013; Thunman H., Alamia A. et al. 2014):

- Biomass de-volatilization is instantaneous in comparison with the char gasification;
- The methanation reaction and shift reaction go fast so that the thermodynamic equilibrium is reached;
- The overall CO conversion could approach to 98%;
- 98% steam is estimated to be condensed;
- The energy required for CO_2 removal is considered to be 4.0 MJ/kg CO_2;
- Biomass to bio-methane energy conversion efficiency ≥ 65%;
- The overall energy conversion efficiency > 90%;
- CH_4 concentration > 95%;
- The CH_4 losses are about 2.0%–4.0%.

3.5.3 Economic Evaluation

Table 3.5: Data for economic analysis (He, Engstrand et al. 2013; Held 2013; Heyne 2013; Thunman H., Alamia A. et al. 2014)

operation time	8000 hr/yr
power generation efficiency	45% (calculated, BIGCC)
specific capital investment	3470 €/$KW_{bio\text{-}SNG}$ (BtSNG) 2300 €/KWel (BIGCC) 1920 €/tpy (TMP+PM)
pulpwood	20 €/MWh
biomass to BtSNG	10 €/MWh (the logging residues) 0 €/MWh (the TMP residues)
O & M cost	0.**065** × the total capital investment
Operators	12 p./shift
operator salary	60000 €/yr
paper	710 €/t
bio-SNG	60 €/MWh
electricity price	40 €/MWh
electricity certificate	20 €/MWh
heat	60 €/MWh
plant lifespan	30 years
discounted payback period	10 years
annual depreciation	
the first 10 years	DDB (factor 1.5)
the next 20 years	Straight-line Depreciation
profit tax rate	0
discount factor	0.1

The economic profitability of TMP+BtSNG is evaluated in terms of NR (after subtracting the depreciation) and IRR. For a TMP+PM mill, its capital investment is about 1920 €/tpy in a given paper production capacity (Holmberg and Gustavsson 2007). The capital investment for BtSNG is 3470 €/$KW_{bio\text{-}SNG}$ (Thunman H., Alamia A. et al. 2014). The prices for some facilities are referred to the literature (Phillips, Aden et al. 2007; Eriksson and Kjellström 2010). The operation and maintenance cost accounts for 6.5% of the capital investment of a combined TMP+BtSNG mill. Electricity is purchased at about 40 €/MWh. An electricity certificate credit of 20 €

/MWh is taken into account. The price of pulpwood is 20 €/MWh. The discounted payback period is set as 10 years. Available raw biomass materials from a TMP mill are free of charge. The overall cost for the logging residues is 10 €/MWh in synergy with pulpwood harvesting. The heat is sold at 60 €/MWh for DH. The plant lifespan is anticipated to be 30 years. In sensitivity analysis, the bio-SNG is priced at 60 or 120 €/MWh, and the pulpwood at, 20 or 40 €/MWh. The other values are unchanged.

4 RESULT AND DISCUSSION

This chapter presents a review of the main results presented in papers I–V. Section 4.1 presents the predicted performance of a DFBG gasifier (Paper I). Section 4.2 presents the results of a techno-economic evaluation of a biomass-to-ethanol process (Paper III). Section 4.3 presents the results of a techno-economic evaluation of a TMP+BIGCC process (Paper IV). Section 4.4 presents the results of a techno-economic evaluation of a TMP+BtSNG process (Paper V).

4.1 DFBG

4.1.1 Effect of temperature

As seen in Fig. 4.1(a), the syngas yield increases with temperature as a result of the enhanced gasification and reforming at a higher temperature. Tar content decreases from 50.0 g/m^3 at 750 ℃ down to about 13.0 g/m^3 at 900 ℃ attributed to tar thermal cracking and steam reforming. Char to be combusted is regarded as an intermediate product. The char fraction decreases from 22.5 wt.% at gasification temperature of 750 ℃ to 11.5 wt.% at 950 ℃. The lower gasification temperature leads to higher char yield, and subsequently results in higher combustor temperature, hotter bed material, and higher gasification temperature, so that less char will be produced.

As seen in Fig. 4.1(b), the concentration of CO increases with temperature, but that of H_2 reaches a maximum value at about 850 ℃. This is because H_2 tends to take part in the hydrogenation reactions at higher temperatures. The H_2 concentration is higher than that of CO under normal DFBG operating conditions, but they will change positions when the gasification temperature is too high above about 950 ℃. The CH_4 concentration is around 10.0 vol. % and not sensitive to temperature. CH_4 is highly stable, and much more difficult to be cracked or reformed than tar. Therefore, CH_4 concentration is far from its chemical equilibrium value which is close to zero. Significant reduction of CH_4 takes place at a temperature higher than 1250 ℃ or with the help of catalysts (e.g., nickel-based catalysts).

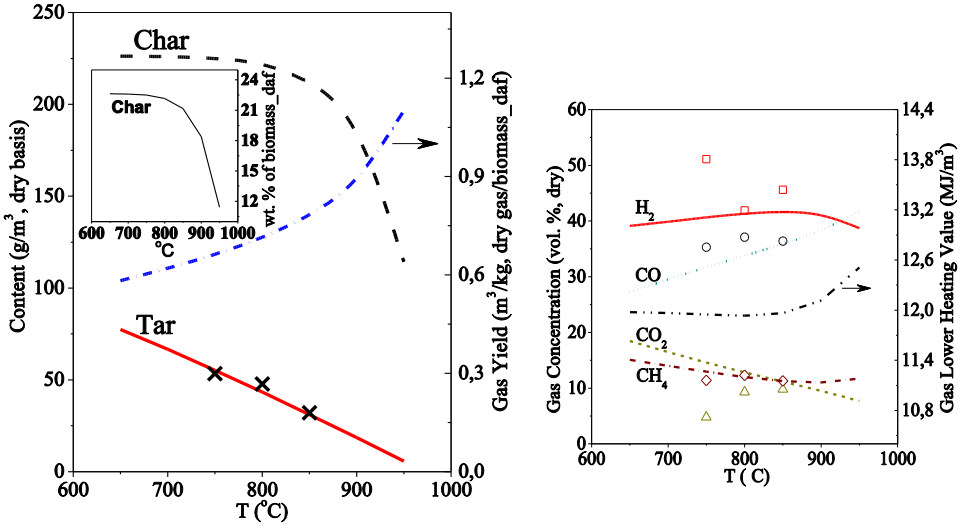
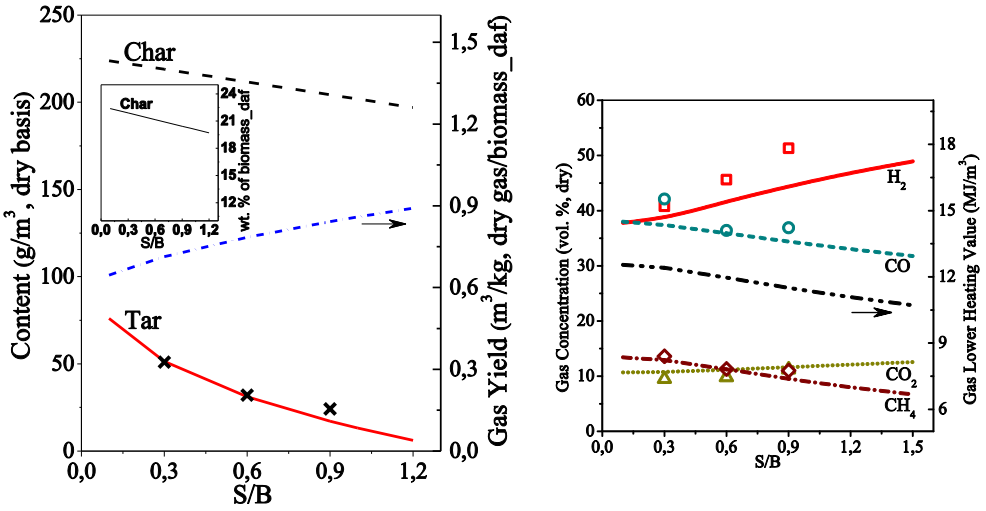


Fig. 4.1: Effect of temperature on the gasification (experiment—MIUN gasifier, wood pellets, sand bed material, S/B=0.6, τ=5.0 s, d_p=5.0 mm)

4.1.2 Effect of S/B

S/B values were calculated with an assumption that the dry biomass has 5.0 wt.% moisture. The tar content decreases from 50.0 g/m³ at S/B = 0.3 down to about 10.0 g/m³ at S/B = 1.2 attributed to the enhanced steam reforming of tar. The char fraction is insensitive to S/B as shown in Fig. 4.2(a). The syngas yield is in the range of 0.8–1.0 Nm³/kg daf biomass, and the LHV is about 11.65 MJ/Nm³. Both calculated data are fairly close to the measurement results from a pilot DFBG plant at Vienna University of Technology (Pfeifer, Rauch et al. 2004).

The H_2/CO ratio is a strong function of the S/B ratio, which is primarily controlled by the water–gas shift reaction. The H_2 concentration is higher than that of CO under normal DFBG operating conditions, but they will change positions when the S/B ratio is too far below bout 0.15 as seen in Fig. 4.2(b). The CH_4 concentration is around 10.0 vol. % and not sensitive to the S/B ratio.



(a) (b)

Fig. 4.2: Effect of S/B on the gasification (experiment—MIUN gasifier, wood pellets, sand bed material, 850 ℃, τ=5.0 s, d_p=5.0 mm)

4.1.3 Effect of biomass moisture content

For an autothermal gasifier, gasification temperature can be held by adjusting the oxygen equivalent ratio. For a DFBG, extra fuel needs to be added in the combustor. Fig. 4.3 shows that the gasification temperature is difficult to be kept above 850 ℃ when the biomass moisture content is higher than 15.0 wt.%. Gasification temperature can be raised about 50 to 100 ℃ when the combusted biomass is 10.0 wt.% of the total biomass feedstock, as seen in Fig. 4.3.

In Fig. 4.4, the exact amount of the combusted biomass can be found out corresponding to different biomass moisture content when the gasification temperature is held at 850 ℃ in three cases of S/B = 0.3, 0.6, and 0.9, respectively.

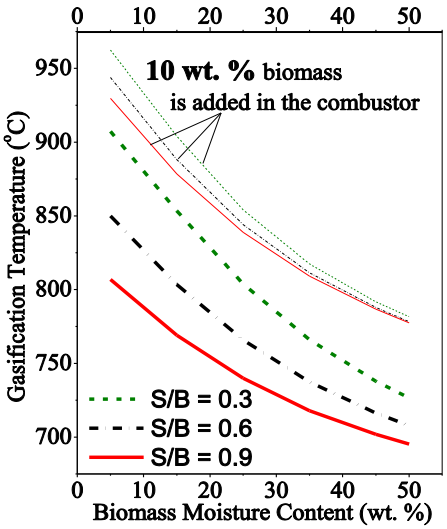


Fig. 4.3: Effect of biomass moisture content on the gasification temperature (experiment—MIUN gasifier, wood pellets, sand bed material, τ=5.0 s, d_p=5.0 mm)

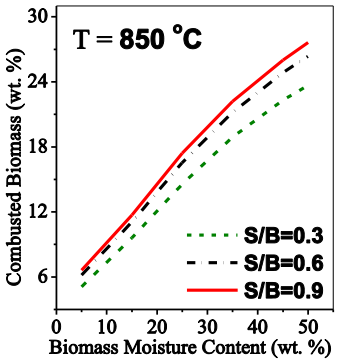


Fig. 4.4: Fraction of biomass combusted to hold the gasification temperature (experiment—MIUN gasifier, wood pellets, sand bed material, 850 ℃, τ=5.0 s, d_p=5.0 mm)

4.1.4 Effect of residence time

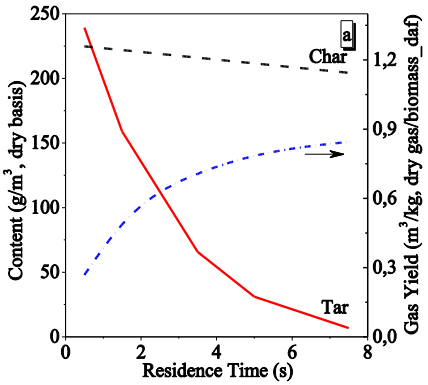


Fig. 4.5: Effect of residence time on the gasification (experiment—MIUN gasifier, wood pellets, sand bed material, 850 ℃, S/B=0.6, d_p=5.0 mm)

The tar content in the syngas decreases significantly with gasification residence time which is a key parameter (Fig. 4.5). But, char content is insensitive to the residence time. The syngas yield is therefore increased.

4.2 Biomass-to-Ethanol

4.2.1 Ethanol production cost vs. plant scale

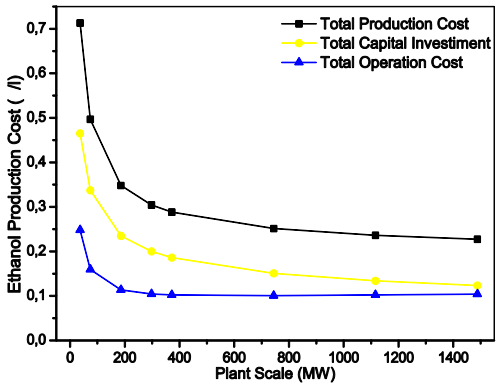


Fig. 4.6: Ethanol production cost as a function of plant scale

A mathematic model for techno-economic assessment of the thermo-chemical biomass-to-ethanol process has been developed mainly with ASPEN Plus. The assessment is made in terms of carbon and CO conversion efficiencies, ethanol yield, synthesis selectivity and ethanol production cost.

As shown in Fig. 4.6, obviously the production cost decreases with the plant size due to the economic scaling effect. In particular, with small scales up to 200 MW, the production cost decreases rapidly and levels off. This suggests that a thermo-chemical biomass-to-ethanol plant should be built at around 200 MW. The production cost at this scale is around 0.33 €/l ethanol, which might be reduced further to 0.25 €/l ethanol in the scale of 1000 MW. However, a 1000 MW ethanol plant based on biomass is not realistic due to limited feedstock availability. The biomass price is held constant in the present model calculation, but it will also rise dramatically for the large plant and leads to a high operation cost.

The economic scaling effect is mainly attributed to the capital investment. For a small ethanol plant, the capital investment is much higher than the operation cost, as shown in Fig. 4.6. The gap between the capital investment and the operation cost is becoming smaller and smaller as the plant is becoming larger and larger, and the process equipment is utilized more efficiently. The first huge capital investment plus the risk in the thermo-chemical conversion technologies is the biggest barrier to BTL commercialization.

4.2.2 Capital Investment

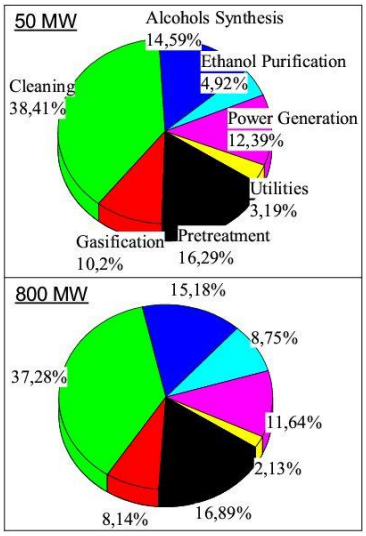


Fig. 4.7: Capital cost breakdown

The capital investment is broken down by the costs of individual processes, pretreatment, gasification, syngas cleaning, alcohols synthesis, alcohols separation and purification, power generation, and the utilities as shown in Fig. 4.7. The biggest share of total capital investment is allocated to the syngas cleaning including tars/CH_4 reforming by about 38%, followed by about 16% of biomass pretreatment and about 15% of alcohols synthesis. The capital cost distribution is not sensitive to the ethanol plant size.

The huge cost of syngas cleaning in response to a limited size of ethanol plant is the most important factor limiting commercial production of ethanol from biomass via thermo-chemical conversion. This is a big drawback compared with biochemical conversion.

4.2.3 Production cost contribution

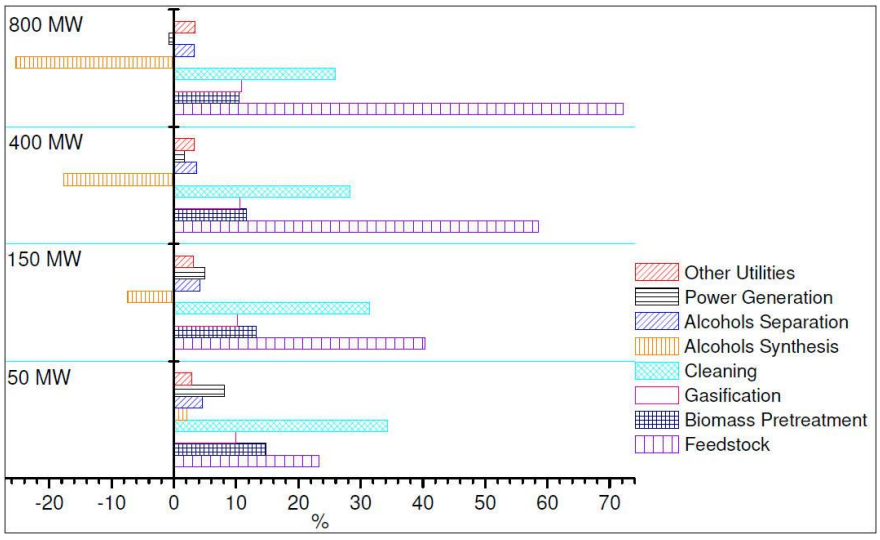


Fig. 4.8: Production cost contribution chart

The total production cost is broken down as shown in Fig. 4.8. The costs of biomass raw material and syngas cleaning are the two biggest shares of the total production cost. As the ethanol plant is becoming larger, the raw material cost grows to make up a larger share of the total production cost, while the syngas cleaning and other capital investment cost shares get smaller. On the other hand, the mixture of higher alcohols is also produced as a valuable by-product to ethanol. The higher alcohols credit exerts a negative effect on the ethanol production cost, and compensates for the high cost of biomass raw material. This cost compensation by the higher alcohols credit is much clearer when the plant size is bigger.

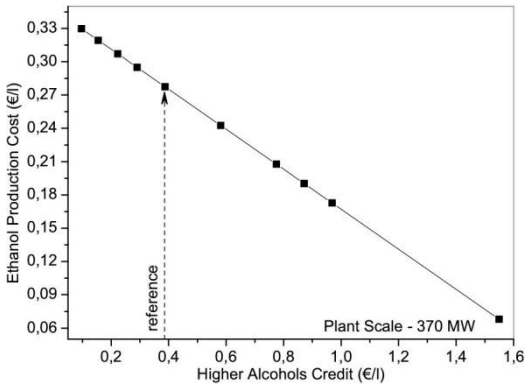


Fig. 4.9: Sensitivity of higher alcohols credit to the ethanol production cost

The degree of compensation depends on higher alcohols' end-use. For a low-value use as an excellent gasoline additive, higher alcohols would have a selling price similar to that of fossil fuels (about 0.16 €/l) (Phillips, Aden et al. 2007). For a high-value use as chemicals, higher alcohols would have a selling price of about 0.81 €/l (Phillips, Aden et al. 2007). Fig. 4.9 shows the ethanol production cost against the higher alcohols' selling price. It can be seen clearly that the production cost is reduced from 0.31 €/l when higher alcohols are used as a gasoline additive to about 0.19 e/l when higher alcohols are used as chemicals. In summary, cost-competitive ethanol production can be realized with efficient equipment, optimized operation, cost-effective syngas cleaning technology, inexpensive raw material with low pre-treatment cost, high-performance catalysts, off-gas and methanol recycling, optimal systematic configuration and heat integration, and a high value by-product.

4.3 TMP+BIGCC

4.3.1 Implementation of BIGCC in a TMP mill

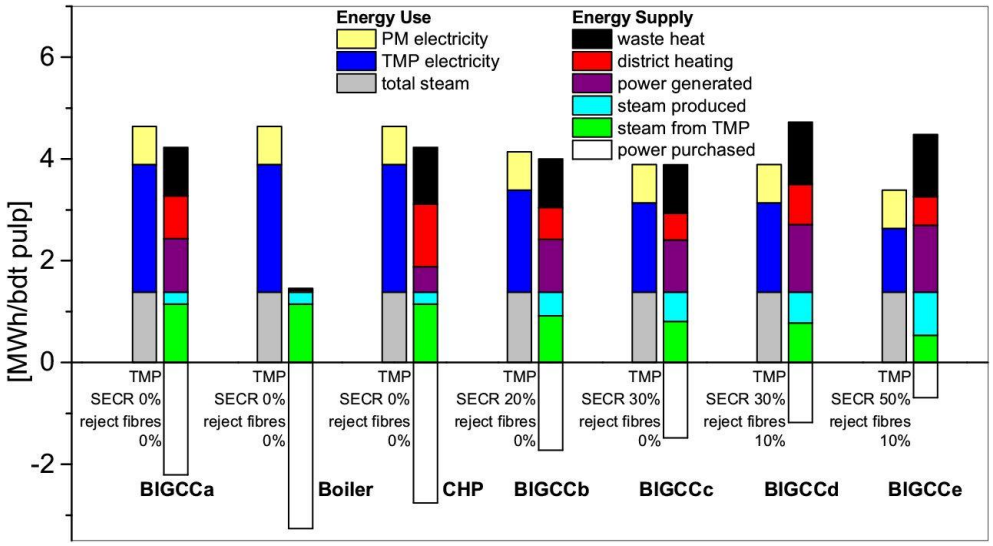


Fig. 4.10: TMP energy use and supply

The energy balance over the BIGCC (or Boiler or CHP) process is studied by applying the model. Table 3.1 shows how much biomass can be available. The TMP+PM required steam is from the TMP and BIGCC, Boiler, or CHP processes. The total steam demand is kept constant because of the constant paper throughput. The enhancement of refining efficiency lowers the steam yield from TMP. Moving out the reject fibres also facilitates the reduction of TMP SEC. Less steam from TMP aggravates the steam supply from BIGCC (BIGCCa = CHP = Boiler < BIGCCb < BIGCCc < BIGCCd < BIGCCe). The model is designed to ensure that the steam consumption is sufficiently satisfied, as the results indicate (Fig. 4.10). For the TMP+PM mill studied, the TMP SEC is about 2.5 MWh/bdt pulp, the PM SEC is about 0.75 MWh/bdt pulp, and the steam consumption is about 1.38 MWh/bdt pulp.

Compared with CHP, BIGCC has a higher electricity generation efficiency of 44%. As a result, by implementing the BIGCC system in a TMP mill, less electricity will need to be purchased, and less when the TMP SEC is reduced, and even less when the reject fibres material is taken into account (BIGCCa > BIGCCb > BIGCCc > BIGCCd > BIGCCe) (Fig. 4.10).

The electricity generation efficiency of a full-scale BIGCC plant can approach to 50%. A BIGCC plant associated with a TMP+PM mill needs to supply PM steam, which lowers the electricity generation efficiency. As shown in Fig. 4.10, for a BIGCC system, intensifying the steam supply weakens its electricity yield. For instance, for the steam supply, the sequence is BIGCCb < BIGCCc (or BIGCCd < BIGCCe), while for the electricity generation efficiency, the sequence is reversed, i.e., BIGCCb > BIGCCc (or BIGCCd > BIGCCe).

The residual low-grade energy from the BIGCC (or Boiler or CHP) process is utilized in DH (Table 3.2). For the TMP+BIGCC cases, the available heat energy for DH drops with the decreasing of TMP SEC (available heat for DH: BIGCCb > BIGCCc; BIGCCd > BIGCCe). Two levels of turbine sets are respectively adopted, a high (from 100 bar to 2.5 bar) and a low (from 100 bar to 0.6 bar) pressure levels (Fig. 3.6). The most heat energy for DH is from the condensing of the discharged 0.6 bar steam (latent heat). As aforementioned, as the TMP SEC falls, a greater part of the original 100 bar steam will be distributed to the 2.5 bar level turbine set. As a result, the usable latent heat is discounted.

4.3.2 Additional biomass

Biomass heat and power plants scaled up to 100 MW (in biomass energy input) have been popular in Sweden as well as other forest-rich countries. Forest logging residues, peat, biomass from short rotation forestry, and some industrial and household wastes, etc. are all available resources that can be taken as feedstock to BIGCC plants. Electricity consumed in a TMP mill can be fully afforded by a BIGCC plant without difficulty concerning biomass availability.

As indicated by the thick solid line in Fig. 4.11(a), the electricity supply from BIGCC, increasing with the amount of biomass used, tends to meet the TMP+PM consumption when about 9.4 MWh biomass per tonne of pulp is used. However, a great amount of heat is also generated along with the electricity production. This huge supply of low-grade energy must be directed to other uses such as DH. As clearly shown in Fig. 4.11, BIGCC yields much more electricity and much less heat than CHP.

Fig. 4.11(c) and (d) show that both the net revenue and the IRR increase significantly with the amount of biomass, and increase faster as the electricity price gets higher. The economic profitability of a TMP mill is more sensitive to the electricity price when a smaller amount of biomass is available to be fed into the gasifier, but is more sensitive to the pulpwood price when a larger amount of biomass is available to be fed into the gasifier (Fig. 4.11(c) and (d)). The electricity

certificate instrument is an effective incitement, and directly adds 30 EUR per MWh electricity produced from biomass to the net revenue of the TMP+BIGCC or TMP+CHP mill. It is more profitable to invest in BIGCC than in CHP when more biomass is used for heat and power production. Plant scale and electricity price are two strong factors for the implementation of BIGCC in a TMP mill.

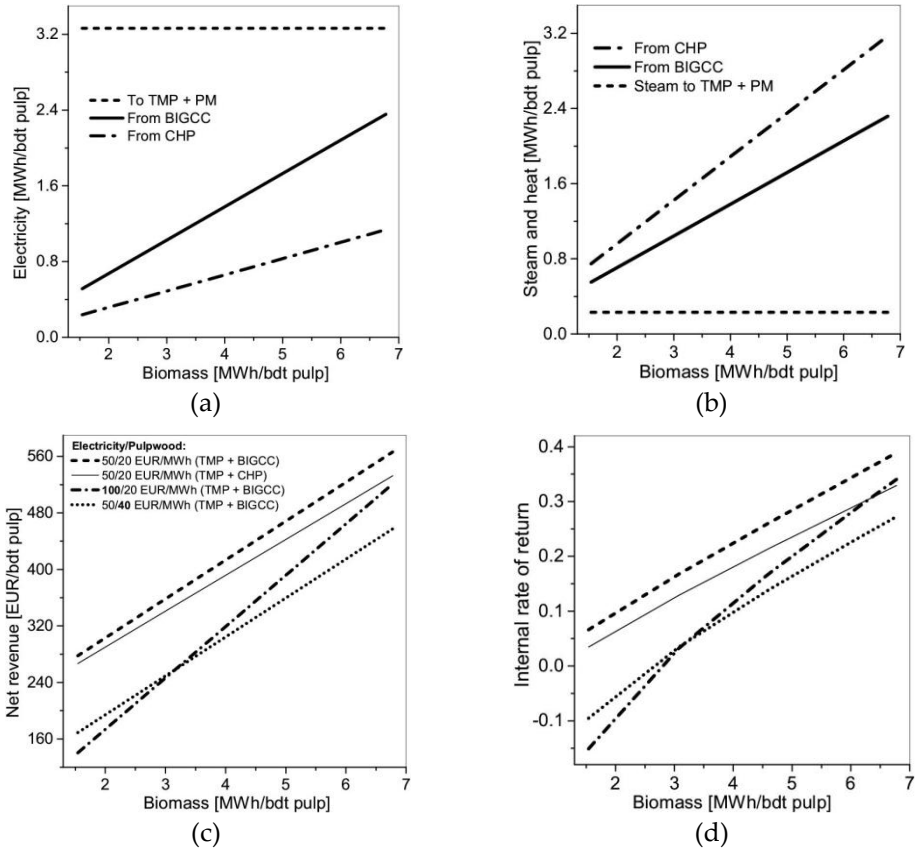


Fig. 4.11: Effect of the amount of biomass

4.3.3 Reject fibres to gasifier

Usually in TMP mills, up to about 10% of the pulp fibres have properties that are not good enough to remain in the final product, and they may be removed as reject fibres. The reject fibres can be utilized as feedstock to biomass gasifiers. 20% TMP SECR should be possible when taking out the 10% worst fibre material with respect to final paper product properties (Westermark and Capretti 1988).

As seen in Fig. 4.12*(a)*, the electricity yield from BIGCC slightly increases with the amount of reject fibres, but is far from the TMP+PM electricity consumption denoted by the dashed line. The electricity yield of BIGCC has been twice more than that of CHP.

The y-axis in Fig. 4.12*(b)* represents the amount of steam and heat produced, including steam from BIGCC to TMP+PM, and heat from BIGCC to DH. The amount gets up as more reject fibres are transferred to the gasifier. Lower TMP SEC will lead to less steam supply from TMP. As a result, the heat and power plant needs to supply more steam. Obviously, CHP gives more steam and heat than BIGCC as much less electricity is generated by CHP.

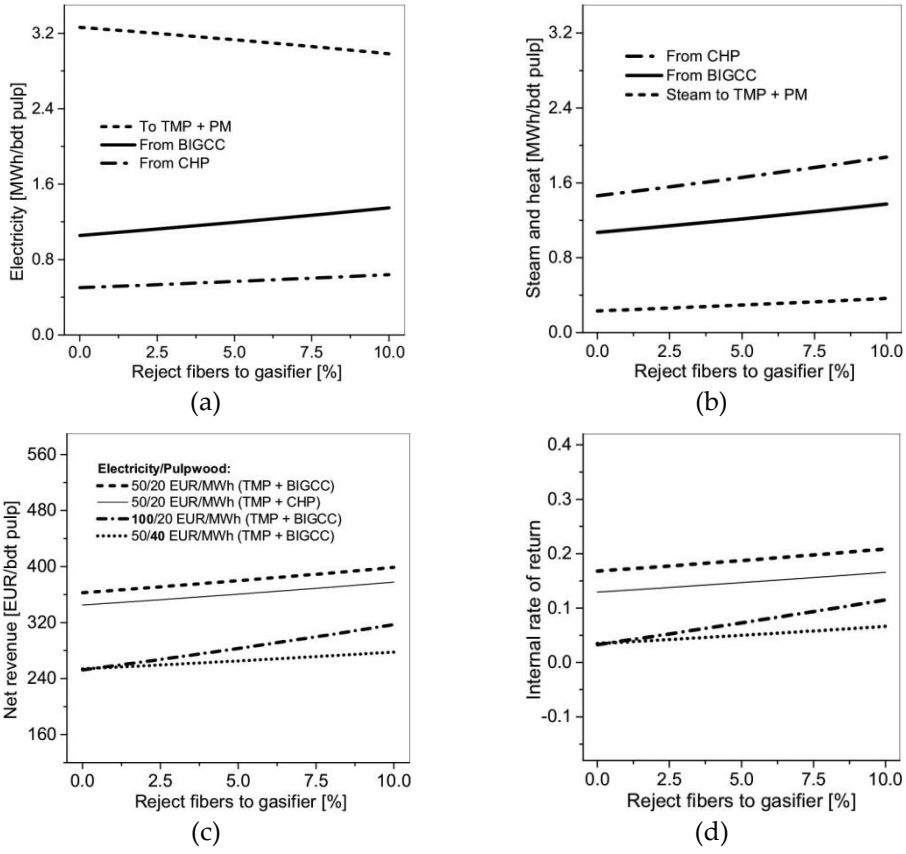


Fig. 4.12: Effect of adding reject fibres

Normally, the prices of electricity and pulpwood are 50 and 20 € /MWh, respectively (Fig. 4.12*(c)* and *(d)*). Both the net revenue and the IRR values increase with the amount of the reject fibres. This can be explained by several factors: 1)

more electricity is generated as more reject fibres are added; 2) the TMP SEC is cut down; 3) the paper yield is held by supplementing pulpwood. Both the net revenue and the IRR values of TMP+BIGCC are much higher than those of TMP+CHP, as shown in Fig. 4.12*(c)* and *(d)*. This is because BIGCC produces much more electricity than CHP for the same amount of biomass residues, and has a lower specific investment cost than CHP (see Table 3.3). An increase in the market electricity price from 50 to 100 €/MWh obviously reduces the net revenue, as shown by the dash-dot line in Fig. 4.12*(c)*. The economic profitability is sensitive to both the electricity and the pulpwood prices (Fig. 4.12*(c)* and *(d)*).

4.3.4 Improved electric energy efficiency of the TMP-line

As discussed above, TMP SEC is a key factor in the high cost pulp production. A 50% SECR is targeted. The SECR is indicated by a dashed line in Fig. 4.13*(a)*. The TMP+PM electricity consumption cannot be fully made up by the electricity supply from BIGCC, even if the TMP SEC goes down by 50%. But the gap becomes fairly small, and much smaller in comparison with the case of CHP. Since a certain amount of 2.5 bar steam is withdrawn from BIGCC, the electricity generation efficiency of the steam turbine cycle will be lowered, which gives rise to a slightly lower electricity yield from BIGCC, as seen in Fig. 4.13*(a)*.

The steam supply by TMP is impaired with the SECR. The margin must be supplemented by BIGCC (or CHP). A resulted increase in the steam and heat from BIGCC (or CHP) can be observed from Fig. 4.13*(b)*. In some TMP+PM mills, a backup boiler is specially used to supply steam without self-production of electricity. In the TMP+Boiler case, a proper amount of biomass will be fed into for offering PM a certain amount of steam. As observed from the inset figure *in* Fig. 4.13*(b)*, the boiler needs more biomass as the SEC declines, and the available biomass (bark + bio-sludge) within the TMP mill will no longer be enough when the SEC is decreased by more than 34%. By further accumulating the reject fibres, it becomes sufficient.

As shown in Fig. 4.13*(c) and (d)*, lower TMP SEC leads to higher economic profit in both the net revenue and the IRR. For both the net revenue and the IRR, TMP+BIGCC > TMP+CHP > TMP+Boiler. This is mainly attributed to the lower specific investment cost in BIGCC. The investment of BIGCC is expected to be further decreased with more research and development towards the commercialization of BIGCC technology. So far, the BIGCC technology has not been fully commercialized. Risks exist when BIGCC is implemented to the industries, including the pulp and paper industry.

In this evaluation, the heat price is assumed to be 80 €/MWh higher than the electricity price of 50 €/MWh. This assumption is in line with the current situation in Sweden that low tax is put on the electricity for industrial use and high tax for domestic use. In the long run, the electricity price for industrial use is reasonably going over the price of heat.

In the case that the electricity price for industries is the same as that for residential use in Sweden, about 150 €/MWh, the IRR of a TMP mill will drop below about -25%, but for a TMP+BIGCC plant, the IRR can rapidly be raised to a positive value, depending on how much biomass residues will be used for electricity production.

Both the pulpwood and the electricity prices are key factors in determining the economic profitability of a TMP mill, as estimated by the model. In the Swedish market, solid bio-fuels and pulpwood have fairly stable low prices, while the electricity price is rather volatile. It can be said from practical viewpoint that the economic profitability of a TMP mill is dominated by the electricity price.

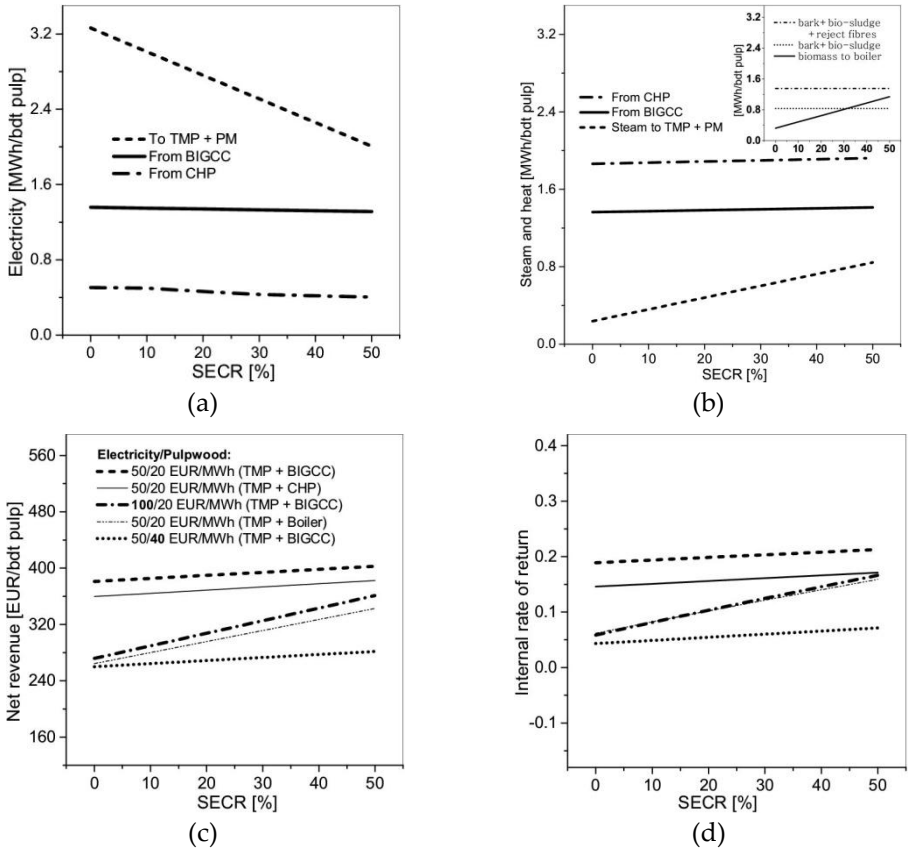


Fig. 4.13: Effect of reducing the TMP-specific electricity consumption

4.4 TMP+BtSNG

4.4.1 Implementation of BtSNG in a TMP mill

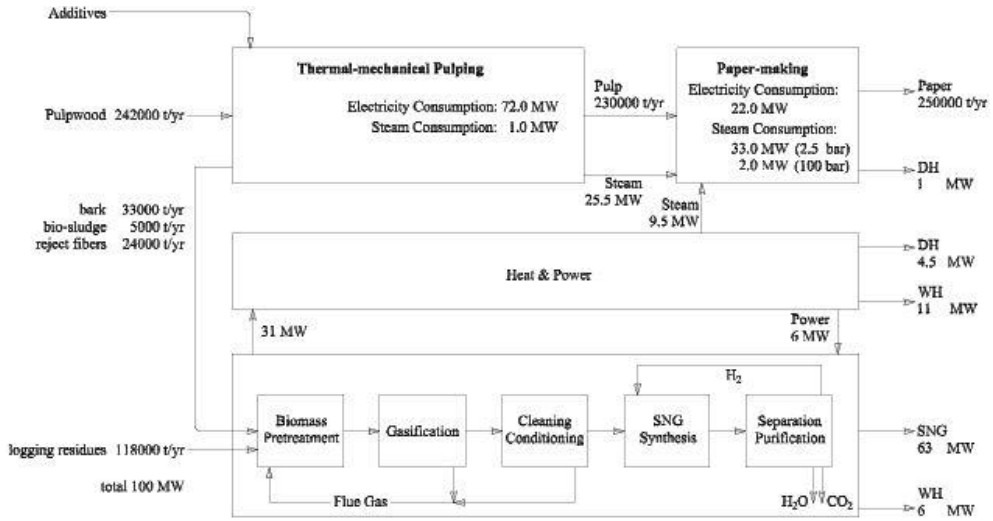


Fig. 4.14: A TMP+BtSNG block flow diagram with the major mass and energy inputs and outputs

The TMP+BtSNG block flow diagram with an outline of mass and energy input and output is shown in Fig. 4.14. About 100 MW of biomass residues including bark, bio-sludge, reject fibres from TMP and logging residues from pulpwood harvesting in forest is available for BtSNG production in the TMP+PM mill with a paper production capacity of 250,000 t/yr. 63 MW of bio-SNG can be produced as the bio-SNG yield of BtSNG is estimated to be 63%. The remaining energy of 37 MW of biomass feedstock is carried by flue gas from the combustor, product gas from the gasifier, the cooling medium from methanation etc. in the form of heat at different temperatures. This heat energy is recovered to generate 31 MW steam going to the steam cycle in the heat & power (H&P) centre with 6 MW heat loss. The H&P centre subsequently supplies TMP+PM with 9.5 MW steam, BtSNG itself with 6.0 MW electricity, and DH with 4.5 MW low temperature heat.

The steam cycle in the H&P centre has a generation efficiency of 20% and produces 6.0 MW electricity to meet the demand of BtSNG for the compression of syngas and bio- SNG, syngas cleaning, CO_2 removal, gasifier operation etc.. Little excess electricity is available for the TMP+PM mill. On the other hand, the H&P centre can supply TMP+PM with enough steam, 9.5 MW, and 4.5 MW low grade heat energy can be recovered as DH. As a result, the H&P centre has a total efficiency of about 65%, and BtSNG has an overall efficiency of 83%.

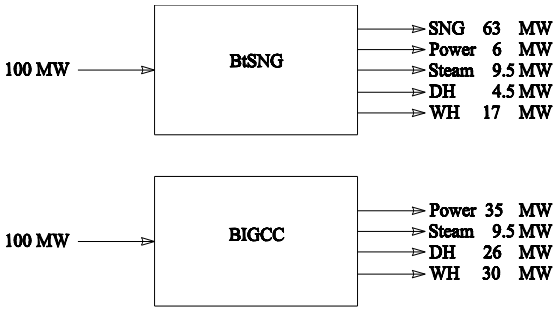


Fig. 4.15: Comparison of BtSNG with BIGCC regarding their outputs in energy content

Comparing to BIGCC as seen in Fig. 4.15, BtSNG gives almost double product yield in terms of energy content, which results in much lower waste heat (WH) and DH.

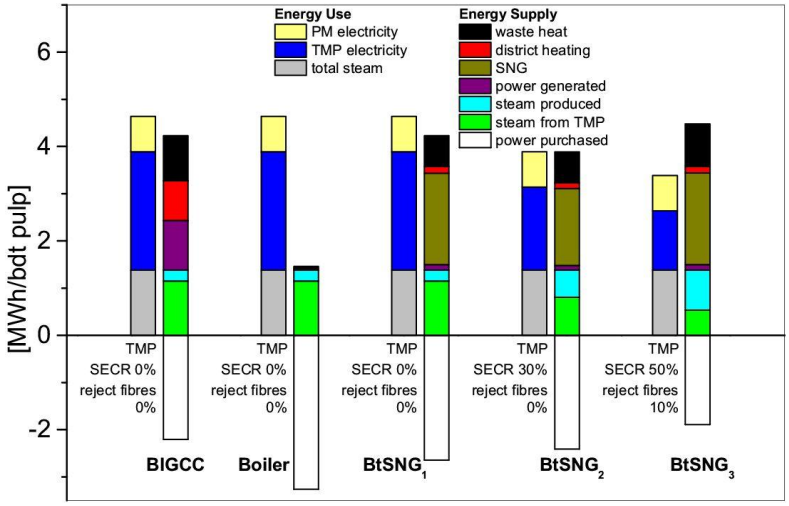


Fig. 4.16: Poly-generation of SNG, electricity, and heat in a TMP mill

The energy balance over the TMP+BtSNG mill is studied by applying the model, in comparison with other two cases of TMP+BIGCC and TMP+Boiler studied previously (He, Engstrand et al. 2013), as seen in Fig. 4.16.

For the TMP+PM mill studied, the TMP SEC is 2.5 MWh/bdt pulp, the PM SEC is 0.75 MWh/bdt pulp, and the steam consumption in the PM is 1.38 MWh/bdt pulp. The total steam demand is kept constant because of the constant paper throughput, and is provided from the steam energy recovered mainly from the TMP refining

process and also from the BtSNG process to a minor degree. The enhancement of refining efficiency lowers the steam yield from TMP. Moving out the reject fibres makes the TMP more energy-efficient, i.e., the TMP SEC is reduced, and the steam yield from TMP is also reduced. A decrease in the steam generation from TMP is compensated for from the BtSNG plant so that the bio-SNG yield may be reduced. The model is designed to ensure that the steam consumption is sufficiently satisfied, as the results indicate in Fig. 4.16. The residual low-grade energy is utilized in DH. The heat energy for DH is from both TMP and BtSNG.

4.4.2 Economics of scale

The above analysis of energy balance over the TMP+BtSNG mill is based on a typical scale of TMP+PM mills with a paper production capacity of 250,000 t/yr. The corresponding scale of the BtSNG plant is 100 MW of biomass thermal input according to Fig. 3.5 and Fig. 4.14 estimation. The scale of the BtSNG will be taken to represent the whole scale of the TMP+BtSNG mill for economical analysis as shown in Fig. 4.17.

As seen in Fig. 4.17(a), the bio-SNG production per tonne pulp holds constant against the scale, which indicates a linear relationship between the bio-SNG production and the TMP pulp output. The steam produced from the H&P centre associated to the BtSNG plant is fairly limited in comparison with the BIGCC plant, but still can meet the demand of the TMP+PM mill as shown in Fig. 4.17(b). Very little heat energy is available for DH, which can also be observed from Fig. 4.16.

The economic profitability is also sensitive to both the SNG price and the pulpwood price as seen in Fig. 4.17(c) and (d). When the SNG price is doubled, the IRR increases from about 2% to about 16%. When the pulpwood price is doubled, the IRR decreases from about 2% down to about -13%.

Comparing to the results of the case of TMP+BIGCC, represented by the dashed curve in Fig. 4.17(c) and (d), the NR and IRR of TMP+BtSNG are much lower. This is attributed to 3 reasons, 1) the specific investment cost is much higher for BtSNG, 2) The electricity certificate instrument in Sweden has added a credit to the electricity production, and 3) Much more DH is produced by BIGCC, and DH has a price unusually high (higher than electricity) in Sweden.

In summary, plant scale and SNG price are two strong factors for the implementation of BtSNG in a TMP mill. A BtSNG plant associated to a TMP mill should be built at a scale above 100 MW in biomass thermal input. Political instruments to support commercialization of bio-transport fuel are necessary.

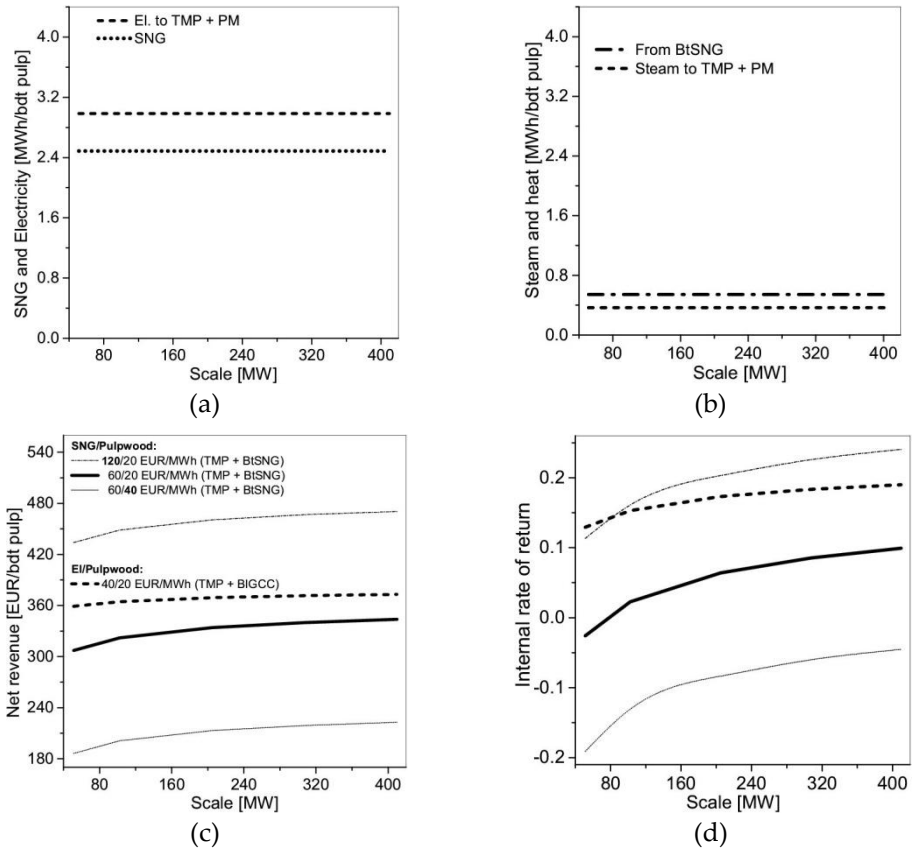


Fig. 4.17: Effect of the scale of TMP+Mill represented by the biomass thermal input to the BtSNG plant

4.4.3 Reject fibres to gasifier

Usually in TMP mills, up to about 10 wt.% of the pulp fibres have properties that are not good enough to remain in the final product, and they may be removed as reject fibres. They can be utilized as feedstock to biomass gasifiers. 20% TMP SECR should be possible when taking out the fibres with respect to final paper product properties (Westermark and Capretti 1988).

As seen in Fig. 4.18(a), with the amount of reject fibres, the bio-SNG yield per tonne pulp clearly increases for two reasons, 1) the reject fibres are directly added in the gasifer, and 2) the usable biomass residues increases as the product paper output is kept constant. Corresponding to the increase in feedstock, the amount of steam and heat produced from BtSNG increases as well. At the same time, the steam demand by the TMP+PM mill also increases since the low quality fibre

rejection possibly leads to a lower TMP SEC and less steam supply from TMP to PM. Thus, the steam demand by TMP+PM is well balanced with the steam supply from BtSNG.

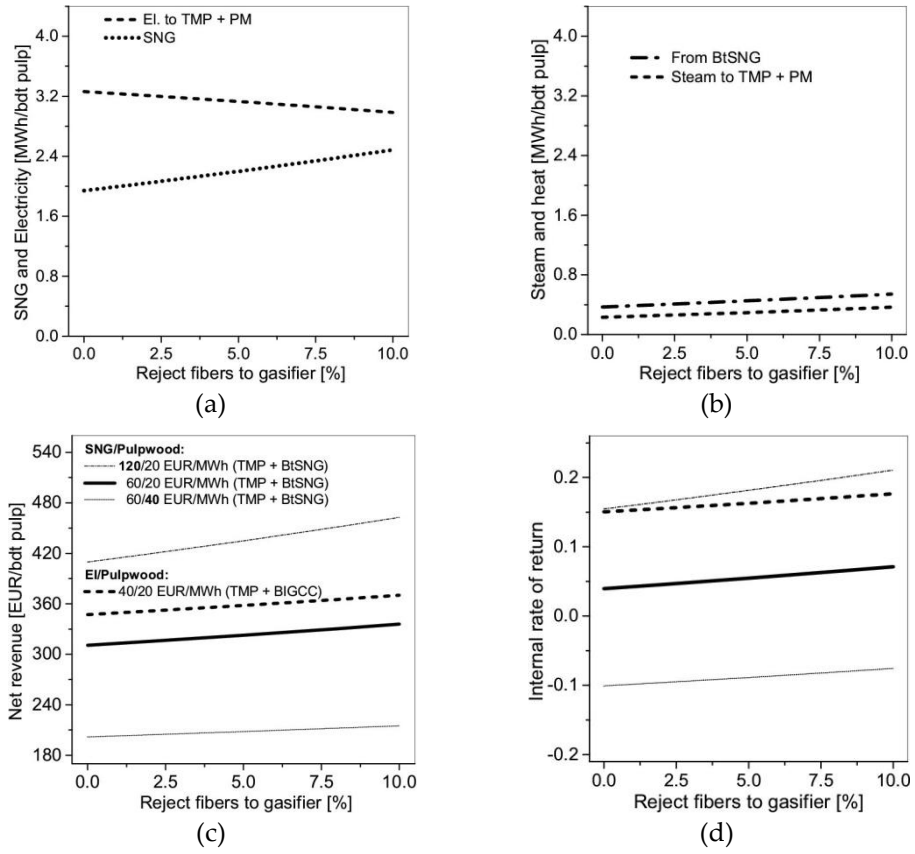


Fig. 4.18: Effect of adding reject fibres

Fig. 4.18(c) and Fig. 4.18(d) show that the NR and the IRR values increase with the amount of the reject fibres. This can be explained by several factors: 1) more SNG is generated as more reject fibres are added; 2) the TMP SEC is cut down; 3) the paper yield is held by supplementing pulpwood. Comparing to the case of TMP+BIGCC, TMP+BtSNG shows a much lower profitability for the same reasons mentioned above.

4.4.4 Improved electric energy efficiency of the TMP-line

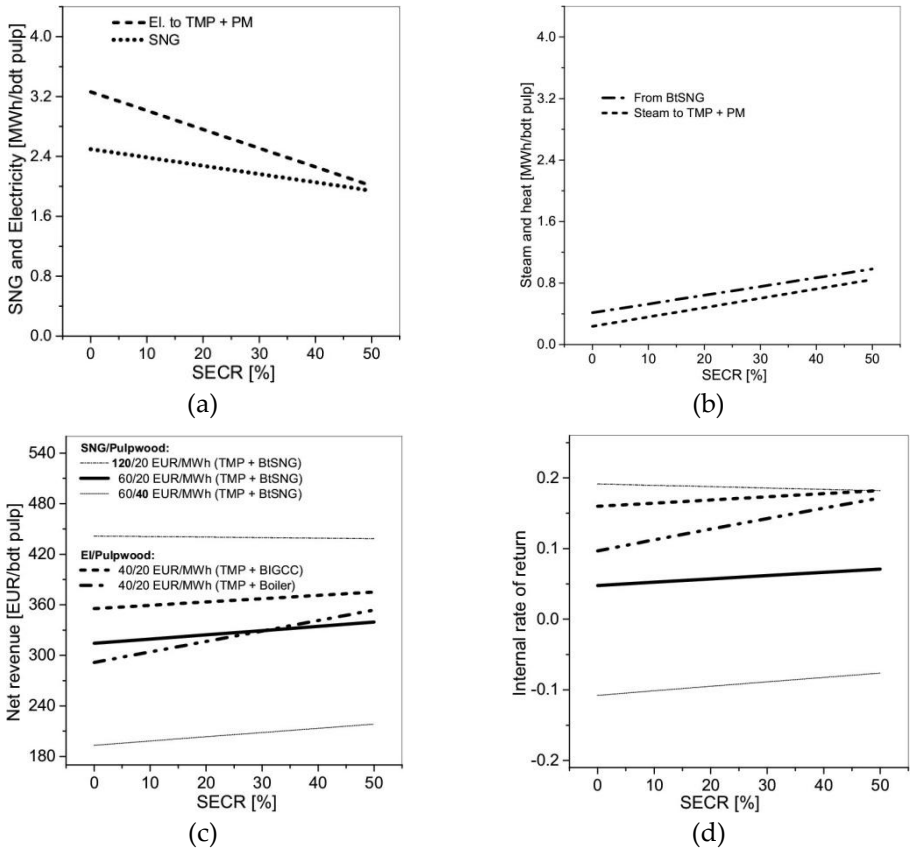


Fig. 4.19: Effect of reducing the TMP-specific electricity consumption

TMP SEC is a key factor in the high cost pulp production. A 50% SECR is targeted. The SECR is indicated by a dashed line in Fig. 4.19(a). With SECR, less steam can be supplied from TMP. BtSNG must make up the balance (Fig. 4.19(b)). The availability of biomass for the conversion from biomass to SNG will therefore be lowered (Fig. 4.19(a)).

A resulted increase in the steam and heat can be observed from Fig. 4.19(b). In some TMP+PM mills, a backup boiler is specially used to supply steam without self-production of electricity. In the TMP+Boiler case, a proper amount of biomass will be fed into for offering PM a certain amount of steam. In the case of TMP+BtSNG, more steam than normal supply from the BtSNG plant must be produced at the expense of bio-SNG yield.

As shown in Fig. 4.19(c) and (d), lower TMP SEC leads to higher economic profit in both NR and IRR. For NR, TMP+BIGCC > TMP+BtSNG > TMP+Boiler, but for IRR, TMP+BIGCC > TMP+Boiler > TMP+BtSNG.

Markets like Sweden, where bio-methane is highly valued, the natural gas price is relatively high, and the feedstock supply is good, are likely to see the first installation of commercial S&M scale bio-SNG production. However, since the bio-methane market in Sweden is far from mature, it is still heavily dependent on political ambitions and associated instruments, as well as regional and local initiatives and the relatively high natural gas price.

5 CONCLUSIONS

Gasification

A mathematic model is established to simulate biomass gasification in the DFBGs. The model predicts that the content of char transferred from the gasifier to the combustor decreases from 22.5 wt.% of the dry and ash-free biomass at gasification temperature 750 ℃ to 11.5 wt.% at 950 ℃, but is insensitive to S/B. The H_2 concentration is higher than that of CO under the normal DFBG operation conditions, but they will change positions when the gasification temperature is too high above about 950 ℃, or the S/B ratio is too low under about 0.15. The biomass moisture content is a key parameter for a DFBG to be operated and maintained at a high gasification temperature. The model suggests that the gasification temperature is difficult to be kept above 850 ℃ when the biomass moisture content is higher than 15.0 wt.%. Thus, a certain amount of biomass needs to be added in the combustor to provide sufficient heat for biomass devolatilization and steam reforming. Tar content in the syngas can also be predicted from the model, which shows a decreasing trend of the tar with the gasification temperature and the S/B ratio. The tar content in the syngas decreases significantly with gasification residence time which is a key parameter.

Biomass-to-Ethanol

A mathematic model for a techno-economic assessment of the thermo-chemical biomass-to-ethanol process has been developed. The assessment is made in terms of carbon and CO conversion efficiencies, ethanol yield, synthesis selectivity, and ethanol production cost.

Calculated results show that major contributions to the production cost are from syngas cleaning and biomass feedstock. A biomass-to-ethanol plant should be built at around 200 MW as the biomass input, which gives the ethanol production cost of 0.33 €/l in the context of a typical developed country. The capital investment is much higher than the operation cost and dominates the total ethanol production cost for small- and medium scale plants. This suggests that the first huge capital investment with technological risk is a big barrier to the commercialization of a thermo-chemical biomass-to-ethanol process. The costs of biomass raw material and syngas cleaning are the two biggest shares of the total production cost. As the ethanol plant becomes larger, the raw material cost makes up a larger share of the total production cost. This can be off-set to a certain extent by the higher alcohols credit, which might reduce the ethanol production cost from 0.31 €/l to about 0.19 e/l when the higher alcohols are used as valuable chemicals.

TMP+BIGCC

A TMP+BIGCC mathematical model is developed to make the techno-economic analysis of the TMP+BIGCC mill in comparison with a TMP+CHP and TMP+Boiler mills.

The electricity yield of BIGCC has been more than double that of CHP. BIGCC has a lower specific capital investment than CHP, which results in a shorter discount payback period and higher IRR. It is more profitable to invest in BIGCC than in CHP when more biomass is used for heat and power production and when the market electricity price is higher. The economic profitability of a TMP mill is more sensitive to the electricity price than the pulpwood price in today's TMP industry when the SEC is high, and no BIGCC is used to provide TMP electricity. The profitability will be dominated by the pulpwood price when the SEC is low, and a great part of electricity to TMP is produced by an associated BIGCC plant. The plant scale and market electricity price are two strong factors determining the implementation of BIGCC in a TMP mill.

Both the net revenue and the IRR increase with the amount of the reject fibres, since more electricity is self-produced on-site, the TMP SEC is reduced, and the paper output is held constant while more pulpwood is added. Rejection of low-quality pulp fibres and their reuse in BIGCC for self-production of electricity, and electricity certificate are highly attractive measures to raise the profitability of a TMP mill.

The TMP+PM electricity consumption cannot be fully made up by the electricity supply from a BIGCC plant, even if the TMP SEC goes down by 50%. But the gap becomes fairly small, and much smaller in comparison with the case of a CHP plant. Lower TMP SEC leads to higher economic profit in both the net revenue and the IRR. The profits are ranked as: TMP+BIGCC > TMP+CHP > TMP+Boiler.

TMP+BtSNG

A TMP+BtSNG mathematical model is developed based on the economical conditions in Sweden. The profitability of the TMP+BtSNG mill is evaluated in comparison with the TMP+BIGCC mill. The model prediction can be concluded below:

The scale of the TMP+BtSNG mill and SNG price are two strong factors for the implementation of BtSNG in a TMP mill. A BtSNG plant associated to a TMP mill should be built at a scale above 100 MW in biomass thermal input.

Comparing to the case of TMP+BIGCC, the NR and IRR of TMP+BtSNG are much lower. This is attributed to 3 reasons, 1) the specific investment cost is much higher for BtSNG, 2) The electricity certificate instrument in Sweden has added a credit to the electricity production, and 3) Much more DH is produced by BIGCC, and DH has a price unusually high (higher than electricity), in Sweden. Political instruments to support commercialization of bio-transport fuel are necessary.

6 FUTURE RESEARCH

The simulation can be extended to the following fields.

Fuel cell

The energy efficiency of a fuel cell is generally between 40–60%, or up to 85% if waste heat is captured for use. It is also important to take losses due to fuel production, transportation, storage and distribution into account. The maximum theoretical energy efficiency of a fuel cell is 83%. Comparatively, an internal combustion engine has a maximum theoretical efficiency of 58%, as indicated by the World Energy Council. The typical internal combustion engine of a car is about 25% energy efficient. While fuel cells are efficient relative to combustion engines, they are not as efficient as batteries.

The link-up of wood gasification with high temperature solid oxide fuel cells (BIGFC) is a promising approach to reach high electrical efficiencies in small-scale biomass fuelled CHP plants.

BtDME

An evaluation can be performed on converting biomass to DME via a gasification–synthesis route. This route has obvious advantages: production flexibility, environmental friendliness, economic feasibility and application versatility. Low temperature and high pressure will be advantageous for DME production. Generally, the conditions are: H_2 : CO ≈ 1–2, 240–275 ℃, 5.0–5.5 MPa.

7 ACKNOWLEDGEMENTS

To my father	Xing-gong HE
To my mother	Cai-xia LIU
To my father-in-law	Quan-sheng LIU
To my mother-in-law	Feng-lan LIU
To my wife	Li-hua LIU
To my sister	Li HE
To my sister	Jiao HE
To my little daughter	Zong-shu HE
To my little niece	Ling-yao Chen
To my little nephew	Lu-teng HUO

To my other relatives, and all teachers and friends!

I would like to acknowledge the project support of EU Regional Development Fund, Toyota, ÅF Foundation for Research and Development, LKAB, Länsstyrelsen Västernorrland, Swedish Gasification Centre (SFC), SCA BioNorr AB, Härnösand. Fokusera Utveckling Sundsvall AB, Suntib Mekaniska Verkstad AB, Härnösand Energi & Miljö (HEMAB), Sundsvall Energi, Härnösand kommun och Elkompaniet i Sundsvall AB.

This thesis would not have come to be without the tireless work of Wennan Zhang, Per Engstrand, and Olof Björkqvist, my supervisors. I am very grateful to them for support, inspiration, and encouragement. I greatly appreciate the support from our colleagues, Ulf Söderlind, Ph.D. student and research engineer, Kristina Göransson, Ph.D. student, and Lars Strömmer (in memory of), a Mechanic.

Thanks to Anna Haeggström, Anne Åhlin, Jan-Erik Berg, Anders Lindberg, Christina Olsson, Viktoria Lilja, Sinke Henshaw and other colleagues at Mid Sweden University.

8 REFERENCES

Agersborg, J. and **E. Lingehed** (2013). Integration of Power-to-Gas in Gasendal and GoBiGas. Göteborg, Department of Energy and Environment, Chalmers University of Technology.

Baeck, R., **O. Danielsson**, et al. (1994). A method of producing mechanical and chemi-mechanical pulp, WO 1994016139 A1.

Balat, M. and **H. Balat** (2009). "Recent trends in global production and utilization of bio-ethanol fuel." Applied Energy **86**(11): 2273-2282.

Berglin, N. and **T. Berntsson** (1998). "CHP in the pulp industry using black liquor gasification: thermodynamic analysis." Applied thermal engineering **18**(11): 947-961.

Brown, J. W., Ed. (2006). Biomass gasification: fast internal circulating fluidised bed gasifier characterisation and comparison. Canterbury, Chemical and Process Engineering, University of Canterbury.

Corella, J. and **A. Sanz** (2005). "Modeling circulating fluidized bed biomass gasifiers. A pseudo-rigorous model for stationary state." Fuel Processing Technology **86**(9): 1021-1053.

Doherty, W., **A. Reynolds**, et al. (2009). "The effect of air preheating in a biomass CFB gasifier using ASPEN Plus simulation." Biomass and Bioenergy **33**(9): 1158-1167.

Dry, M. E. (2002). "High quality diesel via the Fischer–Tropsch process – a review." Journal of Chemical Technology & Biotechnology **77**(1): 43-50.

Emun, F., **M. Gadalla**, et al. (2010). "Integrated gasification combined cycle (IGCC) process simulation and optimization." Computers & chemical engineering **34**(3): 331-338.

Engstrand, P., **J. Jonsson**, et al. (2002). Method of producing bleached thermomechanical pulp (TMP) or bleached chemithermomechanical pulp (CTMP), WO Patent WO/2003/000,982.

Engstrand, P. O., **L. A. Hammar**, et al. (1991). Method of reducing the energy consumption at the refining of cellulose containing material, US 5007985 A.

Eriksson, G. and **B. Kjellström** (2010). "Assessment of combined heat and power (CHP) integrated with wood-based ethanol production." Applied Energy **87**(12): 3632-3641.

Eriksson, H. and **S. Harvey** (2004). "Black liquor gasification—consequences for both industry and society." Energy **29**(4): 581-612.

Fagbemi, L., **L. Khezami**, et al. (2001). "Pyrolysis products from different biomasses: application to the thermal cracking of tar." Applied Energy **69**(4): 293-306.

Fercher, E., **H. Hofbauer**, et al. (1998). Two years experience with the FICFB-gasification process. Proc. 10th European Conference and Technology Exhibition, Würzburg. Germany.

Fletcher, T. H. "http://www.et.byu.edu/~tom/."

Foscolo, P. U. (2007). Biomass: a sustainable energy source. The ICTP Experts Meeting on "Science and Renewable Energy", Trieste.

Gassner, M. and **F. Marechal** (2012). "Thermo-economic optimisation of the polygeneration of synthetic natural gas (SNG), power and heat from lignocellulosic biomass by gasification and methanation." Energy & Environmental Science **5**(2): 5768-5789.

Göransson, K. (2014). INTERNAL TAR/CH_4 REFORMING IN BIOMASS DUAL FLUIDISED BED GASIFIERS TOWARDS FUEL SYNTHESIS. Mid Sweden University. Sundsvall, Sweden, Mid Sweden University. **Ph.D.**

Göransson, K., **U. Söderlind**, et al. (2011). "Review of syngas production via biomass DFBGs." Renewable and Sustainable Energy Reviews **15**(1): 482-492.

Göransson, K., **U. Söderlind**, et al. (2011). "Experimental test on a novel dual fluidised bed biomass gasifier for synthetic fuel production." Fuel **90**(4): 1340-1349.

Gorski, D., **J. Hill**, et al. (2010). "Review: Reduction of energy consumption in TMP refining through mechanical pre-treatment of wood chips." Nordic Pulp & Paper Research Journal **25**(2): 156-161.

Hamelinck, C. N., **G. v. Hooijdonk**, et al. (2005). "Ethanol from lignocellulosic biomass: techno-economic performance in short-, middle-and long-term." Biomass and Bioenergy **28**(4): 384-410.

Harvey, S. and **B. Facchini** (2004). "Predicting black liquor gasification combined cycle powerhouse performance accounting for off-design gas turbine operation." Applied thermal engineering **24**(1): 111-126.

He, J., **P. Engstrand**, et al. (2013). "Techno-economic evaluation of a mechanical pulp mill with gasification." Nordic Pulp & Paper Research Journal **28**(3): 349-357.

He, J., **K. Göransson**, et al. (2012). "Simulation of biomass gasification in a dual fluidized bed gasifier." Biomass Conversion and Biorefinery **2**(1): 1-10.

Held, J. (2013). Small and medium scale technologies for bio-SNG production.

Heyne, S. (2010). Process integration opportunities for synthetic natural gas (SNG) production by thermal gasification of biomass, Chalmers University of Technology.

Heyne, S. (2013). Bio-SNG from Thermal Gasification-Process Synthesis, Integration and Performance, Chalmers University of Technology.

Hofbauer, H., **G. Veronik**, et al. (1997). The FICFB—gasification process. Developments in thermochemical biomass conversion, Springer**:** 1016-1025.

Holmberg, J. M. and **L. Gustavsson** (2007). "Biomass use in chemical and mechanical pulping with biomass-based energy supply." Resources, Conservation and Recycling **52**(2): 331-350.

Kiel, J., **S. Van Paasen**, et al. (2004). Primary measures to reduce tar formation in fluidised-bed biomass gasifiers. ECN, ECN-C-04-014, ECN, Energy Research Centre of the Netherlands, http://www.ecn.nl/docs/library/report/2004/c04014.pdf.

Kumabe, K., **S. Fujimoto**, et al. (2008). "Environmental and economic analysis of methanol production process via biomass gasification." Fuel **87**(7): 1422-1427.

Lee, J. M., **Y. J. Kim**, et al. (1998). "Coal-gasification kinetics derived from pyrolysis in a fluidized-bed reactor." Energy **23**(6): 475-488.

Muhic, D., **L. Sundström**, et al. (2010). "Influence of temperature on energy efficiency in double disc chip refining." Nordic Pulp & Paper Research Journal **25**(4): 420-427.

Murphy, J. and **K. McCarthy** (2005). "Ethanol production from energy crops and wastes for use as a transport fuel in Ireland." Applied Energy **82**(2): 148-166.

Naqvi, M., **J. Yan**, et al. (2010). "Black liquor gasification integrated in pulp and paper mills: A critical review." Bioresource technology **101**(21): 8001-8015.

Naqvi, M., **J. Yan**, et al. (2012). "Synthetic gas production from dry black liquor gasification process using direct causticization with CO_2 capture." Applied Energy **97**: 49-55.

Nikoo, M. B. and **N. Mahinpey** (2008). "Simulation of biomass gasification in fluidized bed reactor using ASPEN PLUS." Biomass and Bioenergy **32**(12): 1245-1254.

Norgren, S. and **H. Höglund** (2009). "Irreversible long fibre collapse at high temperature refining in a TMP system: Effects on fibre and surface properties." Nordic Pulp & Paper Research Journal **24**(1): 19-24.

Ong'iro, A., **V. Ugursal**, et al. (1995). "Simulation of combined cycle power plants using the ASPEN PLUS shell." Heat Recovery Systems and CHP **15**(2): 105-113.

Ong'iro, A., **V. I. Ugursal**, et al. (1996). "Thermodynamic simulation and evaluation of a steam CHP plant using ASPEN Plus." Applied thermal engineering **16**(3): 263-271.

Paisley, M. A., **R. Corley**, et al. (2007). Advanced biomass gasification for the economical production of biopower, fuels, and hydrogen—implementation in Montgomery, New York. 15th Biomass Conference and Exhibition, Berlin.

Pettersson, J. (2005). "Energikartläggning för energiledningssystem-Holmen Paper, Hallsta (energy survey for energy management-Holmen Paper, Hallsta)." from http://epubl.ltu.se/1402-1617/2005/109/LTU-EX-05109-SE.pdf.

Pfeifer, C., **R. Rauch**, et al. (2004). "In-bed catalytic tar reduction in a dual fluidized bed biomass steam gasifier." Industrial & engineering chemistry research **43**(7): 1634-1640.

Phillips, S., **A. Aden**, et al. (2007). "Thermochemical ethanol via indirect gasification and mixed alcohol synthesis of lignocellulosic biomass." NREL/TP-510-41168 **2007**(April).

Piccolo, C. and **F. Bezzo** (2009). "A techno-economic comparison between two technologies for bioethanol production from lignocellulose." Biomass and Bioenergy **33**(3): 478-491.

Porubova, J., **G. Bazbauers**, et al. (2012). "Modeling of the Adiabatic and Isothermal Methanation Process." Scientific Journal of Riga Technical University. Environmental and Climate Technologies **6**(1): 79-84.

Qiu, H., **J. Huang**, et al. (2010). "Bioethanol development in China and the potential impacts on its agricultural economy." Applied Energy **87**(1): 76-83.

Rajagopalan, S., **R. P Datar**, et al. (2002). "Formation of ethanol from carbon monoxide via a new microbial catalyst." Biomass and Bioenergy **23**(6): 487-493.

Ruohonen, P. and **P. Ahtila** (2011). "Qualitative analysis of a thermo mechanical pulp and paper mill using advanced composite curves." Energy **36**(6): 3871-3877.

Sabourin, M. J. (1999). Method of pretreating lignocellulose fiber-containing material for the pulp making process, WO1999007935 A1.

Sassner, P., **M. Galbe**, et al. (2008). "Techno-economic evaluation of bioethanol production from three different lignocellulosic materials." Biomass and Bioenergy **32**(5): 422-430.

Seemann, M. and **H. Thunman** (2009). The new Chalmers research-gasifier. Proceedings of the 20th International Conference on Fluidized Bed Combustion, Xi'an.

Sotudeh-Gharebaagh, R., **R. Legros**, et al. (1998). "Simulation of circulating fluidized bed reactors using ASPEN PLUS." Fuel **77**(4): 327-337.

Starfelt, F., **E. Thorin**, et al. (2010). "Performance evaluation of adding ethanol production into an existing combined heat and power plant." Bioresource technology **101**(2): 613-618.

Stridsberg, A. and **O. Lindgren** (2010). Möjlighet till ökad elproduktion vid Ortviken pappersbruk. Sundsvall, Mid Sweden University.

Subramani, V. and **S. K. Gangwal** (2008). "A review of recent literature to search for an efficient catalytic process for the conversion of syngas to ethanol." Energy & Fuels **22**(2): 814-839.

Sundholm, J., **S. P.-i. Yhdistys**, et al. (1999). Mechanical pulping, Published in cooperation with the Finnish Paper Engineers' Association and TAPPI.

Tarka, T. J., **J. G. Wimer**, et al. (2009). Affordable, low-carbon diesel fuel from domestic coal and biomass. Proc. 25th Annual Pittsburgh Coal Conf., Pittsburgh, PA.

Thunman H., **Alamia A.**, et al. (2014). Beyond 0.8 Efficiency for Standalone Production of Bio-Methane from Wet Biomass, Chalmers University of Technology.

Tunå, P. and **S. G. Center** (2008). Substitute natural gas from biomass gasification, Svenskt gastekniskt center (SGC).

van der Meijden, C., **P. Bergman**, et al. (2010). Preparations for a 10 MWth Bio-CHP demonstration based on the MILENA gasification technology. 18th European Biomass Conference and Exhibition, Lyon.

Westermark, U. and **G. Capretti** (1988). "Influence of ray cells on the bleachability and properties of CTMP and kraft pulps." Nordic Pulp and Paper Research Journal **3**.

Wetterlund, E. and **M. Söderström** (2010). "Biomass gasification in district heating systems–the effect of economic energy policies." Applied Energy **87**(9): 2914-2922.

Younesi, H., **G. Najafpour**, et al. (2005). "Ethanol and acetate production from synthesis gas via fermentation processes using anaerobic bacterium, *Clostridium ljungdahlii*." Biochemical Engineering Journal **27**(2): 110-119.

Yu, S. and **J. Tao** (2009). "Economic, energy and environmental evaluations of biomass-based fuel ethanol projects based on life cycle assessment and simulation." Applied Energy **86**: S178-S188.

Zhang, W. (2010). "Automotive fuels from biomass via gasification." Fuel Processing Technology **91**(8): 866-876.

Zhang W, **Forsman B**, et al. (2005). Biofuels in Sweden. 7th World Congress on Recovery, Recycling and Re-integration. Beijing, China.

Zhang, W., **U. Söderlind**, et al. (2007). Coal Gasification - for LKAB Pelletizing Furnace, Dept. of Engineering, Physics and Mathematics, Mid Sweden University.

Zheng, Y., **Z. Pan**, et al. (2009). "Enzymatic saccharification of dilute acid pretreated saline crops for fermentable sugar production." Applied Energy **86**(11): 2459-2465.

Zwart, R., **H. Boerrigter**, et al. (2006). "Production of synthetic natural gas (SNG) from biomass." Energy Research Centre of the Netherlands (ECN). Available at: https://www.ecn.nl/publications.

Zwart, R., **S. van der Heijden**, et al. (2010). Tar removal from low-temperature gasifiers, ECN Petten, http://www.ecn.nl/docs/library/report/2010/e10008.pdf.