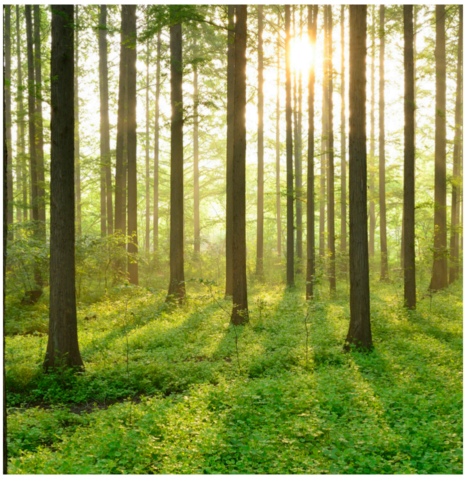
FOSSIL FREE TISSUE DRYING

REPORT 2016:231



ENERGIGASTEKNIK

Energiforsk

Fossil free tissue drying

Feasibility study

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Authors' foreword

This project was carried out mainly by the authors of this report. Valuable contributions were made by a number of suppliers of gasification technology.

This project was co-funded by the Swedish Energy Agency through SGC/Energiforsk. In-kind contributions were provided by all project partners; Rexcell Tissue & Airlaid AB, Valmet AB, Pöyry AB, Södra Skogsägarna, BAxPTC, The Paper Province and Karlstad University.

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Sammanfattning

Energianvändningen vid torkning av mjukpapper är betydande. I moderna mjukpappersprocesser utnyttjas direkteldade torkkåpor där rökgaserna från gasol- eller naturgasförbränning blåses mot det våta mjukpapperet. I denna studie har bytet från gasol till gas från termiskt förgasad biomassa undersökts för ett mjukpappersbruk med en maximal gasolförbrukning motsvarande 7 MW.

Effekten av att ersätta gasol med syntesgas vid mjukpapperstorkning undersöktes genom användning av matematiska modeller. Resultaten från de genomförda simuleringarna visar att torkkapaciteten sannolikt kommer att upprätthållas om gasol ersätts med syntesgas. Om man antar att de undersökta gassammansättningarna är icke-förvärmda vid förbränning beräknas energianvändningen öka med mindre än 3,5% jämfört med referensbränslet gasol.

Den mindre undersökning av bränsleutbytbarhet som gjorts i den aktuella studien visar att de befintliga gasbrännarna sannolikt behöver bytas ut för att kunna bibehålla nuvarande torkkapacitet. För att syntesgas ska vara ett hållbart alternativ i en mjukpapperstork så måste förbränningssystemet utformas för att uppfylla gällande emissionskrav.

Fem kommersiellt tillgängliga förgasningskoncept med efterföljande gasrening har studerats och deras användbarhet och energieffektivitet har analyserats på en bruksövergripande nivå. Alla förgasningstekniker har bedömts vara tillämpliga för att omvandla de planerade bränslena (flisat trämaterial) till gas av tillräcklig kvalitet. Potentiella bränslen i form av slam kan emellertid vara svåra att hantera med fastbäddsteknik på grund av risken för bildandet av täta, ogenomträngliga sektioner i bädden. Motströmsförgasning har funnits vara mindre lämplig ur effektivitetssynpunkt beroende på den höga tjärhalten i produktgasen och de höga energiförluster som därmed uppstår vid kall gasrening. De tre återstående teknikerna skiljer sig endast marginellt åt avseende den totala energieffektiviteten och den totala förbrukningen av biomassa.

Bytet från gasol till biobaserad syntesgas har generellt sett funnits vara genomförbart. Snabba variationer i gasförbrukningen kan dock utgöra en utmaning för en del av förgasningsteknikerna. Baserat på kostnaden för tjärrening å ena sidan och vikten av sotfria, icke-luktande rökgaser för denna applikation å andra sidan, har det identifierats ett behov av experimentell testning för att fastställa sambandet mellan syntesgasens tjärinnehåll och lukt/sot-påverkan på mjukpapper. Sådan testning rekommenderas som ett nästa steg i konceptutvecklingen.

Summary

In tissue production, the energy use for drying is considerable. Modern tissue drying processes utilize direct fired, high temperature, drying hoods where the flue gases from LPG or natural gas combustion are blown towards the wet tissue paper. In this study the exchange of LPG with biomass derived syngas has been examined for a tissue mill with a total LPG consumption corresponding to 7 MW peak load.

The effects of replacing LPG with syngas in the impingement drying of tissue were investigated by use of mathematical models. The results from the simulation study made show that the drying capacity is likely to be preserved if replacing LPG with syngas. Assuming that all investigated gas compositions are non-preheated, the use of heat derived from combustion of the studied syngases was calculated to increase by less than 3.5 % compared to the reference case of LPG.

The minor investigation of fuel interchangeability made within the present study shows that the existing gas burners probably need to be replaced in order to maintain the current drying capacity. Moreover, for syngas to form a viable option in a tissue drying application, the combustion system needs to be designed for compliance with existing emission legislations and to avoid concerns that are shown to occasionally arise during combustion of syngas.

Five commercially available gasification concepts with subsequent gas cleaning have been studied, and their applicability and energy efficiency on a mill-scale level have been analyzed. All gasification technologies have been deemed applicable to convert the foreseen fuels (chipped woody material) to gas of sufficient quality. Potential feedstock in form of sludge might however be difficult to handle with fixed bed technologies due to the risk for formation of dense, impermeable sections in the bed. The fixed-bed updraft gasification technology is deemed less suitable from an efficiency point-of-view due to the high tar content in the producer gas and related energy loss with cold tar cleaning. The three remaining technologies differ only slightly as to the overall energy efficiency and the overall biomass consumption.

The exchange of LPG with biomass-derived syngas is generally found feasible. Rapid variations in gas consumption might form a challenge for some of the gasification technologies. Given the cost for tar cleaning on one hand and the importance of soot-free, non-odorous flue gases for this tissue drying application on the other hand, a need for further experimental testing has been identified in which the correlation between syngas tar content and smell/soot impact on the tissue paper could be determined. Such testing is recommended as a next step in the concept development.

List of content

1 Introduction

In production of paper, the energy use for drying is considerable. In some product segments, for instance tissue paper and coated paper, LPG (Liquefied Petroleum Gas), natural gas or electricity is used for drying. In 2011, the total use of LPG for pulp and paper production in Sweden was estimated to be 743 GWh (skogsindustrierna/ÅF). In Sweden, the pulp and paper industry strive to reduce or in some cases even eliminate usage of fossil energy until 2020.

The majority of tissue paper produced is dried on a circulating yankee cylinder. This process combines two types of heat transfer to the wet web. Part of the heat needed for evaporating the water is provided by conduction from the metal cylinder, which is internally heated by condensing process steam (contact drying). The other part of the heat is provided by blowing hot gases onto the wet web (impingement drying). In Sweden, the process steam condensing inside the yankee cylinder is normally produced in a bioboiler. The impinging gases, on the other hand, are usually produced by combustion of natural gas or LPG. For production of fossil free tissue, an alternative to using natural gas or LPG needs to be developed.

For the full-scale production of fossil free tissue, the LPG used for heating the impingement gas would have to be exchanged for a renewable fuel. The fuel chosen within this project is syngas produced by thermal gasification of biomass. The novelty of the project is the combination of two proceses. One of them, drying of tissue paper, is well established in full industrial scale and the production capacity and product quality must be retained even after the change. The other process, thermal gasification of biomass, has been demonstrated successfully in several pilot-scale reactors in reseach projects (for instance at Chalmers university of technology [1]) and has also been carried out in full-scale plants. The novelty will be the knowledge, on unit operation- and system- level, on the matching of these two technologies in order to phase out fossil fuels. The results might well be applicable for other drying applications as well. The combination of production of biomass-based energy gas with the unit operation drying is of immediate interest in paper drying processes where fossil energy gas or electricity is used today. There are advantages of gas heated drying, however, that might make the technology interesting also for paper drying processes where renewable energy is used today. The introduction of impingement hoods will lead to an increased drying capacity in a multi-cylinder dryer or, alternatively, make it possible to shorten the drying section of the paper machine, for instance compared to OptiDry concept from Valmet [2].

The annual growth of the market for tissue paper grades is almost 4 % [3]. Tissue paper produced without usage of fossil fuels will be an interesting and exciting consumer product. Technology for fossil free tissue is also a product with a global potential. The world-leading tissue paper machine producer Valmet has production facilities and development in Karlstad.

The project has been carried out in close co-operation between organizations covering the entire value chain from raw material, wood chips, to the consumer product tissue paper:

- An industrial tissue paper producer (Rexcell)
- A company specializing in development and production of tissue paper machines (Valmet)

- A supplier of biomass (Södra)
- Experienced process consultants in energy technology and paper making (Pöyry)
- An academic partner with a research portfolio in paper making and energy technology (Karlstad University)

The project has had the full support of the regional industrial cluster organization, The Paper Province or TPP. Thanks to the support from VINNOVA and a number of regional actors, TPP has set as its goal to create a regional demonstrator for a full-scale bioconomy.

1.1 SCOPE AND GOALS

The scope of the project is to contribute to the development of technology for the production of tissue paper without the usage of fossil fuels, while retaining paper quality, production capacity and availability. (In this context, availability represents ratio of the total time the tissue machine is capable of being used during a given interval to the length of the interval.)

The goal of the project is the identification and evaluation of concepts for gas generation, gas cleaning and gas firing relevant also from a financial point of view in the interesting scale (< 10 MW).

Two sub-goals have been set up:

- The identification of a robust and efficient system for the elimination of tar and soot from the gas. The system should be characterized by good operational stability and high mill level energy efficiency.
- The employment of a detailed simulation model to be able to predict and to compensate for any production capacity changes that arise as a consequence of the replacement of fossil gas with an energy gas that has a reduced lower heating value and different chemical composition.

2 Design criteria

The successful introduction of fossil-free tissue drying technology requires that a number of design criteria must be fulfilled. Fuel for gasification must be available close to the plant and the selected gasification technology must be well suited for those fuels that are available in the region. It is of great importance that the flue gas produced is clean and free from contaminations so that the superior quality of the tissue produced is maintained. The maximum capacity of the gasification plant must match the requirements during periods of maximum production from three paper production lines.

This chapter specifies, as far as possible, the design criteria that the selected gasification technology needs to fulfill.

2.1 FUELS

A growing share of the forest-based biomass that cannot be converted to sawn timber or be used for production of pulp is used as bio fuel. All kinds of trees are used for energy purposes; even decay-damaged trees can be used. Södra has identified an assortment of biofuels that could be gasified:

Wood fuel chips oak	(code 6383)
Wood fuel chips	(code 6393)
Wood chips softwood	(code 6493)
Whole-tree chips hardwood	(code 6533)
Whole-tree chips oak/beech	(code 6583)

Out of the list above, the Wood fuel chips (code 6393) and Wood chips softwood (code 6493) were identified as the most interesting assortments.

The starting point of this feasibility study has been that Södra has guaranteed the supply of biomass from the immediate surroundings. In this specific case, this means mainly Wood fuel chips (code 6393) and Wood chips softwood (code 6493), supplying 100 % of the fuel needed for gasification, which can be estimated at approximately 65 GWh/year for the planned gasification plant.

Within a distance of 100 km from the plant, there is also yearly access to approximately 45 000 tons of fiber sludge with a moisture content of approximately 80 %. The high moisture content currently makes transport of the sludge unrealistic. However, the supplier at present strives to develop methods for reducing the moisture content of the sludge.

The reduction in operational cost associated with replacing the LPG will depend on a number of factors. The price for LPG has decreased during the last two years, cf. Figure 1. The price of the fuel substituting the LPG will be different depending on what assortment is finally chosen. The data in Figure 2 represent fuel chips, whereas the other alternatives such as bark are cheaper. Finally, for estimating the reduction in operational cost, also the efficiency of gasification of the integrated system will be needed as well as an estimation of the syngas lost due to production breaks and quick changes in the syngas need that cannot be matched by the gasification process.

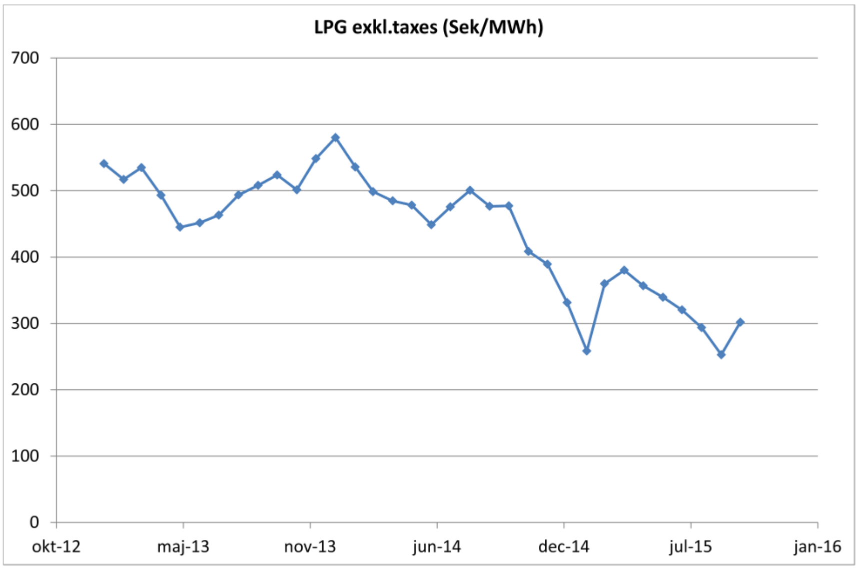

Figure 1. Costs LPG.

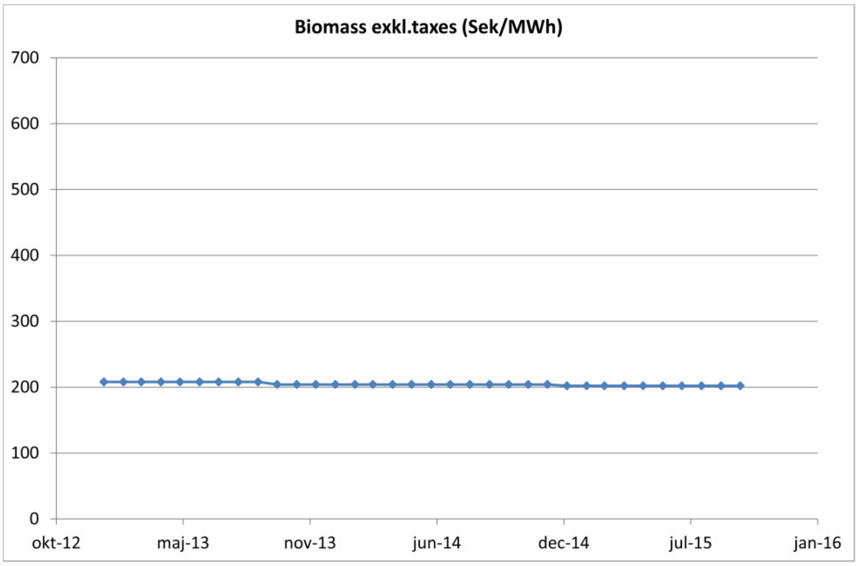

Figure 2. Costs biofuel for gasification.

2.2 GAS QUALITY

Modern tissue drying processes utilize direct fired high temperature drying hoods where the flue gases are blown towards the wet tissue paper.

In this application the gas composition itself is of limited relevance as only the energy released during combustion is utilized. But as the combustion flue gases are brought into contact with the tissue paper it is important that no smelling or hazardous compounds are transferred to the tissue paper during the drying process. The gas quality requirements are mainly linked to the concentration of tar.

Ideally, substitution of LPG with biomass derived syngas should be trouble-free from this perspective as the main combustible syngas components H_2, CO, and CH_4 all burn without soot formation, yielding nothing but CO_2 and H_2O as reaction products. However, in the gas from the gasifier tar is also present. Tar is often defined as organic compounds with molecular weight greater than that of benzene [4]. Soot formation during tar combustion is a highly complex area [5-7]. To determine a safe tar-level from a soot formation perspective is difficult. In this study it has been preliminary foreseen that a tar concentration below 100 mg/m^3 is reached, which is considered sufficient for gas engine applications [8] would be a realistic target. However, this concentration should be practically verified (see chapter 7.1).

2.3 DESIGN CAPACITY AND GAS CONSUMPTION CHARACTERISTICS

At present, LPG is used for drying at three production lines. Each of the machines produces a multiple of qualities and therefore has gas consumptions that vary over time. In Figure 3, Figure 4 and Figure 5 below logged LPG consumption for the 1st quarter of 2015 is shown for the three machines. Sampled values are average measured during a 10 min period. The function of the LPG flow meter for the third production line was unstable during the period, explaining the irregular consumption pattern in Figure 5.

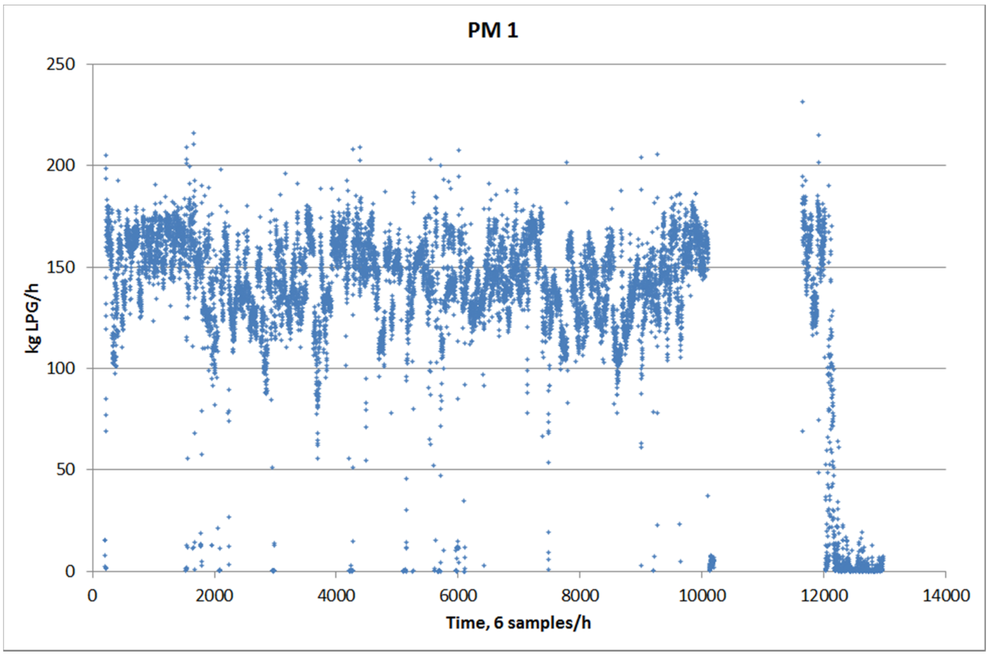

Figure 3. LPG consumption of production line 1.

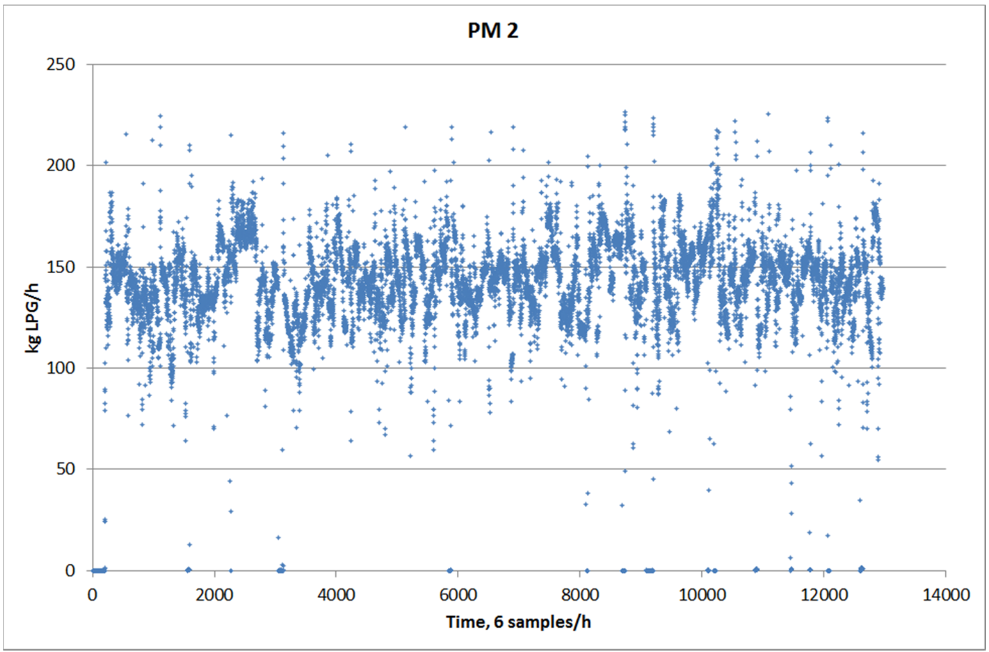

Figure 4. LPG consumption of production line 2.

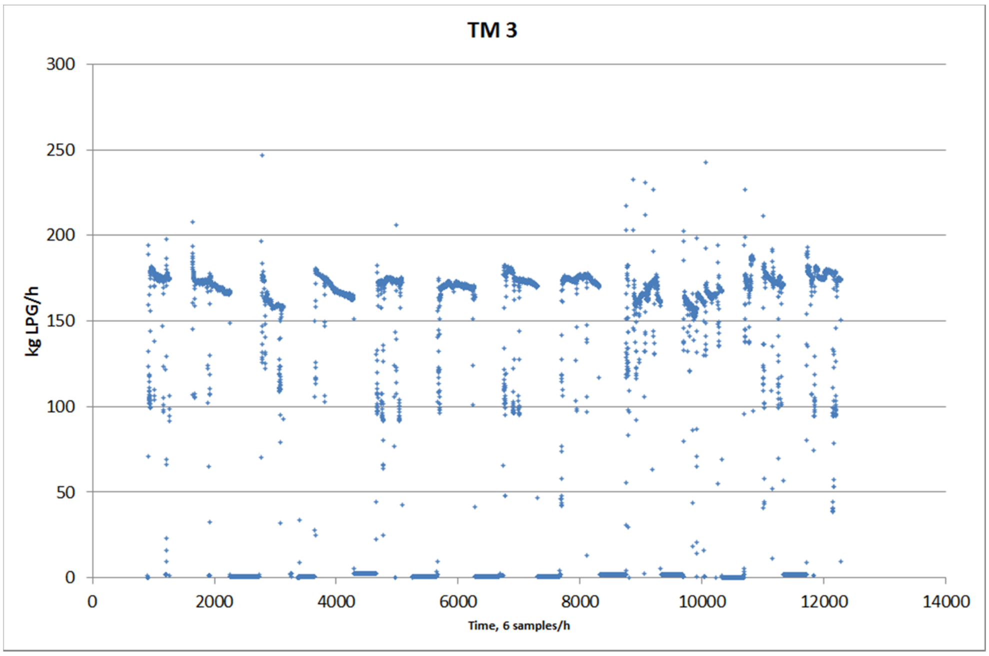

Figure 5. LPG consumption of production line 3.

The total gas consumption when combining the three machines is illustrated in Figure 6 below. Based on the LPG consumption for the period, a design capacity for the gasification plant of 550 kg/h (LPG equivalent), corresponding to 7 MW (LHV) has been set.

As can be seen in Figure 6 the gas consumption typically varies rapidly between 150 and 500 kg/h corresponding to a turndown ratio of 3,3:1. Furthermore, from the consumption statistics it can be observed that the maximum increase and decrease rate of gas consumption is in the region of 20 kg/(min·h), corresponding to almost 250 kW/min. During process disturbances even higher load change rates can occur. Such a fast response from the gasifier may be difficult to achieve. For this reason the system shall comprise regulatory functions in the form of: (i) A flare for combustion of excess gas in case of a rapid decrease in gas consumption, (ii) An LPG back-up for balance of syngas shortage due to rapid increase in gas consumption.

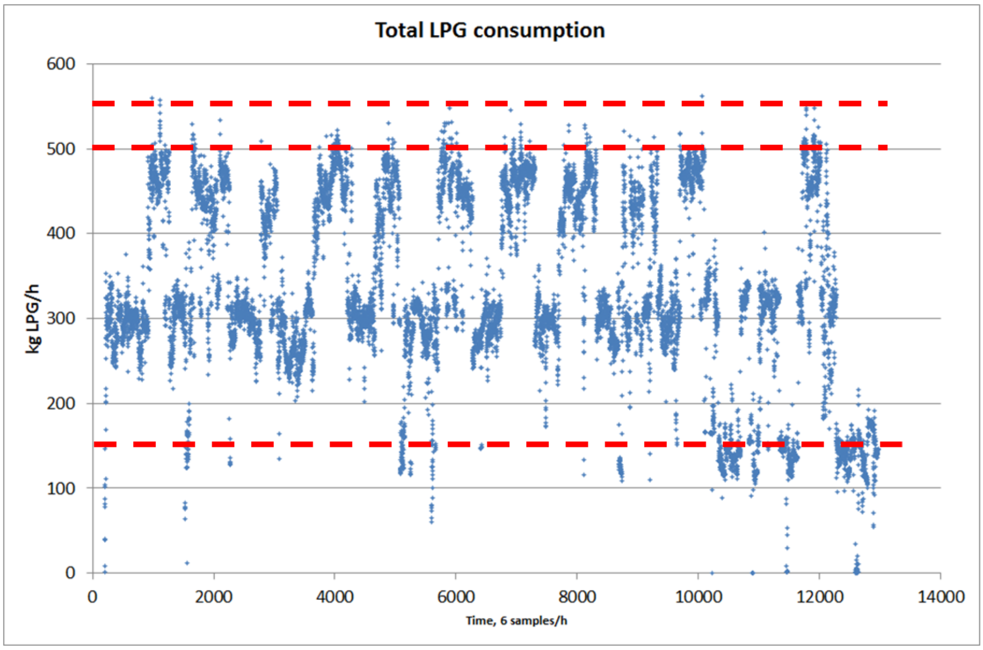

Figure 6. Total LPG consumption of the three production lines. The three red dotted lines indicate that the consumption typically varies between 150 kg/h and 500 kg/h with a top consumption of 550 kg/h.

2.4 CONCLUDING REMARKS

The biomass assortment is primarily planned to consist of chipped woody material. This fuel is a feasible feedstock for all examined gasification technologies. Potential feedstock in form of sludge might however be difficult to handle with fixed bed technology due to its risk for forming of dense, impermeable sections in the bed.

The gas quality requirements in this project are mainly focused on tar content. Chlorine-, sulphur- and nitrogen content as well as H_2, CO, CH_4-concentrations that all are important parameters in syngas utilization based on catalytic conversion are less important in this application. An acceptable tar concentration has tentatively been set to 100 mg/m^3 but this should be further investigated as the relation between tar content and soot formation during combustion is difficult to predict.

The gas consumption variations at the studied tissue mill is significant, with a turn-down ratio of >3. Furthermore, the gas consumption change rate is high. During grade changes the gas requirement can change in the order of 250 kW/min. In connection with production disturbances, even higher rates can be expected.

3 Gasification and gas cleaning

The project aims at evaluating different gasification technologies in terms of their suitability for replacing LPG for tissue paper drying. Several different gasification technologies exist, yielding different gas compositions and syngas with different heating values. This chapter will very briefly present some possible technologies. This review of possible technologies has a number of purposes: (i) Gas compositions are needed for evaluating the suitability of a specific technology from the hood burner's perspective, (ii) Data for the heat and mass balances of the gasification process are needed for evaluating the biomass consumption when the gasification process is integrated in the plant, (iii) Some understanding of the dynamics of the gasification process are needed for evaluating how well a specific gasification technology can be controlled to match the fluctuations in the need for syngas for tissue drying.

The chapter also presents a strategy for gas cleaning to match the design criteria for gas quality.

3.1 ASSESSMENT OF GASIFICATION TECHNOLOGIES

Data, in terms of gas compositions and heating values, have been obtained from two sources: the scientific literature [9-15] and technology supplier information. These data have been used when setting up mathematical models for gasification. The mathematical models for gasification were set up in the commercial flow sheeting software CHEMCAD 6.4.1 (Chemstations Inc., Houston, TX, USA) with the aim of evaluating the possibilities of an advantageous integration of each technology in the plant. The modelling of the gasification reactor was quite crude, trying to find a stoichiometry to match the experimental data. More specific information on the modelling process is given in the section on Process Integration. The gas characteristics from the CHEMCAD models are included already here to provide a quick overview of data from three types of sources: scientific literature, supplier information, and flow sheeting model developed within this study. Three separate columns are included in the tables, although all three types of data are not available for every technology. The quotations obtained also differed somewhat as to the level of detail about the syngas composition.

When comparing data from different sources, it is evident that the water vapour content of the produced syngas might vary considerably. Early on in the project, the high contents of water vapour of the syngas were identified as a potential problem when burning the syngas and it was deemed necessary to reduce the water vapour content by cooling the gas. For these reasons, the gas compositions are given only for dry syngas and the water vapour content has been omitted.

Focus when searching for literature data for gas compositions and gas heating values as well as during contacts with possible technology suppliers was on using woody biomass as a fuel for gasification and syngas generation.

Gasification is a number of endothermal chemical reactions, where solid and liquid components are transformed into syngas containing such energy rich compounds as hydrogen, carbon monoxide and methane. Gasification is a partial oxidation of the fuel, so that the presence of some oxygen in the fuel is necessary, although the oxygen can be provided in several ways, for instance gasification in air, in steam or in carbon dioxide. The heat that is needed for gasification of the fuel is provided either through a partial combustion of the fuel (in case the gasification medium is air) or from an external heat source (in case the gasification medium is steam or carbon dioxide). Some phases in the gasification process have been defined as: drying, pyrolysis, and combustion (only when the gasification medium is air) and gasification. [16]

In case the gasification medium is air, the process is often characterized in terms of the Equivalence Ratio or ER. ER is defined as the quotient of the actual flow of air to the reactor and stoichiometric flow of air. For ER = 0, the process corresponds to pyrolysis and for ER = 1, complete combustion of the fuel occurs. For gasification in superheated steam, the process is instead defined in terms of the Steam to Biomass Ratio or SBR. SBR is the quotient of the flow of steam to the reactor and the flow of dry biomass. [16]

3.1.1 Fixed bed gasification

In a fixed bed gasifier, the gasification medium is blown through the fuel which remains at the bottom of the reactor. The gasification medium can flow upwards or downwards, see Figure 7. A solid bed gasifier is well suited for the gasification of biomass, since it can handle particles with a size up to 50 mm. As the temperature falls in the direction of the fuel feed, an updraft arrangement will lead to higher tar production than the downward flow arrangement. Approximate data for gas composition, the syngas lower heating value and the tar formation are given in Table 1 for an updraft fixed bed gasifier and in Table 2 for a downdraft fixed bed gasifier [11,12,14,16,17].

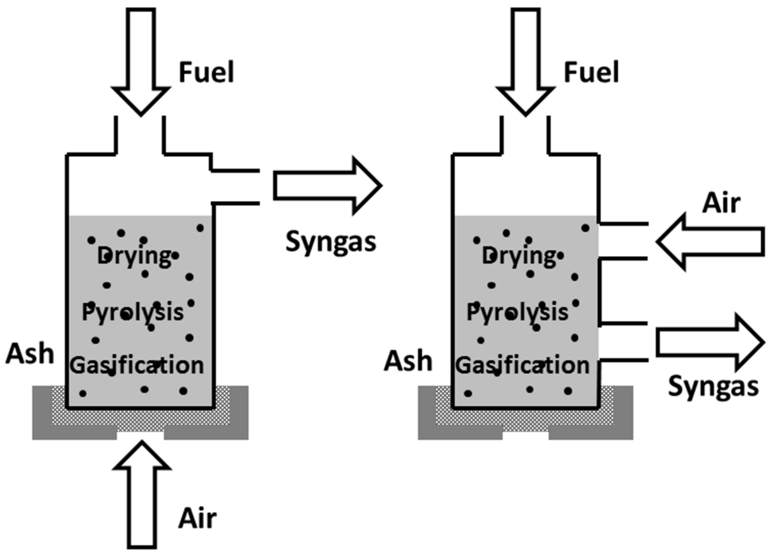

Figure 7. Two examples of fixed bed gasifiers, an updraft reactor to the left and a downdraft to the right [13].

Table 1 (representing the updraft fixed bed gasifier) contains representative literature data and also data from the gasification model set up in the flowsheeting software CHEMCAD. We obtained one quotation for the udraft fixed bed gasification technology. However, it did not fully match our requirements, since the suggestion was installing separate reactors for producing syngas at each production line rather than one gasification reactor producing the syngas needed for all three production lines.

Still, the technology was investigated in terms of the possibilities for process integration, since it was interesting to keep a gasification technology leading to a syngas containing considerable amounts of tar.

Table 2 (representing the downdraft fixed bed gasifier) contains all three types of data, literature data, technology supplier data and our own model data.

Table 1. Data representative of syngas produced in an updraft fixed bed gasifier.

	Literature data	Quotation obtained	CHEMCAD model
Carbon monoxide, CO	20-25 Vol-%	---	18 Vol-%
Carbon dioxide, CO_2	8-12 Vol-%	---	17 Vol-%
Hydrogen, H_2	15-25 Vol-%	---	17 Vol-%
Methane, CH_4	3-6 Vol-%	---	2 Vol-%
Nitrogen, N_2	40-50 Vol-%	---	46 Vol-%
Ethylene, C_2H_4	---	---	0 Vol-%
Tar	<200 g/m^3	---	136 g/m^3
Lower heating value (dry gas)	5-7 MJ/Nm^3	---	5,0 MJ/Nm^3

Table 2. Data representative of syngas produced in a downdraft fixed bed gasifier.

	Literature data	Quotation obtained	CHEMCAD model
Carbon monoxide, CO	20-25 Vol%	20	22
Carbon dioxide, CO_2	8-12	12	11
Hydrogen, H_2	15-25	20	17
Methane, CH_4	2-5	1-3	2
Nitrogen, N_2	40-50	45-47	48
Ethylene, C_2H_4	---	---	0
Tar	<5 g/m^3	0 g/m^3	4,2 g/m^3
Lower heating value (dry gas)	5-7 MJ/Nm^3	5 MJ/Nm^3	5,4 MJ/Nm^3

3.1.2 Suspension gasifier

In a suspension gasifier, very small fuel particles are needed. The particles are suspended in flowing air and are gasified, see Figure 8. The temperature is often higher than in a fixed bed gasifier. The particles need to be very small, no larger than 0.15 mm in diameter, which makes this technology less suitable for biomass since grinding of the fuel might be necessary.

A similar technology to the suspension gasifier, a cyclone gasifier, was offered by one technology supplier.

Table 3 compares syngas data representing the suspension gasifier taken from the literature [12] to supplier information regarding the cyclone gasifier. The gas composition and heating values are similar to the data for the fixed bed gasifiers and this technology was not used as a basis for setting up a specific CHEMCAD model.

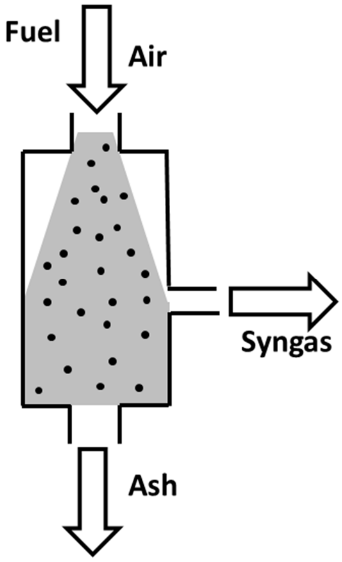

Figure 8. Schematic illustration of a suspension gasifier [13].

Table 3. Data representative of syngas produced in a suspension gasifier.

	Literature data	Quotation obtained	CHEMCAD model
Carbon monoxide, CO	20-25	20	---
Carbon dioxide, CO_2	8-12	12	---
Hydrogen, H_2	20-25	11	---
Methane, CH_4	1	3	---
Nitrogen, N_2	40-50	50	---
Ethylene, C_2H_4	---	2	---
Tar	<30 g/m^3	≈10 g/m^3	---
Lower heating value (dry gas)	5-7 MJ/Nm^3	6,0-6,3 MJ/Nm^3	---

3.1.3 Dual bed, steam blown

A dual bed gasifier combines the gasification reactor with a combustion reactor, see Figure 9. Superheated steam can be used as a gasification medium, leading to the gasification being endothermal. Any solid residue (gasification char) is separated from the syngas and combusted. The heat of gasification is supplied by circulating bed material between the two reactors.

Since gasification can occur in superheated steam, it is possible to produce a syngas without excessive amounts of nitrogen. The syngas gets a higher lower heating value, as illustrated in

Table 4, which compares literature data [9,12], data from a technology supplier and CHEMCAD model data.

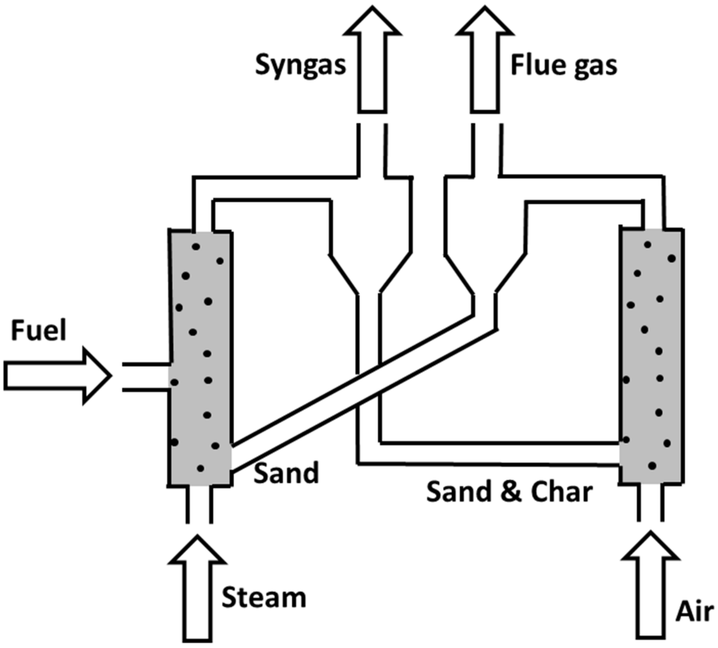

Figure 9. Schematic illustration of a steam-blown dual bed gasifier [9].

Table 4. Data representative of syngas produced in a steam-blown dual bed gasifier.

	Literature data	Quotation obtained	CHEMCAD model
Carbon monoxide, CO	20-30	35	32
Carbon dioxide, CO_2	15-25	19	16
Hydrogen, H_2	35-45	26	34
Methane, CH_4	8-12	13	15
Nitrogen, N_2	<10	2	0
Ethylene, C_2H_4	---	4	4
Tar	<40 g/m^3	???	32 g/m^3
Lower heating value (dry gas)	14-16 MJ/Nm^3	16,4 MJ/Nm^3	15,1 MJ/Nm^3

3.1.4 Two stage

In a two stage gasification process, the fuel is pyrolysed and the pyrolysis char is separated from the pyrolysis gas. The pyrolysis char is gasified in superheated steam and the heat needed for pyrolysing the fuel as well as for gasification of the pyrolysis char is supplied by combustion of the pyrolysis gas, as illustrated schematically in Figure 10. This technology is offered in a suitable scale and the great advantage is claimed to be the production of tar-free syngas with a relatively high lower heating value.

Table 5 provides a comparison between syngas data taken from the literature [15], technology supplier data and data from our CHEMCAD model.

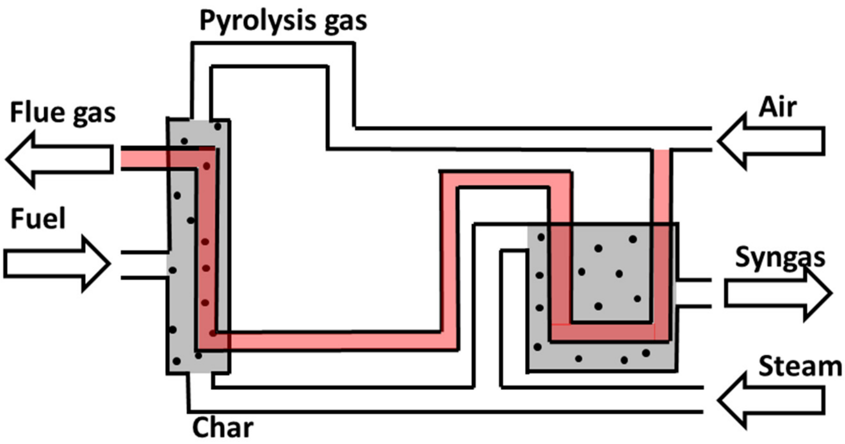

Figure 10. Schematic illustration of a two stage gasifier [15].

Table 5. Data representative of syngas produced in a two-stage gasifier.

	Literature data	Quotation obtained	CHEMCAD model
Carbon monoxide, CO	(20-30)	18-30	34
Carbon dioxide, CO_2	(8-12)	8-17	9
Hydrogen, H_2	(50-60)	50-60	54
Methane, CH_4	(3)	1-3	3
Nitrogen, N_2	0	0	0
Ethylene, C_2H_4	---	---	0
Tar	0 g/m^3	0 g/m^3	0 g/m^3
Lower heating value (dry gas)	10-11 MJ/Nm^3	10-12 MJ/Nm^3	11,2 MJ/Nm^3

3.2 GAS CLEANING TECHNOLOGIES

Gas cleaning technologies can be grouped into: cold-, warm-, and hot- systems [8]. In many applications a hot gas cleaning system is preferred as this potentially enables higher energy efficiency due to less loss of sensible heat. Such hot gas cleaning employs hot gas filtering and catalytic tar cracking. In-spite of extensive research and recent achievements [18] these technologies have not found broad commercial utilization and most realized gasification plants utilizes cold cleaning by means of textile- and activated carbon filters and scrubbing with oil and/or water. Sometimes an Electro-Static Precipitator (ESP) is used to capture aerosols that are formed in the scrubber system.

In this small scale application where cold gas is preferred from a distribution point-of view, the obvious technology for tar cleaning is oil scrubbing followed by activated carbon filtration, which is foreseen to eliminate sufficient amounts of tar to prevent soot formation during combustion.

A gas cleaning concept according to Figure 11 below has been considered sufficient for the studied application.

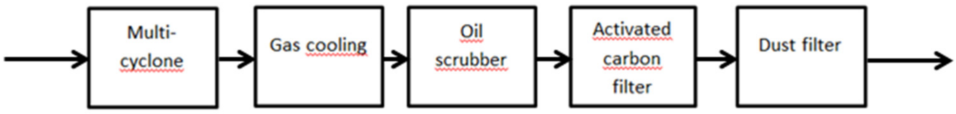

Figure 11. A gas cleaning set-up suitable for the studied application.

As a first step after the gasifier a particle separator is used to reduce the amount of solids entering the heat exchanger and the subsequent gas cleaning system. An oil scrubber is placed after the gas cooling. Meaning that gas at approximately 200 ^{o}C is fed into the scrubber where it is cooled to 30 ^{o}C. In the scrubber, tar is condensed and absorbed into the bio oil. After the oil scrubber, the gas passes an activated carbon (AC) filter where residual tar is adsorbed, yielding a tar concentration below 50 mg/m^3. After the AC filter, the gas is filtered in a textile fabric dust filter. Such a filter is capable of reducing the dust concentration to <1 μg/m^3 (for particles larger than 1 μm) [8]. These levels of tar and particulates are deemed sufficient for a trouble-free operation of subsequent gas handling equipment as well as for soot- and dust free combustion.

3.3 DYNAMICS

The gas consumption variations as described in chapter 2.3 have been briefly discussed with the potential gasification suppliers. All suppliers consider these variations as possible to handle. However, based on the discussions and the supplier statements, the variations seem to be somewhat easier to manage with suspension gasifiers than with fixed bed- and dual fluidized bed gasifiers. Concepts with multiple gasification units needs to shut-off one or several units during low load periods. Restart of these units at fast increase in gas consumption will be difficult to manage and LPG backup will be important to have.

The gas cleaning concepts foreseen in this project generally has a high tolerance for gas flow variations. The most sensitive process section will be the multi-cyclones for removal of coarse particles. The other process steps consisting of scrubbers and barrier filters are less sensitive to flow variations.

3.4 CONCLUDING REMARKS

Several technologies for gasification have been identified as interesting for the current application. These include fixed bed gasification, suspension gasification, steam-blown dual bed gasification and two-stage gasification. Furthermore, all these technologies are available commercially and five (or at least four) relevant quotations have been obtained. The gasification technologies produce syngas differing in composition and heating value.

Gas characteristics from the quotations complemented with data from the scientific literature will be used for evaluating the different technologies in terms of tissue drying process and regarding the possibilities for process integration.

Gasification processes are available commercially in the scale of technology relevant to the application at the plant.

4 Use of syngas in direct heated impingement drying of tissue

The investigation presented in this chapter studies the effects of replacing LPG with syngas in the process of combined contact and impingement drying used in the manufacture of tissue.

4.1 EFFECTS ON THE HEAT AND MASS BALANCES OF YANKEE DRYING – A SIMULATION STUDY

In processes for manufacture of tissue utilizing water-laid forming, a fiber suspension is laid on a fabric for subsequent operations of dewatering. Valid for the production process of the current study, post forming processes of water removal involves the usage of pressing and thermal drying. The thermal dewatering is performed by the usage of simultaneous contact and impingement drying in which the hot gas impinged onto the web is directly heated by combustion of LPG. The aim of the work presented in this chapter is to quantify the effects of replacing LPG with syngas on the local and overall drying behavior as well as on the heat and mass balances of tissue drying. This includes studying effects on the drying capacity, on the use of thermal and electrical energy and on the potential for recovery of exhaust gas excess heat.

4.1.1 System description

The Yankee dryer considered in the present work comprises a steam heated cylinder used for drying and conveying at the web. The potential for rapid water removal allowed by the low thickness of the web is utilized by the usage of two hot gas impingement hoods employing recirculation of the impinging gas, Figure 12. The recirculating drying gas is directly heated by combustion of energy gas. To maintain the anticipated moisture content of the recirculating gas of the second hood, a counter-current flow is transferred to the first hood from which the exhaust gas stream of the dryer system is expelled. The stream of fresh air feeding the energy gas combustors (hereafter called combustion air) and diluting the recirculating gas (hereafter called make-up air) is preheated using excess heat recovered from the exhaust gas stream.

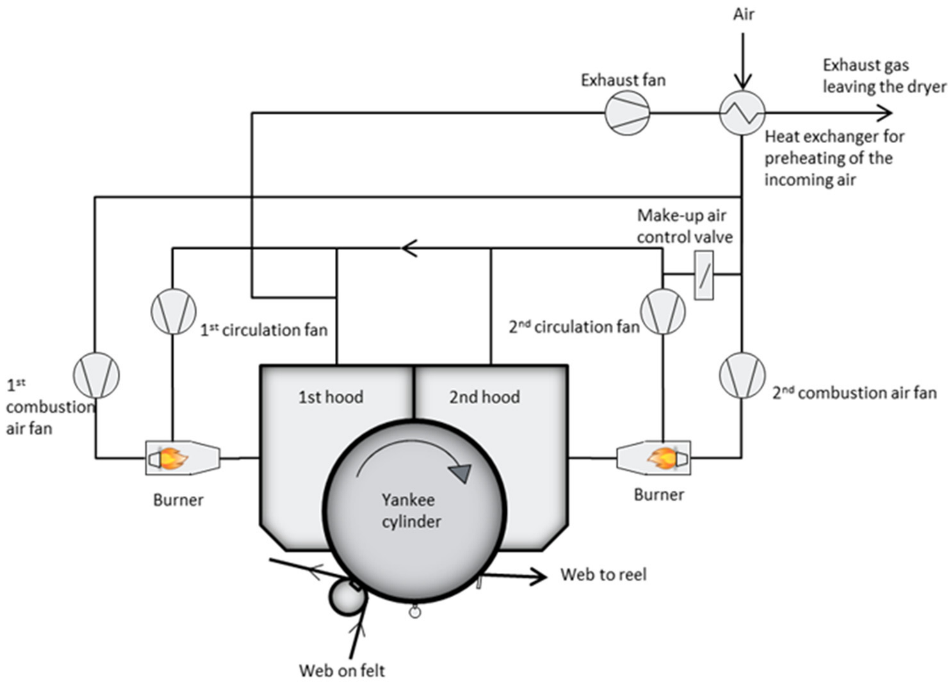

Figure 12. Flowsheet of the Yankee dryer system air and gas flows.

4.1.2 Mathematical models

A mathematical model developed to enable simulations of Yankee drying was used to assess the effects of replacing LPG with syngas. The model used was presented by Ottosson et al. [19] and it can be employed for simulations of both local and overall drying behavior.

In order to quantify the influence on energy use and on the potential for excess heat recovery, the mass and energy balances of the drying system were solved. In this work, numerical values for temperature, humidity and impingement velocity of the drying gas were for both hoods taken from results retrieved by employing the drying model mentioned above. The content of dry gas of the exhaust gas stream is determined by summing the combined fresh air inflows together with total dry energy gas flow deducted for combustion induced water generation. The mass flow of water of the same stream is determined from the water evaporated from the web and from the moisture content of the used energy gas with the addition of the combustion generated water vapor. Knowing the described relationship between in- and outgoing flows of material as well as the properties of the impinging gas allows for iteratively solving the mutually dependent variables of the balances for water, dry gas and enthalpy.

Heat losses from the dryer body are assumed to amount to 5 % of the total evaporation load [20]. Enthalpy estimations made assume gases to consist of humid air with the exception for the inflow of energy gas. It is assumed that the combustion system can burn the investigated energy gases at the rates required to fulfill the conditions set by the heat and mass balances of the drying operation. The stream of fresh air distributed to the recirculating gas and to the energy gas combustors are assumed to be preheated to 200 °C utilizing excess heat recovered from the exhaust gas stream. The composition of the flue gas resulting from syngas combustion was calculated in the software

CHEMCAD. The size of the flue gas mass flows were subsequently scaled to match values predicted for the drying system use of syngas.

4.1.3 Properties of considered energy gases

Effects of use of two biomass derived energy gases of varying composition, calorific value and combustion characteristics are considered in the present work, Table 6. The reference gas used is LPG which for convenience is assumed to consist of 100 % propane, C_3H_8. The main differences between the considered syngases are the hydrogen and the nitrogen content as well as an accompanying change in calorific value.

Table 6. Assumed dry basis composition and combustion characteristics of considered energy gases.

	LPG ref. energy gas	Syngas 1 low H_2 content	Syngas 2 high H_2 content
Propane, C_3H_8	100 Vol-%	0 Vol-%	0 Vol-%
Hydrogen, H_2	0 Vol-%	17 Vol-%	54 Vol-%
Carbon monoxide, CO	0 Vol-%	22 Vol-%	34 Vol-%
Methane, CH_4	0 Vol-%	2 Vol-%	3 Vol-%
Carbon dioxide, CO_2	0 Vol-%	11 Vol-%	9 Vol-%
Nitrogen, N_2	0 Vol-%	48 Vol-%	0 Vol-%
Lower heating value	90.0 MJ/Nm^3	6.2 MJ/Nm^3 dry syngas	11.2 MJ/Nm^3 dry syngas
Lower Wobbe index [MJ/Nm3 dry gas]	75	5.7	16
Stoichiometric air-fuel ratio [kg dry air/kg dry gas]	15.6	1.29	4.54
Water content [kg water/kg dry gas]	0.0	0.032	0.014
Combustion derived water generation [kg water/kg dry gas]	1.714	0.148	0.717

Four simulation cases were defined in order to study the effects of replacing propane with syngas of varying composition. Case 1 is the reference where propane is used as energy carrier. Case 2 and 3 utilize syngas 1 and syngas 2, respectively. The combustion reactions of case 1, 2 and 3 were supplied with 40 % excess of air. However, stoichiometric combustion of gas mixtures of carbon monoxide and hydrogen can result in an adiabatic flame temperature significantly higher than what is reached in stoichiometric combustion of propane [21]. The hydrogen and carbon monoxide content of at least one of the energy gases involved in the present study might therefore require the application of strategies to control formation of thermally formed nitrogen oxide. Using sufficient levels of excess air can under certain conditions reduce the flame temperature sufficiently to avoid unwanted levels of thermally formed nitrogen oxides [22]. To investigate effects of such a strategy on the heat and mass balances of tissue drying, a case utilizing 100 % excess of combustion air were defined for the use of syngas 2.

The parameters describing the tissue production conditions, shown in Table 7, were held constant for all simulated cases in order to form an appropriate basis for comparison. To establish the conditions of the impinging gas required to dry the web to the expected final dryness, simulations using the aforementioned drying model were made. As there is a mutual dependency between the rate of evaporation and the humidity of the impinging gases of the hoods, an iterative solution was used to find the appropriate values for the moisture content of the drying gases.

Table 7. Input parameters valid for all simulated cases.

Machine speed	1485 m/min
Web basis weight on the Yankee cylinder	11.65 g/m2
Web basis weight at reel	15.3 g/m2
Post pressure roll web consistency	42 %
Final dryness	94 % ± 0.1
Temperature of Yankee dryer condensing steam	171.4 °C
Impinging gas temperature of the 1st hood	394 °C
Impinging gas temperature of the 2nd hood	390 °C
Impinging gas velocity of the 1st hood	106 m/s
Impinging gas velocity of the 2nd hood	100 m/s

4.1.4 Simulation results

Using the numerical values presented in Table 7, a simulated final web dryness of 94 % was, for all involved energy gases, obtained without the need for case individual adjustments of the impinging gas temperature or velocity. However, as the investigated energy gases have different calorific values, contain varying amounts of water, and use different amounts of combustion air as well as produce different quantities of water during combustion, adjustments of the make-up air flow were necessary to maintain a constant drying capacity, see Table 8.

Table 8. Simulation results.

	Case 1	Case 2	Case 3	Case 4
Combustion air excess [%]	40	40	40	100
Impinging gas humidity of the 1st hood [g water/kg dry air]	354	348	357	341
Impinging gas humidity of the 2nd hood [g water/kg dry air]	234	238	228	245
Exhaust gas humidity [g water/kg dry air]	454	448	457	440
Flow of dry air for combustion [kg/s]	1.094	0.785	0.919	1.318
Flow of dry air for make-up [kg/s]	0.970	0.883	1.095	0.786
Propane mass flow [kg/h]	180.3	0.0	0.0	0.0
Propane volume flow [Nm^3/h]	92.93	0.0	0.0	0.0
Dry mass flow of syngas 1 [kg dry gas/h]	0.0	1561	0.0	0.0
Dry volume flow of syngas 1 [Nm^3/h]	0.0	1386	0.0	0.0
Dry mass flow of syngas 2 [kg dry gas/h]	0.0	0.0	520.1	521.9
Dry volume flow of syngas 2 [Nm^3/h]	0.0	0.0	772.6	775.2
Mass flow of water in energy gas stream [kg/h]	0.0	49.87	7.059	7.084
Combustion derived water generation [kg/h]	294.9	230.5	372.9	374.2

If it is possible to keep the temperature, velocity and humidity of the impinging gas constant for the simulated cases, this means that the drying conditions are identical. However, due to the differences in the characteristics of the examined energy gases, it is not possible to accomplish an identical impinging gas humidity for the investigated cases, implying that local drying conditions are to some extent varying. The time averaged rate of drying is however identical if equal final web dryness is reached.

Valid for the syngas cases employing 40 % air excess (case 2 and 3), the need for combustion air is reduced compared to the reference case of LPG, Figure 13. For the case of syngas 1, the reduction is approximately 30 %. However, the energy gas flow was increased 8.7 times in terms of mass flow and 14.9 times in terms of volume flow.

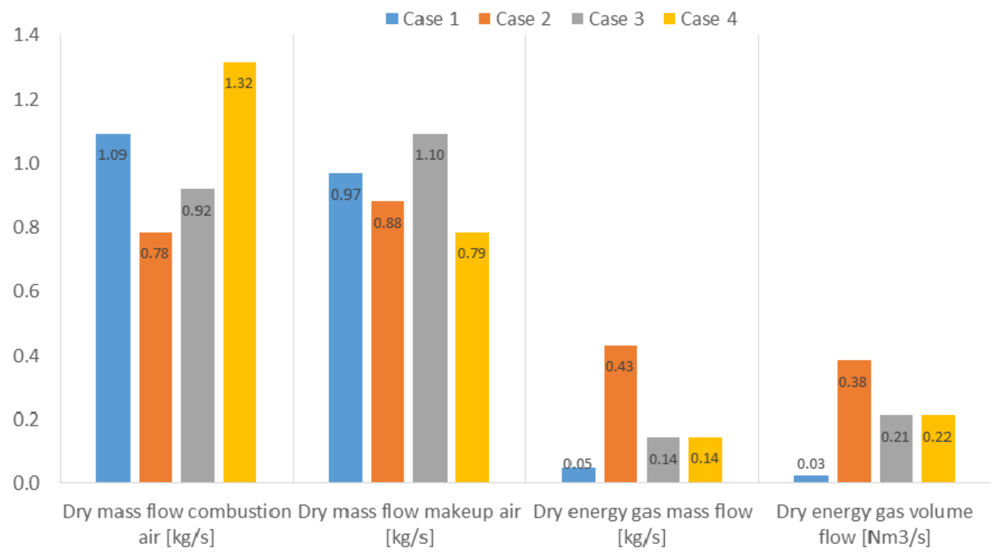

Figure 13. Total inflow of make-up air, combustion air and energy gas entering the drying system.

Figure 14 presents the mass flows of the gas components resulting from combustion of the investigated energy gases using oxygen from atmospheric air as oxidant. The air excess was set to 40 % with the exception of case 4, where it was set to 100 %. The combustion reaction products of carbon dioxide and water of the syngas cases are the components computed to deviate most compared to the reference case. Emissions of carbon dioxide are calculated to increase by 78 % and 29 % for case 2 and case 3 respectively.

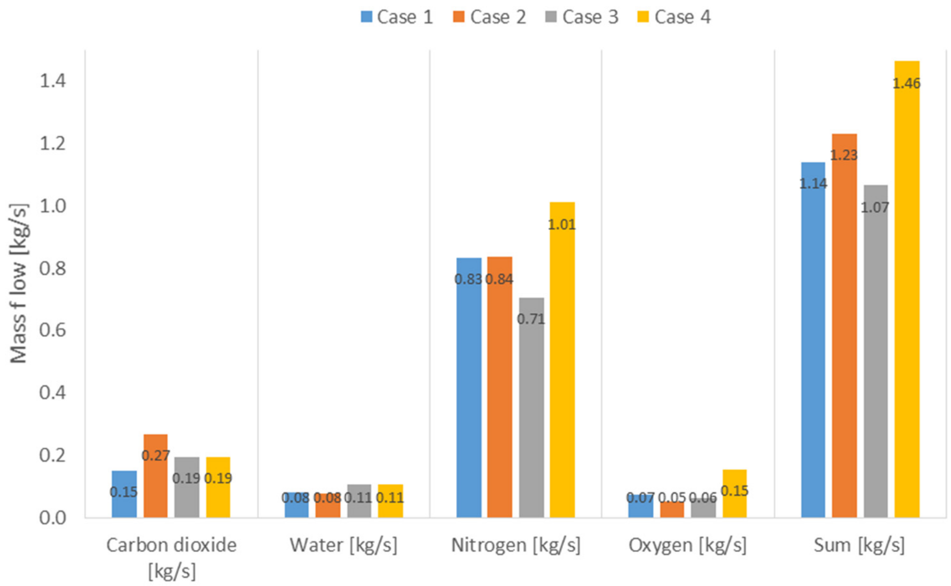

Figure 14. Combustion flue gas components entering the recirculating drying gas.

Although the relative differences between the concentrations of combustion flue gas components are substantial, the components of carbon dioxide and water constitute a relatively small fraction of the combined combustion flue gas and make-up air stream, Figure 15. Compared to the results presented in Figure 14, only atmospheric air (make-up air) is added and consequently differences are mainly experienced for the components of nitrogen and oxygen together with the total mass flow. The relative difference in total mass flow entering the drying gas stream is, comparing cases utilizing 40 % air excess, less than 3 %.

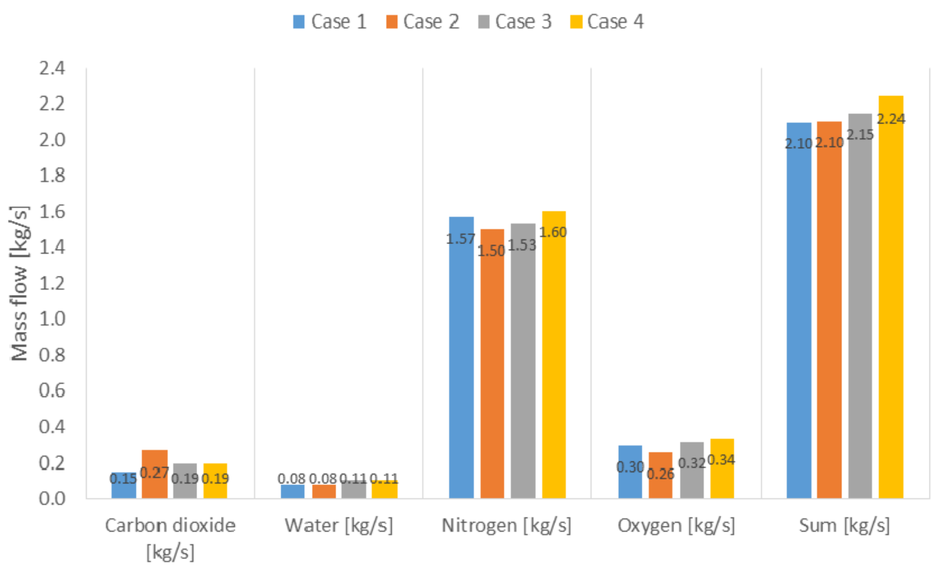

Figure 15. Components of combustion flue gas and make-up air entering the recirculating drying gas.

Aspects on energy efficiency

The predicted use of energy carriers involved in the investigated drying process are compared in Figure 16. As mentioned earlier, the drying process simulations made for the different cases have common values for web dryness at the start and the finish of drying, thus the same amount of water is removed by means of thermal dewatering.

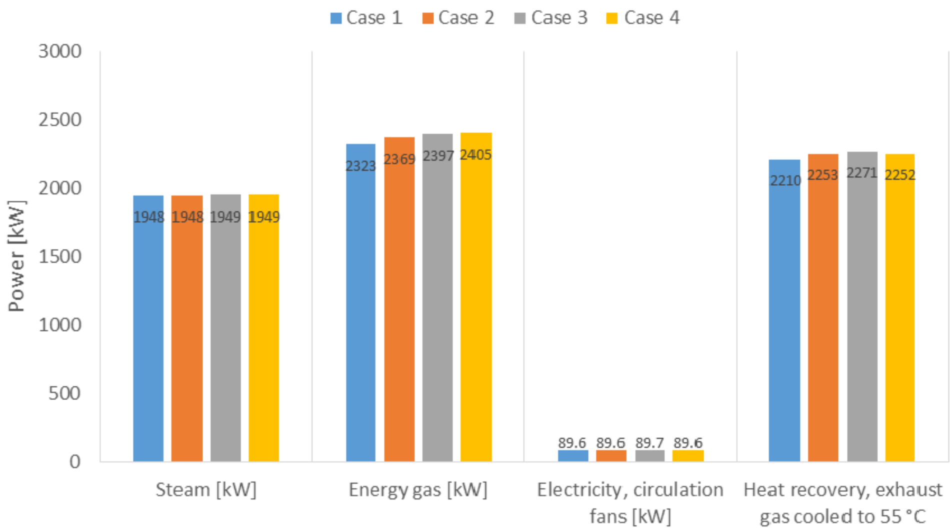

Figure 16. Use of energy for involved energy carriers and potential for recovery of exhaust gas excess heat.

The use of steam for heating of the dryer cylinder is calculated to be equal for the compared cases. Hence, the calculated variation regarding the usage of heat produced from energy gas implies that the thermal efficiency of the impingement hoods is slightly dependent on the characteristics of the used gaseous fuel.

Results presented above show that a higher inflow of energy gas due to a lower calorific value was accompanied by an expected reduced need for combustion air. However, the total mass flow of combustion air and energy gas only changed slightly. Therefore, as streams of combustion and make-up air are assumed to be preheated to 200 °C while the energy gas has a temperature of 30 °C prior to admission of the combustion system, the enthalpy inflow to the dryer is lower for the syngas cases. The lower inflow of enthalpy needs to be compensated for to preserve the drying capacity. This compensation is achieved by an increased rate of combustion of energy gas at the cost of a reduced thermal efficiency of the drying process. Here, enthalpy coming from excess heat based preheating is replaced by thermal energy produced by use of energy gas.

The amount of water added to the drying gas due to combustion varies between the studied energy gases. This water stems from moisture content in the energy gas and/or water generated in the combustion reaction. In order to maintain the desired drying capacity, increased addition of water to the drying gas requires an increased outflow and inflow of exhaust gas and make-up air respectively. Increased outflow of warm exhaust gas is a loss of enthalpy that is compensated for by energy gas combustion for heating of the needed supplement of dry air, leading to a reduction in thermal efficiency of the drying process.

For the syngas used in case 2, the calculation results presented in Figure 16 show that the demand for thermal energy derived from combustion of energy gas increases slightly compared to the reference case. The thermal efficiency of the dryer is reduced due to less use of preheating as heat source. On the other hand, the amount of water added to the drying gas by combustion is approximately 5 % lower compared to the reference case. Combined, these effects have a negative impact on the drying efficiency, resulting in an increased need for heat from energy gas of approximately 2 %.

Considering the calculated results for use of the hydrogen-rich syngas of case 3, also in this case the demand for heat produced by energy gas combustion is higher than for the reference case. This is the result of a somewhat reduced use of preheating as thermal energy source as well as of an increased addition of combustion derived water of around 30 %. Still, the predicted increase in use of primary energy is relatively small, being approximately 3 %.

The potential for recovering exhaust gas excess heat was for the investigated cases assessed by calculating the sensible and latent heat acquired when cooling the exhaust gas stream to 55°C, Figure 16. The dependency of the energy gas used was found to be low. However, at constant air excess the potential for heat recovery correlates well with use of primary energy.

As previously described, data for predicted energy use presented in Figure 16 are calculated assuming an energy gas temperature prior to combustion of 30 °C. However, the cases of syngas combustion experience a lower contribution from preheating to the overall heat balance. Therefore, the effects of preheating the energy gas on the need for primary energy was also considered. Results from calculations assuming availability of recovered excess heat to warm the energy gas are presented in Figure 17. Preheating the syngas of case 2 to a temperature of 110 °C is predicted to result in a drying efficiency equal to the reference case. The effect of preheating the syngas of case 3 is less pronounced due to the lower mass flow of energy gas.

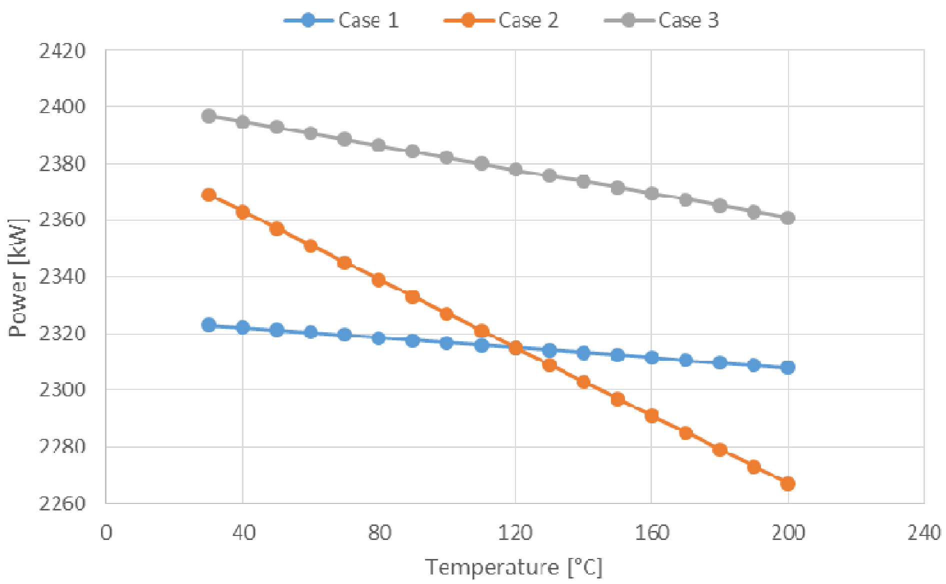

Figure 17. Effect of preheating energy gases on use of thermal energy derived from combustion.

Effects of varying equivalence ratio

In the simulation made for the parameters of case 4, the hydrogen-rich syngas 2 is burned at an air excess of 100 %. Compared to the results for case 3, where the same energy gas is used but the air excess is set to 40 %, use of heat derived from combustion of syngas is only marginally increased, see Figure 16. The somewhat reduced potential for recovery of excess heat is a result of the decreased concentration of water vapor in the exhaust gas stream from the dryer, see Table 8.

4.2 REPLACING LPG WITH SYNGAS – EFFECTS ON THE COMBUSTION SYSTEM

The simulation study presented in chapter 4.1 pointed out the significant increase in the energy gas flow. The focus of the investigation presented in the current chapter will therefore be on assessing the fuel interchangeability of the burners in the existing combustion system and on operational issues plausible in combustion of syngas.

4.2.1 Assessment of fuel interchangeability of the energy gas burners

The viability of replacing a gaseous fuel with a replacement fuel is dependent on several factors [23,24], however, a main issue is obviously to ensure the ability to generate a sufficient amount of heat. A widely used fuel interchange parameter developed to address this question is the Wobbe index, shown in Eq. (1).

$$WI = \frac{LHV}{\sqrt{SG}} \qquad (1)$$

LHV is the lower heating value and SG is the specific gravity of the investigated fuel. For a specific burner and a given gas pressure, two fuels having equal Wobbe index generate equal amounts of heat. Hence, this parameter indicates the rate of energy flow of the gas flow passing through the burner nozzle at a given pressure drop. Although the Wobbe index is a useful parameter in evaluating fuel interchangeability, it does however not address effects on burner operability, that is, phenomena such as flashback, blowout and autoignition.

Calculated Wobbe indices for the energy gases selected for evaluation in the current study are presented in Table 6. As the Wobbe indices for Syngas 1 and Syngas 2 are only 8 % and 21 % respectively of the value for propane, it is concluded that the gas pressure or component/components of the burner or both are subjects for amendments in order to preserve the amount of generated heat.

In a recent study [25], implications of replacing fossil fuels in industrial applications utilising directly heated processes were investigated. No experimental work was made and statements regarding needed combustion system component replacements or modifications were therefore reliant upon reports from burner suppliers and from the industrial sectors involved in the project. Use of a syngas of low calorific value, typically produced by air blown gasification, was concluded to result in a need for replacement of the burner assembly. The range of lower heating values of the considered syngas was in this case 4 to 6 MJ/m^3 which is relatively close to the value for Syngas 1, Table 6. Use of a syngas of higher hydrogen content and therefore higher calorific value and, most likely, also higher Wobbe index was concluded to implicate a major modification to the existing burner assembly including new burner nozzles and seals. The considered range of lower heating values for this higher calorific value syngas was 12 to 29 MJ/m^3, thus somewhat higher than the value for Syngas 2, Table 6.

Existing burners used in the direct heated processes investigated in the cited study were designed for combustion of natural gas.

4.2.2 Syngas combustion in Yankee Hood Burners: operability issues and implications on combustion system design

Syngas, or synthesis gas, is a fuel mixture containing hydrogen, carbon monoxide and carbon dioxide, in variable ratio, depending on the type of gasification process.

In the Syngas fuel mixture also nitrogen is present, and as a result of the presence on N_2 and CO_2, the calorific value of the mixture is usually much lower compared to LPG.

When burning syngas one has then to take in account these two key factors:

- High hydrogen content
- Low calorific value

The lower calorific value impact is mainly in the higher fuel flow needed. This will reflect both in a larger size of the burner components, starting from gas piping to burner nozzles, and in the heat and mass balance of the burner itself due to the higher quantity of gas that is introduced in the combustion chamber and in the heat/mass balance need to be heated up to hood impingement temperature.

Lower calorific value requires also a burner that develops the flame in a hot reaction area like a refractory block or reaction chamber. This will exclude the possibility to install so-called "in-line" burners, and force to choose corner burner, with combustion chamber and slave designed in order to keep flame temperature as high as possible. This will also help to burn possible contaminants present in syngas even after the cleaning process.

More complicated is the complete analysis of the issues linked to the high hydrogen content. Those aspects are analyzed both by McDonell [23] and Lieuwen et al. [24]. As highlighted by McDonell [23], hydrogen behaves differently than a hydrocarbon in many ways including specific heat (hydrogen has a much higher specific heat than other gases, even if syngas mixture will have a lower one due to its inert components), diffusivity (hydrogen has a much higher diffusivity than other gases), flammability limits (hydrogen has a wide range of volume concentrations over which it is flammable), and flame speed (hydrogen has a much higher laminar flame speed than do other gases).

As mentioned before, corner burner should be used due to low LHV. Corner burners are characterized by mixing of fuel and oxidant (combustion air) in the burner nozzle. Given both the high flame speeds of hydrogen and wider flammable limits, the possibility of reaction evolving into the premixing region, not designed to accept high temperature, is a major concern that must be examined carefully during the design phase.

Lieuwen et al. [24] summarise the most critical of these operability issues of operating a combustor with Syngas in four categories: blowout, flashback, combustion instability and autoignition.

> *Blowout refers to situations where the flame becomes detached from the location where it is anchored and is physically ''blown out'' of the combustor. Blowout is often referred to as the ''static stability'' limit of the combustor. Blowoff involves the*

interactions between the reaction and propagation rates of highly strained flames in a high speed, often high shear flow. Blowoff events can require a lengthy and often expensive system shut down, purge cycle, and restart.

A second issue is flashback, where the flame propagates upstream of the region where it is supposed to anchor and into premixing passages that are not designed for high temperatures. Flashback involves turbulent flame speed propagation in a highly inhomogeneous, swirling flow. Since premix nozzles are not well cooled, flame flashback is a serious safety risk. After flashback has occurred, flame anchoring in the nozzle leads to a fast rise of material temperatures, with subsequent overheat and failure.

Combustion instability refers to damaging pressure oscillations associated with oscillations in the combustion heat release rate. These oscillations cause wear and damage to combustor components and, in extreme cases, can cause liberation of pieces into the hot gas path, damaging downstream components.

Autoignition refers to the homogeneous ignition of the reactive mixture upstream of the combustion chamber. Similar to flashback, it results in chemical reactions and hot gases in premixing sections, but its physical origins are quite different from those of flashback. Rather than the flame propagating upstream into the premixing section, autoignition involves spontaneous ignition of the mixture in the premixing section.

There are other possible operability issues due to water and other contaminants coming from the gasification process.

Presence of water is problematic, not necessarily during operation but mostly during a shut-down, when water condenses inside piping and instrumentation. Even if pipelines could be designed to collect condensate or could be traced to avoid condensation, water in syngas could have severe consequences on the operational reliability and increase the cost of the instrumentation that needs to be installed, especially when combined with acid fractions.

Dust, greasy or oily fractions must be eliminated in fuel gases. These have a terrible effect on the pipe-train instrumentation. There are methods to fire these dirty gases but this involves heavy ball valves and possibly steam cleaning cycles which are very difficult to apply in Yankee Hood burners and cannot be justified.

Tar or other aromatic substances could also have a negative impact on the papermaking process, being transferred to paper during drying. This situation absolutely needs to be avoided and further investigations have to be done. If investigations will give a negative response (smelling or contaminant substances transferred to paper) there is still one possibility, i.e. the use of indirect burners such as radiant tube burners. This system consists of a nozzle-mixing burner that is firing in a radiant tube, that could have different shapes, and that is exchanging heat with the process through its external surface, without any contact between combustion products (and then possible contaminants) and tissue-making process.

Radiant Tubes exhaust fumes could be used in a heat exchanger to preheat combustion air, in order to increase the overall burner efficiency, that will be of course lower than direct firing.

By proper selection of hood operating point and radiant tube burner recuperator, an overall efficiency higher that 70% can be reached. Further amount of energy could be recovered after fumes/combustion air heat exchanger, to be used in other part of the tissue-making process (process water heating) or gasification process (biomass heating).

4.3 CONCLUDING REMARKS

The effects of replacing LPG with syngas in the impingement drying of tissue were investigated by use of mathematical models. The study focused on examining the impact on drying capacity and thermal efficiency as well as on the influence on the potential for recovery of excess heat.

Assuming that the combustion system can burn the investigated energy gases at the rate required to fulfill the calculated process heat demand, the results from the simulation study show that the drying capacity is likely to be preserved if replacing LPG with syngas.

Assuming that all investigated gaseous fuels are non-preheated, the use of heat derived from combustion of the studied syngases was calculated to increase by less than 3.5 % compared to the reference case of LPG.

At 40 % excess of combustion air, the potential to recover excess heat from the exhaust gas stream was predicted to correlate well with the use of primary energy. The potential for recovery of excess heat is thereby predicted to be relatively unaffected by the replacement of LPG with syngas.

The minor investigation of fuel interchangeability made within the present study shows that the existing gas burners probably need to be replaced in order to preserve the drying capacity. Moreover, for syngas to form a viable option in a tissue drying application, the combustion system needs to be designed for compliance with existing emission legislations and to avoid concerns (e.g. blowout and flashback) that are shown to occasionally arise during combustion of syngas.

5 System studies

Based on our literature survey of gasification and gas cleaning technologies, on information from technology suppliers and on process data from the three production lines, this chapter investigates the advantages and disadvantages of integrating a biomass gasification process in the three production lines.

5.1 ASSUMPTIONS AND METHOD

The overall data regarding steam production and LPG use in the present process are illustrated in Figure 18. The process steam at the plant is produced in a boiler powered with biofuels. At present, no flue gas condenser is installed so that the flue gases leave the system at a temperature of 142°C. The LPG consumption for the three production lines can be estimated as 25,0 GJ/h – almost 7 MW – during periods with top production. These data for the consumption of process steam and energy gas are used as a basis for the analysis throughout the chapter even though the need for energy gas is periodically lower.

The method used for energy system analysis involves setting up and solving the heat and mass balances for the production system after the integration of the biomass gasification using the commercial flowsheeting software CHEMCAD. In order to simulate the thermochemical conversion of biomass, the component list in CHEMCAD needs to be updated with three components representing biomass, pyrolysis char and gasification char. The elemental compositions as well as the lower heating values of the new components are listed in Table 9. The two new components pyrolysis char and gasification char are similar in their heating values but differ somewhat in their elemental compositions. The gasification char is the solid residue from a higher temperature process than the pyrolysis char and has a higher content of carbon. [26-28]

Table 9. The new components that were added to the database in CHEMCAD in order to model thermal gasification of biomass.

Component	wt-% C	wt-% H	wt-% O	LHV (MJ/kg)
Biomass	52.0	6.0	42.0	19.0
Pyrolysis char	83.0	4.0	13.0	29.8
Gasification char	95.0	0.6	4.4	30.4

The concept of Lower Heating Value (LHV) assumes that the condensation enthalpy of the flue gases cannot be utilized within the system. Normally, the energy efficiency is based on the LHV, so that a system including flue gas condensation might reach a total energy efficiency that is higher than 100 %. When defining the Higher Heating Value (HHV) or calorimetric heating value, the opposite assumption is made: All water vapor is assumed to condense within the system and leave in the form of liquid water. The biomass component defined according to Table 9 will have a HHV of 20.3 MJ/kg. Any moisture content of a solid fuel will act as an inert in the context of the Higher Heating Value but will lead to a further reduction in the Lower Heating Value due to the energy need for vaporization. For a biomass with a moisture content of 50 % as assumed in the present study, the values for the lower and higher heating values will be 8,92 MJ/kg and 10.14 MJ/kg respectively, when the Biomass component in Table 9 is taken to represent the dry fuel.

When using the flowsheeting software CHEMCAD, the material and energy flows into the system must be defined along with the unit operations. In the models set up the following unit operations are used:

1. Stoichiometric reactors for simulating the four gasification processes. This means that the stoichiometry was fixed to yield a syngas composition in good agreement with scientific literature and technology supplier data. The pyrolysis process in the two-stage gasification technology was modelled in the same way, using a stoichiometric reactor. Once the stoichiometry has been defined, the simulation results will provide relevant information as to the energy balance of the reaction (heat needed or heat produced).
2. Gibbs free energy reactors for simulating the bio boiler and the combustion of the syngas. As long as excess oxygen is provided to such a Gibbs free energy reactor, combustion will be complete. The simulation result then provides relevant information as to the energy balances of the system.
3. Dryers for simulating the drying of the biomass prior to gasification
4. Flashes for simulating cold gas cleaning
5. Separators for simulating the separation of solid residues from gasification (pyrolysis char and gasification char) from the syngas as well as for simulating removal of the final tar in an active coal filter
6. Heat exchangers for simulating air heaters and steam generators
7. Controllers (not included in the inserted process diagrams) for keeping track of any system constraints that cannot be defined in the unit operation blocks themselves. This includes for instance controlling the air flow to the boiler so that the oxygen content of the flue remains at a set value or controlling the flow of gasification medium to the gasification reactor according to the stoichiometric constraints defined.

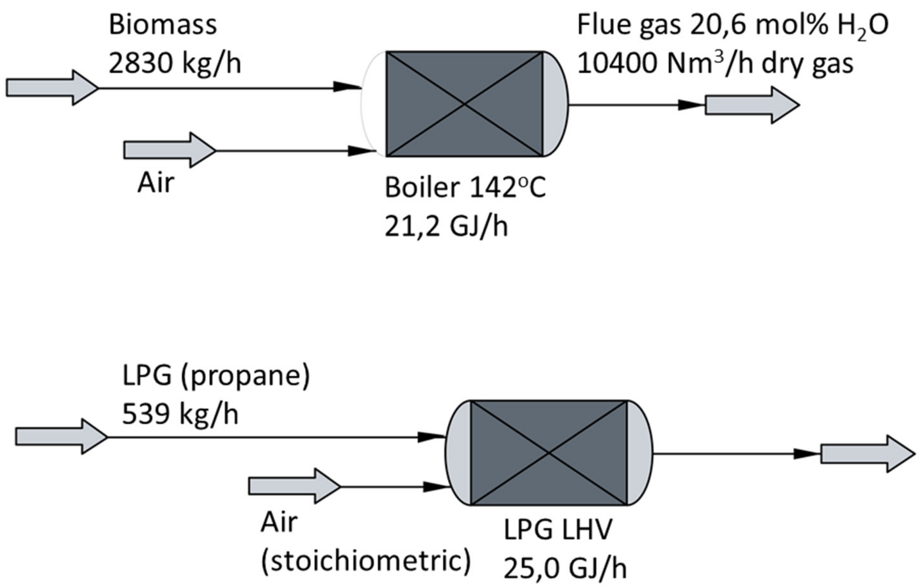

Figure 18. The base case energy system – a bioboiler and tissue machine hoods heated with LPG.

For comparing the technologies, a number of assumptions were made that were applied to all four systems:

- The need for process steam for the present processes will not change. The only change in the steam consumption is the additional steam used as a gasification medium for two of the studied technologies (steam blown dual bed and two-stage gasification).
- It is assumed that the same biomass that is used for steam production in the boiler is also gasified. The moisture content of the biomass prior to drying is assumed to be 50 wt%.
- Prior to gasification the biomass is dried to a moisture content of 10 %.
- When exchanging the LPG for green syngas, a 3 % increase in the heat needed from the energy gas is assumed. This assumption is based on results in the chapter on tissue drying and means that the product of the flow of syngas and its LHV should be 25.75 GJ/h.
- For representing tar in the CHEMCAD models, the component naphthalene was used.
- For removing tars and excess water, the syngas is cooled to 30°C, resulting in two liquid fractions that are assumed to be easy to separate. The liquid fraction that is rich in tar will be used for steam production. The water fraction leaves the system as a condensate at 30°C.
- An active carbon filter is used for removing the tar that remains in the syngas after the condenser. The tar that is removed here represents an energy loss.
- The temperature of the flue gases from the bio boiler will remain at 142°C in all systems.
- Hot gas streams will be used for steam generation. The gas temperature after each steam generator was assumed to be 190°C.
- Any pressure drops in the added process equipment will be neglected, hence the need for electricity for pumps and fans was not taken into account.

In addition to the list of assumptions common for all technologies above, some technology-specific assumptions were also made. Table 10 contains the assumptions for the flow of the gasification media along with, for instance, the resulting compositions of the syngas and the temperature of the gasification reactor. Some of the data in Table 10 were already presented in the chapter on gasification technologies to provide a comparison of our original work in the project, literature data and technology supplier information. In addition to the parameters presented in Table 10, it could be mentioned that no preheating of the air for gasification was assumed for the two fixed bed technologies where air is used as a gasification medium. This might explain (to some degree) the rather low gasification temperature resulting for the fixed bed, downdraft. For the two technologies where superheated steam is used as a gasification medium, the steam is assumed to be produced within the system adding to the need for process steam as compared to the base case presented in Figure 18.

Table 10. Mass balances for the four modelled gasification processes. .

	Fixed bed, updraft	Fixed bed, downdraft	Dual bed	Two stage
Gasification reactor	Adiabatic	Adiabatic	Isothermal	Istothermal
Gasification temp	616°C	868°C	800°C	1100 °C
LHV syngas (dry gas)	5,0 MJ/Nm³	5,4 MJ/Nm³	15,1 MJ/Nm³	11,4 MJ/Nm³
Carbon monoxide, CO	18 Vol-%	22 Vol-%	32 Vol-%	34 Vol-%
Carbon dioxide, CO_2	17 Vol-%	11 Vol-%	16 Vol-%	9 Vol-%
Hydrogen, H_2	17 Vol-%	17 Vol-%	34 Vol-%	54 Vol-%
Methane, CH_4	2 Vol-%	2 Vol-%	15 Vol-%	3 Vol-%
Ethylene, C_2H_4	0 Vol-%	0 Vol-%	4 Vol-%	0 Vol-%
Nitrogen, N_2	46 Vol-%	48 Vol-%	0 Vol-%	0 Vol-%
Tar	136 g/Nm³	4,2 g/Nm³	32 g/Nm³	0 g/Nm³
Gasification char (kg char/kg dry biomass)	0,006	0,006	0,128	0
Pyrolysis char (kg char/kg dry biomass)	0	0	0	0,399
Gasification medium	Air ER = 0,168	Air ER = 0,339	Steam SBR = 0,667	Steam SBR = 0,518
Flow of gasification medium	3850 kg/h	3770 kg/h	1270 kg/h	890 kg/h

5.2 INTEGRATED SYSTEMS

In order to evaluate the suggested technologies from a process integration point of view, a number of key parameters characterizing the thermodynamic performance and the operational cost of the technologies have been defined. The base case is characterized in terms of a boiler energy efficiency η_{boiler} that is defined as the quotient between the heat for producing process steam Q_{steam} and the lower heating value of the biomass LHV used in the base case, Eq. (2):

$$\eta_{boiler} = \frac{\dot{Q}_{steam}}{\dot{m}_{basecase} \cdot LHV} \quad (2)$$

The marginal energy efficiency of gasification $\eta_{gas,marginal}$ is defined as the quotient between the heat from the syngas produced $1.03 \cdot Q_{LPG}$ and the product of the increase in biomass consumption $m_{increase}$ and its lower heating value, Eq. (3). Here, the left hand side is a thermodynamic property of the system whereas the increase in biomass consumption is a direct measure of the additional operating cost, which should be related to the cost of the LPG that is bought at present:

$$\eta_{gas,marginal} = \frac{1.03 \cdot \dot{Q}_{LPG}}{\dot{m}_{increase} \cdot LHV} \quad (3)$$

The total energy efficiency of the system $\eta_{total,integrated}$ is defined as the sum of the heat from the syngas and the heat from the steam divided by the product of the total biomass consumption $m_{basecase} + m_{increase}$ and its lower heating value, Eq. (4).

$$\eta_{total,integrated} = \frac{1.03 \cdot \dot{Q}_{LPG} + \dot{Q}_{steam}}{(\dot{m}_{basecase} + \dot{m}_{increase}) \cdot LHV} \quad (4)$$

The four integrated systems are illustrated in Figure 19, Figure 20, Figure 21 and Figure 22. For the two fixed bed systems, no extra steam is needed for gasification so that the steam production from the hot syngas leads to a decrease in the steam produced in the boiler. For the updraft system (Figure 19), the excessive tar production leads to the situation that all the demand for process steam is covered by firing the tar that is separated from the syngas in the condenser. For the downdraft system (Figure 20), much less tar is separated from the syngas and the need for biomass for steam production is far from eliminated.

The steam blown dual bed (Figure 21) and the two-stage gasification (Figure 22) are similar in that some additional process steam is needed as a gasification medium. Here, additional process steam can be produced from the hot syngas, but also from the hot flue gases. The flue gases are not assumed to be mixed with the flue gases from the boiler but rather leave the system at a temperature of 190°C after the steam generator.

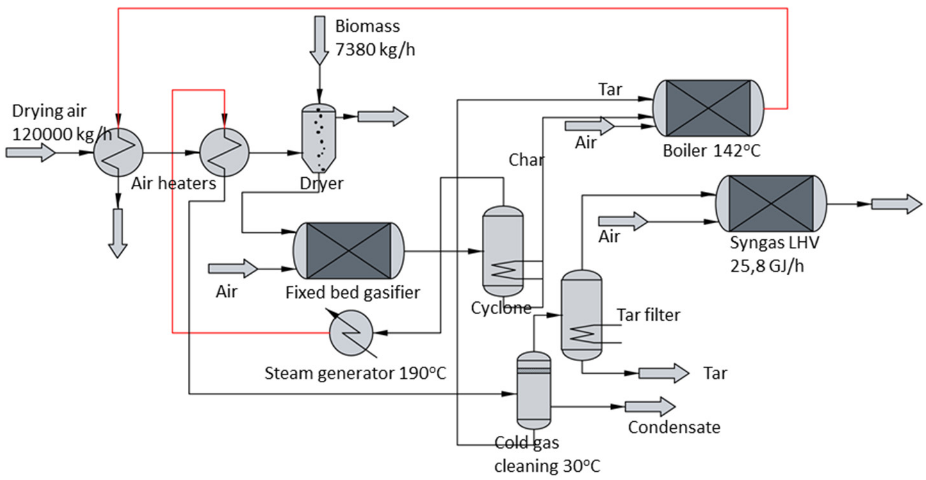

Figure 19. The energy system after the integration of an updraft fixed bed gasification reactor for production of green syngas replacing the LPG used at present.

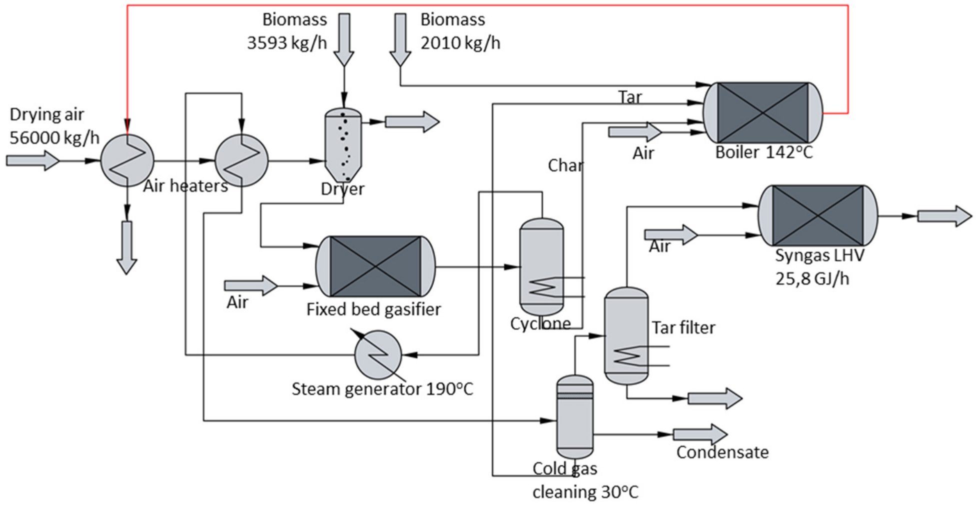

Figure 20. The energy system after the integration of a downdraft fixed bed gasification reactor for production of green syngas replacing the LPG used at present.

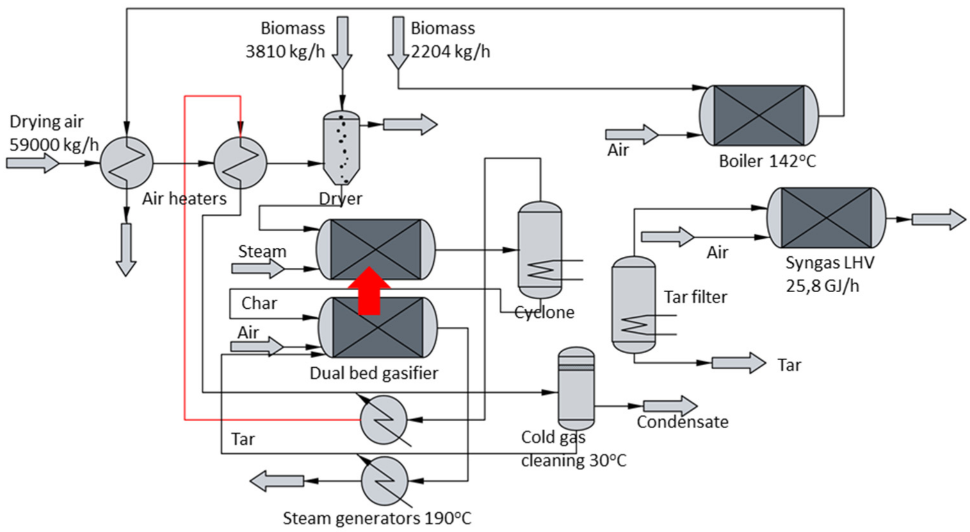

Figure 21. The energy system after the integration of a steam blown dual bed gasification process for production of green syngas replacing the LPG used at present.

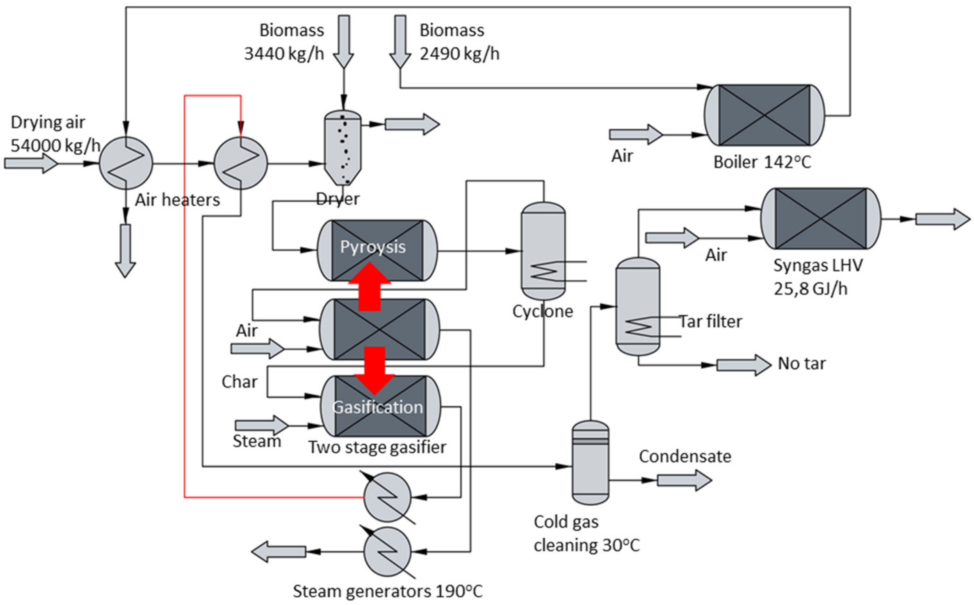

Figure 22. The energy system after the integration of a steam blown two stage gasification process for production of green syngas replacing the LPG used at present.

5.3 STANDALONE SYSTEMS

For the purpose of evaluating the importance of process integration for the operational cost of the technologies, simulations assuming instead a stand-alone gasification plant were performed. This was done in order to evaluate the energy efficiency of the technologies assuming instead a stand-alone operation of the gasification as opposed to the concept of an integrated system.

Figure 23 illustrates the changes made for the downdraft fixed bed system when setting up syngas production and process steam production as two standalone operations. The flue gases from the boiler are no longer used for heating the dryer. Instead, heat for drying not supplied from the hot syngas is assumed to come from a separate system for combustion of biomass. The hot syngas is no longer used for steam generation so that all the process steam needed is assumed to be produced in the boiler. Any tar formed during gasification is assumed to leave the system and will be counted as energy (and resource) lost from the system.

The benefits of process integration can be expressed as the decrease in biomass consumption of the integrated plant as compared to a system where the process steam and the syngas are produced in standalone units.

The standalone energy efficiency of gasification $\eta_{gas,standalone}$ is defined as the quotient between the heat from the produced syngas produced and the product of the biomass consumption of a standalone gasification plant $m_{gasification,standalone}$ and lower heating value of the biomass, Eq. (5):

$$\eta_{gas,standalone} = \frac{1.03 \cdot \dot{Q}_{LPG}}{\dot{m}_{gasification,standalone} \cdot LHV} \quad (5)$$

The total energy efficiency of the system is defined as the sum of the heat from the syngas and the heat from the steam divided by the product of the total biomass consumption $m_{basecase} + m_{gasification,standalone}$ and its lower heating value, Eq. (6). The definition is analogous to the definition of the total energy efficiency of the integrated system.

$$\eta_{total,standalone} = \frac{1.03 \cdot \dot{Q}_{LPG} + \dot{Q}_{steam}}{(\dot{m}_{basecase} + \dot{m}_{gasification,standalone}) \cdot LHV} \quad (6)$$

As is evident from the data presented in Table 11, the total energy efficiency of the integrated system will be higher than the total energy efficiency of the two standalone systems, so that process integration leads to reduced operational costs due to lower biomass consumption. However, a highly integrated system is also somewhat vulnerable, if the high total energy efficiency is a result of successful process integration alone. For that reason, it is interesting also to describe the decrease in biomass consumption that results from process integration, Eqs. (7) - (8):

$$\frac{1}{\eta_{gas,standalone}} - \frac{1}{\eta_{gas,marginal}} = \frac{\dot{m}_{standalone} - \dot{m}_{integrated}}{1.03 \cdot \dot{Q}_{LPG}} \quad (7)$$

$$\frac{1}{\eta_{gas,standalone}} - \frac{1}{\eta_{gas,marginal}} = \frac{\dot{m}_{gasificatio,standalone} - \dot{m}_{increse}}{1.03 \cdot \dot{Q}_{LPG}} \quad (8)$$

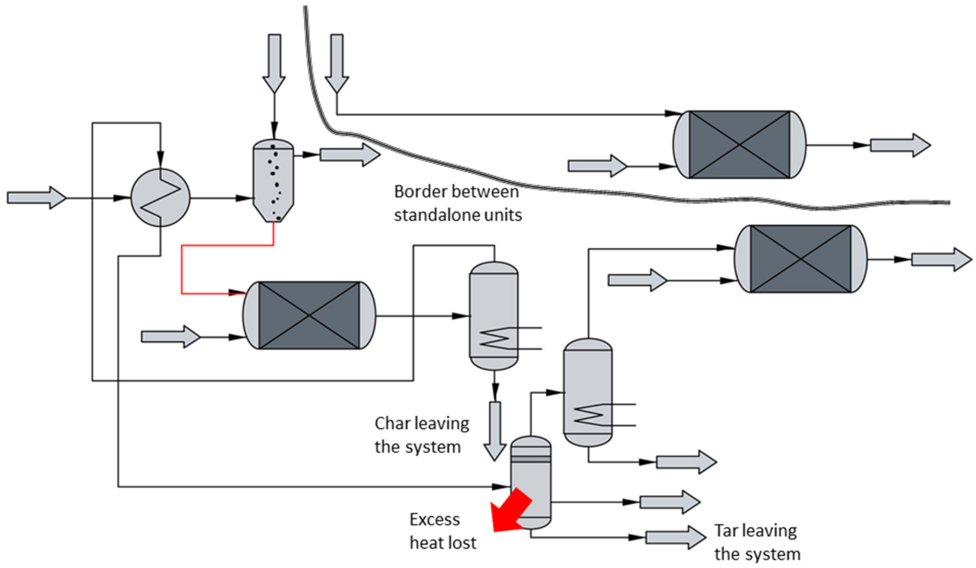

Figure 23. One example of a system where gasification and steam production occur in non-integrated, standalone units.

This example represents the downdraft fixed bed gasification technology. All process steam is produced in the bioboiler and all energy for heating the drying air comes from the hot syngas.

5.4 DISCUSSION

The key parameters in the form of energy efficiencies and biomass flows are summarized in Table 11. The first two rows represent the marginal energy efficiencies of gasification and increased biomass consumption of the integrated systems. Figure 24 illustrates the marginal gas energy efficiency and the increase in biomass consumption for the four gasification technologies together with the analytical expression deduced in Eq. (3). The upper theoretical limit of the marginal gas energy efficiency is also illustrated together with the corresponding lower theoretical limit of the increase in biomass consumption. The theoretical limit assumes that all water vapour is condensed before leaving the system, so that the total energy efficiency of the system equals 100 % if it is based on the higher heating value of the biomass rather than (as convention dictates) the lower heating value.

The results for all four technologies summarized in Figure 24 agree with the theoretical expression deduced in Eq. (3). This serves to support that the flow sheeting models were successfully implemented.

It is evident from the data presented in Figure 24 that the highest marginal energy efficiency and correspondingly lowest operational cost for biomass consumption is reached for the downdraft fixed bed. The main reason for this is that the heat recovery from the syngas for steam generation and drying means that little excess heat is wasted from the system. For the two systems involving separate combustion reactors, the steam blown dual-bed and the two stage gasification technology, the results are very close. For these two technologies, there will be a flue gas stream leaving the system with a temperature of 190°C representing an energy loss from the system. The flue gas is used for steam generation, but no use of the low grade heat can be found within the system since the flue gas from the bioboiler and the hot syngas provides the required drying energy. The updraft fixed bed exhibits the lowest marginal energy efficiency and thereby the highest operational cost. The tar production in this technology is considerable, compare Table 10. In fact, the tar contains so much heat that it cannot be utilized within the system even assuming that no biomass at all is combusted in the bio boiler. This leads to the conclusion that this technology is not suitable for the application.

Table 11. Some key parameters related to the energy efficiencies and operational costs and to the benefits of process integration for the studied gasification technologies.

	Fixed bed, updraft	Fixed bed, downdraft	Dual bed	Two stage
Marginal energy efficiency of gasification	0,685	1,124	1,157	1,007
Increased flow of biomass (kg/h)	4550	2770	2690	3090
Standalone energy efficiency of gasification	0,408	0,867	0,817	0,907
Decreased biomass flow due to process integration (kg/h)	3080	820	1120	342
Total energy efficiency integrated system	0,767	1,010	1,024	0,955
Total energy efficiency standalone units	0,543	0,885	0,855	0,907

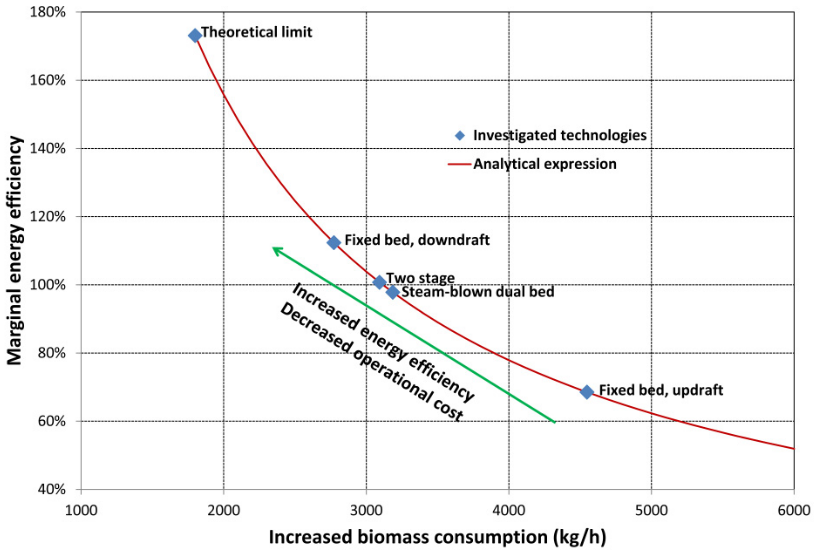

Figure 24. Two key operational parameters indicating the marginal energy efficiency and the increase in the biomass consumption as a consequence of integrating biomass gasification in the plant.

Table 11 also contains the data for the standalone systems. Figure 25 depicts the decrease in biomass consumption of a process integrated plant as compared to a plant where steam and syngas are produced in standalone processes. Again, the results for all four technologies agree with the theoretical expression deduced in Eq. (7). A system with high standalone gasification energy efficiency will be somewhat more robust. For a gasification process where the energy efficiency of the standalone process equals the marginal energy efficiency of the integrated system, no biomass is saved as a consequence of process integration.

The steam-blown dual bed and the two stage gasification have almost the same performance in terms of the marginal energy efficiency and the biomass consumption of the integrated systems. However, successful process integration is somewhat more crucial for the good performance of the two-stage gasification technology than for the other technology (Table 11).

It is also interesting to compare the magnitudes of the flowrates, compare

Table 12. For the two systems where the fluidization medium is air, considerably higher flow rates will result as a consequence of the inert nitrogen present in the syngas.

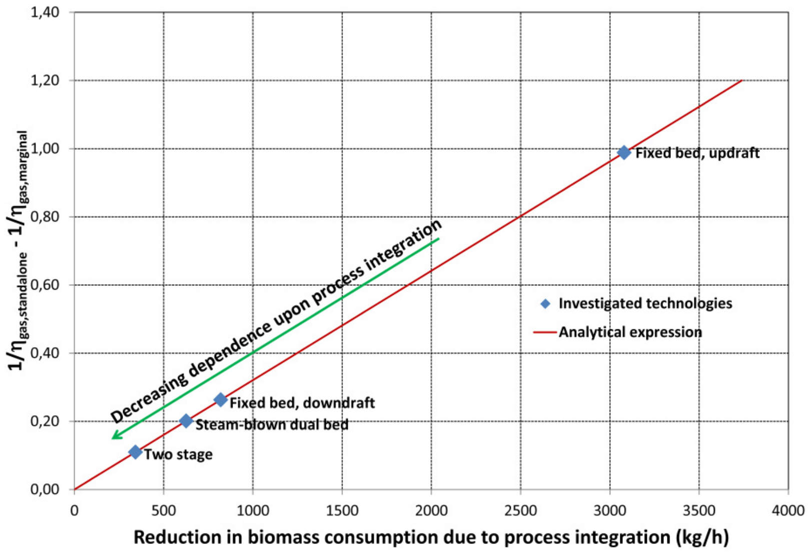

Figure 25. Two key parameters indicating the importance of process integration for the investigated technologies.

Table 12. Some additional process parameters related to the flow rates.

	Fixed bed, updraft	Fixed bed, downdraft	Dual bed	Two stage
Flow of syngas (kg/h)	6220	55	1580	1574
Flow of syngas (Nm³/h)	5420	4990	1780	2330
Heat in syngas (GJ/h)	25,75	25,75	25,75	25,75
Steam production (GJ/h)	31,6	21,2	21,2 + 3,5	21,2 + 3,0
Air flow to dryer (kg/h)	120 000	56 000	59 000	54 000

A number of assumptions were made in the system analysis. The liquid fraction of the syngas after condensation at 30°C will contain water as well as tar. Here, it was assumed that those two fractions were easily separated into one tar-rich fraction and one water-rich fraction. Combustion of the tar increased the energy efficiency of the system whereas the water-rich fraction was taken to cleaning. (Only the tar removed in the filter is assumed to represent an energy loss.) However, it is likely that separation of these two fractions is not as easy as assumed here. Gasification technologies producing low amounts of tar might have an additional advantage. Table 13 lists the flows of condensate and the tar removed in the filter.

Table 13. Tar flows and condensate flows connected to cold gas cleaning together with the amount of tar removed in the filter.

	Fixed bed, updraft	Fixed bed, downdraft	Dual bed	Two stage
Tar flow gas cleaning (kg/h)	896	9	113	0
Flow of condensate (kg/h)	7998	183	1437	0
Tar removed in filter (kg/h)	15	13	5	0

5.5 CONCLUDING REMARKS

Four gasification technologies: updraft fixed bed, downdraft fixed bed, steam-blown dual bed, and two stage gasification, were investigated in terms of the possibilities to integrate these technologies in the plant. Process integration was investigated for steady-state conditions corresponding to the maximum production of syngas foreseen according to the data presented in section 2.3 of this report.

The flue gas from the bio boiler and the hot syngas generated provides enough heat for drying the biomass prior to gasification. It is also possible to use excess heat from the gasification process for steam production, so that the steam production in the bio boiler can be somewhat reduced as compared to the base case. With the introduction of flue gas condensation, the marginal energy efficiency of gasification for three of the technologies is above 100%.

The technology producing a syngas with the highest tar content (the updraft fixed bed) can be ruled out. The heat contained in the tar cannot be utilized within the system, which leads to a poor energy efficiency. The three remaining technologies are all very interesting from a process integration point of view. They differ slightly as to the overall energy efficiency and the overall biomass consumption. However, other aspects than biomass consumption alone should be considered. Such aspects include the flow of tar-containing condensate from the cold gas cleaning.

6 Conclusions

The main conclusion of the study is that a number of gasification technologies are commercially available in the scale needed to supply the three production lines with syngas, approximately 7 MW. Fixed bed updraft gasification technology is less feasible due to the potentially high tar content of the syngas produced and the related low overall energy efficiency obtained. Exchanging LPG for green syngas has only a limited influence on the gas consumption in terms of the energy content (the product of the flow of syngas and its lower heating value) which remains close to constant. Probably, new burners will need to be installed when exchanging the LPG for a syngas with a much reduced heating value as compared to LPG. At steady-state, there are possible benefits in integrating the production of syngas and the production of process steam, since the total energy efficiency of an integrated system will be considerably higher than the total energy efficiency of two standalone units, one for syngas production and one for steam production.

7 Future work

7.1 VERIFICATION OF THE APPLICABILITY OF SYNGAS AS LPG SUBSTITUTE FOR TISSUE DRYING.

Given the cost for deep tar cleaning on one hand and the importance of soot-free, non-odorous flue gases for this tissue drying application on the other hand, there has been identified a need for experimental testing in order to determine correlation between syngas tar content and smell/soot impact on the tissue paper.

Principally there are two possible approaches to such a test:

1. Bring syngas to a paper machine
2. Bring paper to a gasification plant

To our knowledge there is no portable gasification equipment available with a capacity sufficient for actual production tests at a pilot machine for tissue production. Furthermore, such a test would be costly and possess a high risk of fouling of valuable equipment. For this reason, approach 1 is considered non-viable.

The other alternative (2) would be to arrange for combustion of biomass-derived syngas with subsequent transfer of the flue gases towards a wet paper sheet at any of the gasification plants, already in operation in Sweden or Europe. Such an approach should have the potential to be significantly less costly and risky, compared to alternative 1.

Practically, the test arrangement could be carried out in a test rig where a tissue paper is supported on a wet sponge, securing a wet sheet for at least some 10-20 seconds thereby enabling a substantial amount of flue gases to be brought in contact with the paper.

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FOSSILFRI TISSUETORKNING

Det går åt mycket energi vid torkning av mjukpapper. I moderna mjukpappersprocesser utnyttjas direkteldade torkkåpor där rökgaserna från gasol- eller naturgasförbränning blåser mot det våta pappret. I den här förstudien har forskarna undersökt vad som händer vid ett byte från gasol till gas från termiskt förgasad biomassa i ett mjukpappersbruk med en maximal gasolförbrukning motsvarande 7 MW.

Det visar sig att torkkapaciteten sannolikt kommer att upprätthållas om gasol ersätts med biobaserad syntesgas. Resultaten visar också att de undersökta förgasningsteknikerna alla kan tillämpas för att omvandla flisat trämaterial till gas av tillräcklig kvalitet. Tre tekniker har visat sig vara mest lämpade avseende den totala energieffektiviteten och den totala förbrukningen av biomassa. Det finns dock behov av ytterligare experimentella test för att fastställa sambandet mellan gasens tjärinnehåll och påverkan av lukt och sot på mjukpappret i nästa steg av en konceptutveckling.