BIOFUELS IN LIME KILNS

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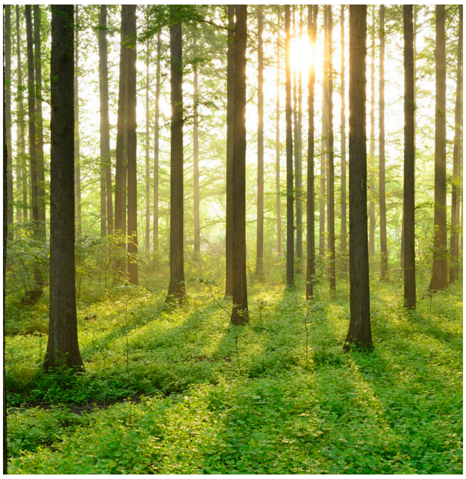

SKOGSINDUSTRIELLA PROGRAMMET

Energiforsk

Biofuels In Lime Kilns

Operating experience in the Nordic pulp and paper industry

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Förord

Denna rapport är slutrapportering av projekt Projekt KVU45114 *Erfarenheter av biobränslen i mesaugnar* inom Energiforsks skogsindustriella program.

Programmet handlar i första hand om energieffektivisering, att kunna nyttiggöra sidoströmmar och restvärme samt effektiv användning och återvinning av kemikalier. Projekt som genomförs inom programmet ska ge lösningar på upplevda problem på bruken och vara så generaliserbara så att flera har möjlighet att implementera forskningsresultaten inom en överskådlig tid.

Detta projekts syfte är att ge en samlad bild av erfarenheter av att använda andra bränslen än olja och naturgas i mesaugnen, särskilt olika typer av biobränslen, i syfte att ge bättre underlag för investeringsbeslut som syftar till att reducera fossila koldioxidutsläpp.

Arbetet har genomförts av NiNa Innovation med Niklas Berglin och Anna von Schenck som projektledare. Projektets referensgrupp har bestått av Pär Johnsson (BillerudKorsnäs Gävle), Cecilia Edström (SCA), Rikard Konradsson (BillerudKorsnäs Gruvön), Håkan Edvinsson (Södra) och Johan Isaksson (Södra).

Forskningen har möjliggjorts ekonomiskt genom medel från ÅForsk, Valmet samt dessa bruk:
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Södra Cell Värö

Samtliga har representanter i programstyrelsen.

Författarna vill tacka alla som ställt upp på intervjuer, svarat på enkäter och på andra sätt bidragit med data och underlag till rapporten.

Helena Sellerholm
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Sammanfattning

Mesaugnen är en central process i det kemiska massabruket, där ombränning sker av mesa till kalk. Processen är energikrävande och förbrukar stora mängder fossilt bränsle. Konvertering till drift med biobränsle är intressant både för att minska koldioxidutsläpp och för att reducera kostnader. Globalt används ca 50 TWh bränsle per år.

Biobränslen har effekter på kalkugnens drift, kausticering och resten av lutcykeln, t.ex. kalkkvalitet, temperaturprofil, kapacitet och utsläpp. Tillgänglighet och underhållsbehov är viktiga för den verkliga besparingen av fossilt bränsle som kan uppnås.

I projektet har vi intervjuat personal i bruk som använder fasta, flytande eller förgasade biobränslen för att ersätta eldningsolja eller naturgas i sina mesaugnar. Vi har även genomfört två bredare undersökningar i enkätform, en relaterad till bränsleförbrukning och en relaterad till drift och underhåll, som även omfattade mesaugnar eldade med fossilt bränsle. Målet med projektet var att ge en samlad bild av erfarenheter av att använda andra bränslen än olja och naturgas i syfte att ge ett bättre underlag för investeringsbeslut som kan minska fossila koldioxidutsläpp.

I Sverige och Finland fanns det tio bruk som under 2020 använde biomassapulver eller förgasad biomassa som huvudbränsle i mesaugnen, och ytterligare två anläggningar byggs eller håller på att tas i drift. Det finns även åtta anläggningar i drift eller under uppbyggnad utanför Norden. Sju av dessa är förgasare. Fjorton bruk i Sverige och två bruk i Finland använde tallbeckolja som huvudbränsle.

Vår kartläggning av bränsleförbrukningen i svenska mesaugnar visade att den totala bränsleanvändningen 2020 var 3,8 TWh och att 90 % av energin tillfördes som biobränslen. Tallbeckolja var det dominerande bränslet med 63 % av den totala förbrukningen, följt av trä- och barkpulver (24 %) och eldningsolja (10 %). Cirka 3 % av energin som används har sitt ursprung i metanol och icke kondenserbara gaser som förbränns i mesaugnarna.

Av cirka 4,2 TWh som användes i finska mesaugnar var cirka 45 % biobränslen. Förgasad bark var det vanligaste biobränslet (18 %), följt av tallbeckolja (13 %) trä- och ligninpulver (8 %) samt metanol/NCG (6 %). De fossila bränslena som användes var naturgas (36 %) och eldningsolja (18 %).

En övergripande slutsats från studien av driftserfarenheter är att eldning med fasta biobränslen, antingen som pulver eller efter förgasning, är en mycket mer mogen teknik nu än när en liknande studie genomfördes 2006.

Ett par skillnader i utformningen av bränsleförsörjningssystemen jämfört med 2006 är att bandtorkar används i alla nya installationer och att doseringssystem baserade på massflöde används i de flesta nya installationer för pulverbränslen. Barkförgasare har ökat avsevärt i storlek, till över 100 MW för en enskild förgasare i de nyaste installationerna. Ligninpulverbränning har etablerats som ett beprövat alternativ.

Faktorer att ta hänsyn till vid drift av ett bränsleförsörjningssystem med fasta biobränslen inkluderar: (1) erosion, mest betydande i rörböjar och brännarmunstycken; (2) ojämnt flöde av pulver på grund av densitetsvariationer; (3) förebyggande underhåll för att säkerställa korrekt funktion av gnistdetektions- och brandsläckningssystem och för att förhindra luftläckage; (4) goda städrutiner för att förhindra ansamling av damm runt anläggningen, för att minimera risken för brand och dammexplosion.

Faktorer att beakta vid driften av själva mesaugnen inkluderar: (1) kapaciteten hos en mesaugn är oftast lägre vid eldning av biobränslen, (2) god kontroll av partikelstorleksfördelningen och fukthalten när pulver eldas direkt i mesaugnen. ; (3) optimering av virvelluft i brännaren för att maximera förbränningseffektiviteten och kontroll av flamman; (4) NOx-utsläppen kan öka, både till följd av högre kvävehalt i bränslet och på grund av lokala variationer i luft/bränsle-förhållande i flamman.

Faktorer relaterade till kalk- och lutcykeln: (1) fosfor är det processfrämmande grundämne (PFG) som oftast bestämmer behovet av utstötning av mesa för att reglera barlasten i ugnen; (2) med sågspån är andra PFG än fosfor av liten betydelse, men med användning av bark måste man fokusera även på Si, Al, Mg, Mn, Fe och K på grund av deras möjliga effekter i indunstningen och sodapannan.

En lösning för många svenska och finska bruk är användningen av tallbeckolja som ersättning för eldningsolja. Även dessa system kännetecknas av hög tillgänglighet, men det behöver läggas fokus på att förebygga tätningsläckage i pumpar. Korrosionshastigheten är acceptabel förutsatt att rostfritt stål eller syrafast stål används i lagringstankar och förvärmare.

Summary

The lime kiln is a central process in the chemical pulp mill. The process is energy intensive and consumes large amounts of fossil fuel. Conversion to operation with biofuel is interesting both to reduce carbon dioxide emissions and to reduce costs. Globally, about 50 TWh of fuel is used per year.

Biofuels have effects on the operation of the lime kiln, causticizing and the rest of the liquor cycle, e.g. lime quality, temperature profile, capacity, and emissions. Availability and maintenance needs are important for the real saving of fossil fuel that can be achieved.

In the project we have interviewed managers in mills that use solid, liquid or gasified biofuels to replace fuel oil or natural gas in their lime kilns. We have also conducted two broader surveys, one related to fuel consumption and one related to operations and maintenance, which also included lime kilns fired with fossil fuel. The goal was to provide a comprehensive picture of experiences of using fuels other than oil and natural gas with the aim of providing a better basis for investment decisions that can reduce fossil carbon dioxide emissions.

In Sweden and Finland there were ten mills in 2020 using biomass powder or gasified biomass as the primary fuel in the lime kiln, and two more installations are under construction. There are also eight installations in operation or under construction outside the Nordic countries. Seven of these are gasifiers. Fourteen mills in Sweden and two mills in Finland used tall oil pitch as the main fuel.

Our survey of fuel consumption in Swedish lime kilns showed that the total energy used was 3.8 TWh in 2020 and that 90% of this energy was supplied with biofuels. Tall oil pitch was the dominant fuel with 63% of the overall consumption, followed by wood and bark powder (24%) and fuel oil (10%). About 3% of the energy used originates in methanol and non-condensable gases that are incinerated in the lime kilns.

Of about 4.2 TWh used in Finnish lime kilns, approximately 45% was supplied with biofuels. Gasified bark was the most common biofuel (18%), followed by tall oil pitch (13%) wood and lignin powder (8%) and methanol/NCGs (6%). The fossil fuels used were natural gas (36%) and fuel oil (18%).

An overall conclusion from the study of operating experience is that lime kiln firing with solid biofuels, either as wood powder or after gasification, is a much more mature technology now than when a similar study was carried out in 2006.

Some notable developments in the design of the fuel supply system since 2006 are that belt dryers are used in all new installations and that mass flow metered dosing systems are used in most new pulverized fuel installations. Bark gasifiers have increased considerably in size, to above 100 MW_{th} for a single gasifier in recent installations. Lignin powder firing has been established as a proven option.

Factors to be considered when operating a fuel supply system with solid biofuels include: (1) erosion, most significant in pipe bends and burner nozzles; (2) uneven flow of powder due to density variations; (3) preventive maintenance to ensure proper operation of spark detection and fire extinguishing systems and to prevent air leakage; (4) high standards of housekeeping to prevent accumulation of fine and dry particles around the plant, in order to minimize the risk for dust explosion.

Factors to be considered in the operation of the lime kiln itself include: (1) the capacity of a lime kiln is most often lower when firing biofuels, (2) good control of the particle size distribution when powder is fired directly in the lime kiln; (3) optimization of swirl air in the burner to maximize combustion efficiency and control of the flame; (4) NO_X emissions may increase, both as a result of higher nitrogen content in the fuel and due to poor local air/fuel mixing.

Factors related to the lime and liquor cycle include: (1) phosphorus is the primary non-process element that determines the purging rate of lime mud to control dead load; (2) with sawdust, other NPEs than P are of little concern, but with the use of bark there needs to be a focus also on Si, Al, Mg, Mn, Fe and K because of their possible effects in the evaporation plant and the recovery boiler.

An intermediate solution for many Swedish and Finnish mills is the use of tall oil pitch as a replacement for fuel oil. Also these systems are characterized by high availability, but there needs to be focus on prevention of seal leakage in pumps. Corrosion rate is acceptable provided that stainless steel or acid-proof steel is used in storage tanks and preheaters.

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1 Introduction

The lime kiln is a central unit operation in the chemical pulp mill, where burning of lime mud (CaCO3) to lime (CaO) takes place. The process is energy-intensive and today consumes large amounts of fossil fuel, mainly oil and natural gas. Globally, 25-30 million tonnes of lime are produced per year in lime kilns and fuel consumption corresponds to approximately 50 TWh per year. In many pulp mills, lime reburning is the only remaining use of fossil fuels.

Converting lime kilns to run on biofuel is interesting both to reduce carbon dioxide emissions from fossil fuels and to reduce costs. A number of Nordic mills have converted their kilns to biofuel operation, primarily with tall oil pitch, but the supply is not sufficient to completely replace other fuels. Other biofuels used today are wood powder, bark powder, gasified bark and lignin powder. Globally, a number of alternative fuels are also used, which are primarily aimed at reducing costs without necessarily reducing carbon dioxide emissions, such as petroleum coke.

Alternative fuels and technologies have effects on the operation of the lime kiln, as well as on causticizing and the rest of the liquor cycle. Part of the impact is the indirect effect due to the addition of non-process elements, such as potassium, phosphorus and silicon that accumulate in the liquor and lime cycle. Temperature profile and flame stability in the kiln also tend to change, which e.g. can have effects in the form of ring formation. It can also risk leading to reduced capacity. Emissions change, for example NOx emissions are affected by the proportion of nitrogen bound in the fuel. Availability and maintenance needs for various technical solutions are important for the real savings of fossil fuel that can be obtained over a longer period.

In summary, the area is important from both an energy and environmental and cost point of view. Increased knowledge and opportunities to make better use of the experience of others provide the conditions for strengthening the competitiveness of Nordic producers in the industry and to strengthen the long-term global competitiveness of the pulp and paper industry vis-à-vis other material-producing industries. The project links to several UN sustainability goals, in particular goal 7 (sustainable energy supply), goal 9 (sustainable industry and innovations) and goal 13 (combating climate change).

1.1 SCOPE AND OBJECTIVE

The aim was to provide an overall picture of experiences of using fuels other than oil and natural gas in the lime kiln, especially different types of biofuels, in order to provide a better basis for investment decisions aimed at reducing fossil carbon dioxide emissions.

In the project, we have interviewed people responsible for the facilities that have been added in the Nordic region since a previous study was done in 2006 [18] and supplemented with new information from the mills that previously used solid biofuels. Together with the University of Toronto, we have conducted a new global survey to investigate the use of alternative fuels and operational experiences in general for other fuels as well.

The approach has been broad with a focus on process-related issues (e.g. lime quality, non-process elements), combustion-related issues (e.g. temperature profile, flame stability, ring formation), environmental issues (e.g. emissions of NO_x, SO_2, TRS, dust) and economically important aspects. (e.g. availability, maintenance needs, capacity).

1.2 ACTIVITIES

The main activities in the project were:

- Planning of on-site interviews with Nordic mills who have experience of burning biofuels in the lime kiln. Focus on those that have been added since 2006. The goal was to visit the main part of these for documentation and discussion.
- Interviews and visits to the Nordic mills. Focus on powder firing and gasification, but also on tall oil pitch, which is the most common biofuel.
- Analysis and discussion of results in relation to the 2006 study.
- Planning and sending out a global survey on lime kiln operating experience (regardless of fuel) together with the University of Toronto. Analysis of collected data and comparison with previous studies.
- Reporting to Energiforsk.

The activities had to be modified and the project timeline extended due to the covid-19 pandemic. Most of the interviews were conducted in video meetings, but it was also possible to make six site visits during times when travel restrictions were less severe. The pandemic also prevented the University of Toronto from completing their part of the analysis of the global survey within the time frame of the Energiforsk project. We have handled this by evaluating separately the surveys compiled from Nordic mills. We have also added a separate survey of actual fuel use in all Swedish lime kilns during 2020 and have collaborated with the University of Lappeenranta to compile similar data for Finnish lime kilns.

2 Background

There is experience from about 40 years of replacing oil and natural gas in lime kilns with different types of biofuels, and a number of plants have been added during the last ten-year period. A project carried out in 2006, which included interviews with all companies in Sweden that then used some form of solid biofuel to supply the lime kiln, showed variations in, e.g., availability, lime quality and emissions [18].

A global survey conducted in parallel showed a large difference in the use of alternative fuels on different continents [21], but also large differences in specific fuel consumption between different kilns. It is valuable to now compile use and operational experiences from the facilities that have been added both in the Nordic region and globally to further facilitate reduced use of fossil fuels in lime kilns.

The in-depth interviews conducted in 2006 with five plant owners showed a number of challenges when converting to solid biofuels. Three of the mills had systems with biomass gasifiers and two used powder burners.

The total availability of biofuel systems was low compared to other parts of a modern kraft pulp mill. The gasifier plants indicated an availability of 65-75%. Those with powder burning had a higher availability, 80-90%.

In general, fires were a major problem in biofuel systems, especially in connection with drying. Most of the fires occurred in connection with dry silos and bag filters. Two mills reported a frequency of about one dry silo fire per month. To reduce the problems with fires, three measures have been applied in particular: spark indication systems, extinguishing systems with steam, and control of the oxygen content in the flue gases.

A longer flame during biofuel heating gives rise to a flatter temperature profile, which in turn leads to the need to increase the fuel flow and thus also the flue gas flow. All in all, this leads to reduced capacity and increased heat losses. Four out of five mills stated that they had lower capacity when the furnace was fired with biofuel than when it was fired with oil. CFD calculations have also shown similar effects in simulations [25, 26].

The most noticeable change in emissions in the 2006 study was that the NO_x content of the flue gases increased. This applied to both powder and gas firing for all mills except one, which instead reported increased emissions of CO and SO_2.

Two mills reported major problems with dusting. One highlighted low temperature with subsequent poor sintering as the main cause. Two mills had moderate problems with ring formation, about once every two months, while the other three mills stated that they did not have ring formation to any great extent.

Maintenance of the brick lining varied greatly between the mills, where one mill stated a service life of two years, while two rebuilt parts of the burning zone several times a year. There was no direct correlation to the way biofuels are burned. A relatively large mechanical impact from the biofuels was erosion in burners and fuel lines due to entrained ash, sand and bed material.

Overall, the operating experiences from the lime kiln itself were relatively good and the problems were fewer than in the systems for preparing the fuel to be used in the kiln. It should be pointed out that all five mills operating in 2006 had found it economically worthwhile to burn biofuels instead of oil for a long series of years, despite the challenges that have existed in operation and maintenance.

The global survey conducted in 2008 [21] on operational experience, energy consumption and alternative fuel use provided responses from 59 pulp mills with a total of 67 lime kilns in Argentina, Australia, Brazil, Canada, Finland, New Zealand, Norway, Sweden and the United States. Comparisons with the results of a similar survey conducted in 1991 [22] generally showed more efficient operation, including increases in the proportion of kilns equipped with product coolers and lime mud dryers. The average specific fuel consumption was 6.6 GJ/t CaO. Ring formation and dusting were the most common operational problems among the respondents.

In the responses to the 2008 survey, there were no clear connections between alternative fuel use and specific fuel consumption or perceived operational problems. Relatively few of the responding mills had then used alternative fuels, but almost two thirds of the respondents stated that they had definite or possible plans for alternative fuels within the next five years. It should be noted, however, that the oil price was very high during the period in which the survey was conducted. The most common motives stated for alternative fuel use were lower energy costs and the desire to use more renewable energy.

All facilities with gasifiers in Sweden have been closed, but a couple of new ones have been added in Finland. In Sweden, a few more plants have switched to wood powder firing. A plant in Finland burns lignin powder in the lime kiln, a technology that was first tested in a Swedish mill [19]. In total, there are about ten plants in the world that have many years of experience in using solid biofuels in the lime kiln. Another large number of plants, especially in the Nordic countries, use tall oil pitch or tall oil as a supplementary fuel.

3 Technologies

There are several technologies in use for supply of solid, liquid or gaseous biofuels to lime kilns. In this chapter, these are described briefly.

3.1 DIRECT FIRING WITH WOOD OR BARK POWDER

One option of introducing solid biomass as a fuel into the lime kiln is to pulverize it and fire the biomass powder in a burner designed for powder combustion. For efficient milling, transportation, and combustion of the biomass it needs to be dried to a moisture content below 10%.

Such systems thus normally include (1) a biomass dryer, (2) a hammer mill, (3) a dosing system, (4) a blower for pneumatic conveying of the powder, and (5) a powder burner. Figure 1 shows an example of a configuration from one supplier.

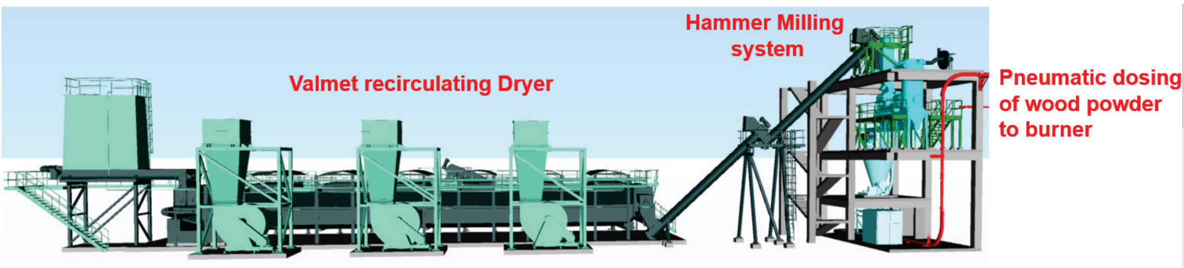

Figure 1. Typical configuration of system for lime kiln firing with pulverized wood. Source: Valmet.

3.2 GASIFICATION OF BARK OR WOOD FOLLOWED BY GAS FIRING

Gasification is carried out by partially oxidizing the biomass with air under sub-stoichiometric conditions. The gas produced consists mainly of hydrogen, carbon monoxide and various hydrocarbons as active components. It has a much lower heating value than natural gas, typically 5-7 MJ/Nm^3, but additional energy is transferred to the lime kiln by maintaining the producer gas hot and by allowing entrained biochar to accompany the gas into the kiln.

The gasification plant is composed of the gasifier itself followed by a solid-gas separator and a gas duct. These are all refractory lined. In addition, there is equipment for fuel and bed material feeding, bottom ash discharge, and supply of air as the gasifying agent.

Gasifiers used in the pulp and paper industry are air-blown circulating fluidized bed (CFB) gasifiers operating at atmospheric pressure. Bed material, usually limestone, is used to facilitate fluidization.

Gasification air is introduced from the bottom of the gasifier through a grid which ensures proper air distribution in the gasifier. The gasification air can be preheated to reduce fuel consumption and increase product gas quality. Solids containing unreacted fuel char and circulating bed material are returned to the gasifier through a return pipe to maximize fuel conversion. These solids are partly removed through the bottom ash discharge. The hot fuel gas is fed to the lime kiln burner via a gas duct.

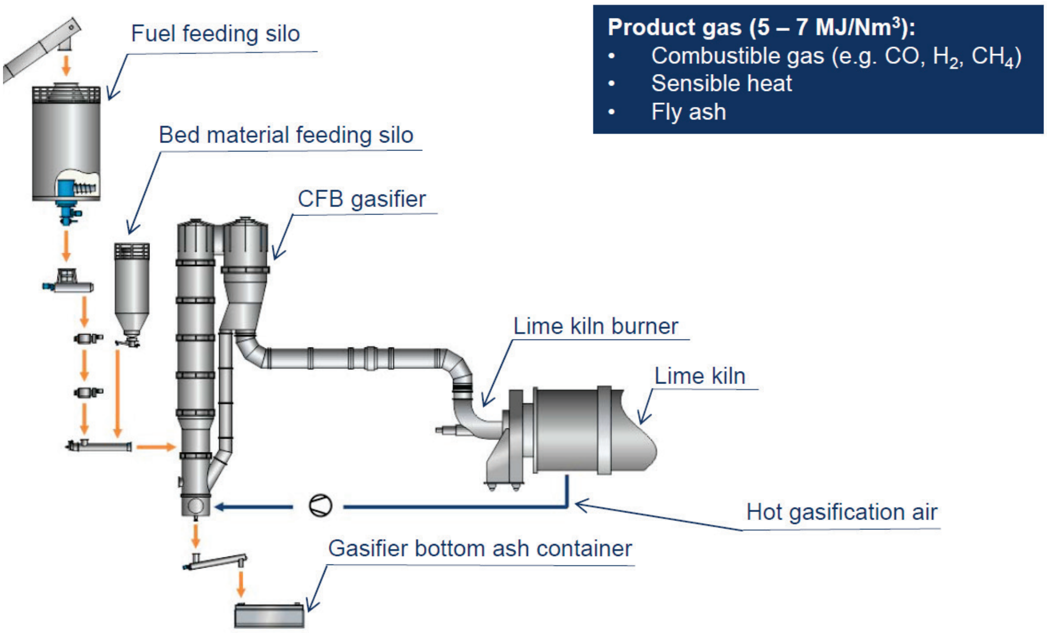

Figure 2. Typical configuration of circulating fluidized bed (CFB) gasifier system used for woody biomass gasification. Source: ANDRITZ.

3.3 FIRING WITH BIO-OILS

The most common solution of introducing biofuels into a lime kiln is the use of bio-oils. Tall oil pitch is the dominant liquid biofuel used for this purpose, but also other bio-oils have been used by some mills, e.g., mixed fatty acids. Also crude tall oil has been used by some mills, but it is generally economically favorable to sell the crude tall oil and buy back the residual tall oil pitch. This is a common arrangement between pulp mills and tall oil distillers in the Nordic countries.

Tall oil pitch can be fired in a similar burner as for fuel oil, but due to the high acidity of the pitch, storage and pumping systems need to be made from corrosion-resistant materials. The viscosity of tall oil pitch is comparable to heavy fuel oil and requires that the pitch is stored in a heated tank and further preheated before the burner.

4 Plants in operation

We have focused on the Nordic mills which use either biomass powder or gasified biomass, and this chapter contains brief descriptions of the systems at a number of mills in Sweden and Finland. We have also included a few mills that use tall oil pitch as the main fuel. The information has been collected either directly from the mill, via suppliers, or from open information sources.

Out of 21 Swedish kraft mills, 19 used either wood powder or tall oil pitch as the main fuel. Out of 14 Finnish kraft mills, six used gasified bark, wood or lignin powder, or tall oil pitch.

4.1 OVERVIEW OF MILLS THAT USE BIOFUELS

4.1.1 Plants in operation or under construction in the Nordic countries

In Sweden and Finland there were ten mills in 2020 using biomass powder or gasified biomass as the main fuel in the lime kiln (Table 1). Some mills have two kilns, and the total number of biomass-fired kilns is therefore thirteen.

One more mill in Sweden is converting to wood powder firing and started up the new kiln in late 2021. One mill in Finland will start up a new kiln with a bark gasifier in 2022.

Table 1. Mills in the Nordic countries that use solid or gasified biomass as lime kiln fuel.

Company	Mill	Country	Technology	Capacity	Feedstock	Supplier	Start-up
SmurfitKappa	Piteå	Sweden	Powder burner		Sawdust	FLS (Valmet)	1981
Södra Cell	Mönsterås	Sweden	Powder burner		Bark (spruce, pine, birch)	Pillard	1985
SCA	Östrand	Sweden	Powder burner		Wood pellets	Andritz	2011
Södra Cell	Värö	Sweden	Powder burner		Sawdust	FLS (Valmet)	2014
SCA	Munksund	Sweden	Powder burner		Wood pellets	FLS (Valmet)	2015
SCA	Obbola	Sweden	Powder burner		Wood pellets	Valmet	2021
Stora Enso	Enocell	Finland	Powder burner		Sawdust	Valmet	2015
Stora Enso	Sunila	Finland	Powder burner		Lignin	KFS	2015
Stora Enso	Varkaus	Finland	Gasifier	12 MW	Bark and sawdust	Foster Wheeler	2009
Metsä Fibre	Joutseno	Finland	Gasifier	48 MW	Bark (spruce, pine, birch)	Andritz	2012
Metsä Fibre	Äänekoski	Finland	Gasifier	87 MW	Bark (spruce, pine, birch)	Valmet	2018
Metsä Fibre	Kemi	Finland	Gasifier	100 MW	Bark (spruce, pine, birch)	Valmet	2022

4.1.2 Plants in operation or under construction outside the Nordic countries

There are also eight installations in operation or under construction outside the Nordic countries, see Table 2. All of these are located in Asia or South America.

Seven of the plants are based on gasification, with gasifiers operating on a 100 MW scale per gasifier.

Table 2. Mills in Asia and South America that use (or plan to use) solid or gasified biomass as lime kiln fuel.

Company	Mill	Country	Technology	Capacity	Feedstock	Supplier	Start-up
Bracell	Lencois Paulista	Brazil	Gasifier x 2	87 MW x 2	Bark and wood residues	Valmet	2021
Klabin	Ortigueira	Brazil	Gasifier	51 MW	Wood chips (eucalyptus)	Andritz	2021
Suzano	Cerrado	Brazil	Gasifier x 2			Andritz	2024
Chenming	Huanggang	China	Gasifier	50 MW	Bark and wood residues	Valmet	2018
Chenming	Zhanjiang	China	Gasifier	65 MW	Bark and fines (eucalyptus)	Andritz	2014
Chenming	Meilun	China	Gasifier	80 MW	Chip screening fines	Andritz	2019
APP	OKI	Indonesia	Gasifier x 2	110 MW x 2	Bark and fines	Valmet	2017
Sun Paper	Xepon	Laos	Powder burner		Wood chips (acacia)	Valmet	2017

4.1.3 Plants that have been decommissioned

It can be noted that there were also six gasifier installations built in Europe in the 1980s, some of which operated for 15-25 years [1,2]. They are listed in Table 3.

The Norrsundet mill operated its gasifier until 2008 when the mill was shut down. The Karlsborg mill decommissioned its gasifier in 2000, when there was a need for major reinvestments. Instead, they converted to tall oil pitch. The Värö mill operated its bark gasifier until 2014, when a new lime kiln was built for firing with wood powder.

Table 3. Biomass gasifiers installed in the 1980s that are no longer in operation.

Company	Mill	Country	Technology	Capacity	Feedstock	Supplier	Start-up
Wisa Forest	Pietarsaari	Finland	Gasifier	35 MW	Bark and sawdust	Ahlström (Sumitomo)	1983
Stora Enso	Norrsundet	Sweden	Gasifier	25 MW	Bark and sawdust	Ahlström (Sumitomo)	1985
BillerudKorsnäs	Karlsborg	Sweden	Gasifier	27 MW	Bark	Ahlström (Sumitomo)	1986
Portucel	Rodao	Portugal	Gasifier	15 MW	Bark	Ahlström (Sumitomo)	1986
Södra Cell	Värö	Sweden	Gasifier	27 MW	Bark	Götaverken Energy (Valmet)	1987
Pöls	Pöls	Austria	Gasifier	35 MW	Bark	Lurgi	1987

In addition, there were 20 mills using tall oil pitch as a liquid biofuel in the Nordic countries in 2020 (Table 4). Fourteen mills in Sweden and two mills in Finland used tall oil pitch as the main fuel.

Table 4. Mills in the Nordic countries that used tall oil pitch as lime kiln fuel in 2020.

Company	Mill	Country	Use of tall oil pitch
Ahlström-Munksjö	Aspa	Sweden	Main fuel
Ahlström-Munksjö	Billingsfors	Sweden	Main fuel
BillerudKorsnäs	Gruvön	Sweden	Main fuel
BillerudKorsnäs	Karlsborg	Sweden	Main fuel
BillerudKorsnäs	Skärblacka	Sweden	Main fuel
BillerudKorsnäs	Frövi	Sweden	Main fuel
BillerudKorsnäs	Gävle	Sweden	Main fuel
Holmen	Iggesund	Sweden	Main fuel
Metsä Board	Husum	Sweden	Main fuel
Mondi	Dynäs	Sweden	Main fuel
Nordic Paper	Bäckhammar	Sweden	Main fuel
Rottneros	Vallvik	Sweden	Main fuel
Smurfit Kappa	Piteå	Sweden	Secondary fuel
Södra Cell	Mönsterås	Sweden	Secondary fuel
Södra Cell	Mörrum	Sweden	Main fuel
Södra Cell	Värö	Sweden	Secondary fuel
Stora Enso	Skutskär	Sweden	Main fuel
Metsä Fibre	Äänekoski	Finland	Secondary fuel
Stora Enso	Oulu	Finland	Main fuel
UPM	Pietarsaari	Finland	Main fuel

4.2 MILLS USING PULVERIZED FUELS

4.2.1 Piteå

The Piteå mill is the mill that has the longest experience of burning solid biofuel in the lime kiln. As early as 1979, the plant was installed to burn biomass powder directly in the two lime kilns with a capacity of 150 and 200 tonnes of lime per day, respectively. The biomass is dried in a dryer and then ground in a hammer mill to a particle size below 1 mm. The dryer is fed with flue gases from the recovery boiler and the bark boiler. The capacity is about 6 tonnes dried material per hour. Bark and sawdust are the fuels used. During the first year, peat was also burned. The dried and ground fuel is fired in combination burners for oil and powder, supplied by Pillard.

4.2.2 Mönsterås

Mönsterås has also chosen the solution of burning the biofuel powder directly in the lime kiln. The biofuel supply system was started up in 1985. Birch bark, softwood bark and chip screening rejects are used as fuel. The drying takes place in a pneumatic dryer, where flue gases from the recovery boiler are used for drying. The capacity is about 5 tonnes of dried bark per hour. There was also a belt dryer installed at the mill in 2012 that is used for partial drying of softwood bark to the bark boiler, and this dryer can deliver bark also to the lime kiln when there is excess capacity. The mill has two lime kilns with a capacity of 570 and 275 tonnes of lime per day, respectively. Both kilns are equipped with lime mud dryers. The larger kiln has been equipped with a powder burner since the conversion from oil firing in 1985. The smaller kiln was rebuilt to be able to burn biofuel in 2004.

Figure 3. View of the powder burner at one of the lime kilns at the Mönsterås mill.

4.2.3 Värö

The Värö mill installed a new lime kiln in 2014. The bark gasifier that had been operating since 1987 was shut down at the same time, and the new kiln is fired with wood powder directly. The wood powder is produced from sawdust at the co-located sawmill, which also has a pelletizing plant. Sawdust for pellets production and for lime kiln fuel is dried in a common belt dryer. The dried sawdust is ground in a hammer mill and then blown to the lime kiln burner. There is an intermediate storage silo for dry wood powder, and the dosing system consists of a rotor weighfeeder. The capacity of the kiln is 680 tonnes per day.

Figure 4. Belt dryer for sawdust (left) and storage silo (right) at the Värö mill.

4.2.4 Östrand

The Östrand mill installed a new lime kiln in 2011 and at the same time converted to wood powder as the main fuel instead of fuel oil. The wood powder is produced from purchased softwood pellets in a fuel supply system consisting of a receiving bin, two hammer mills in parallel, a wood powder silo, volumetric screw feeders, and a blower that delivers the powder to the lime kiln burner. The burner was replaced in 2019 to include methanol as the secondary fuel. The capacity of the kiln is about 770 tonnes per day, which at the time of writing makes it the largest lime kiln in operation in Sweden.

4.2.5 Munksund

The Munksund mill installed a new lime kiln in 2015 to replace an older fuel oil-fired kiln. The capacity is 300 tonnes per day and the main fuel is wood powder. Methanol and strong gases are also fired in a multifuel burner. The fuel supply system consists of a wood pellet receiving bin, two hammer mills, a small (15 m^3) wood powder silo, and a rotor weighfeeder for dosing of the wood powder into the feed air system. The kiln is equipped with a lime mud dryer, a scrubber, and an electrostatic precipitator.

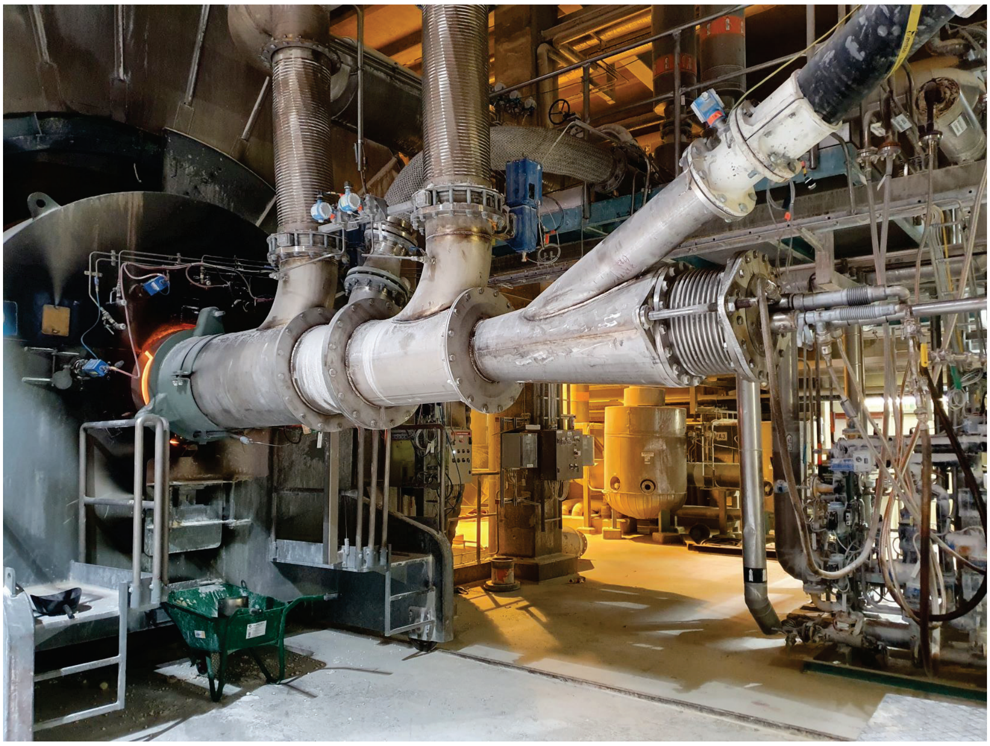

Figure 5. Combination burner (wood powder and methanol) at the Östrand mill.

4.2.6 Obbola

The Obbola mill installed ad started a new lime kiln in 2021. The kiln is fired with wood powder, using methanol and tall oil pitch as secondary fuels. It replaces two kilns that were fired with fuel oil. The fuel supply system contains a wood pellet receiving bin, two hammer mills, a 100 cubic meter wood powder silo, and the dosing system is a rotor weighfeeder. The capacity of the kiln is about 220 tonnes per day. It is also equipped with a lime mud dryer and an electrostatic precipitator.

4.2.7 Enocell

The Enocell mill converted its lime kiln to wood powder firing in 2014. The capacity of the kiln is 580 tonnes per day. The wood powder is produced from sawdust that is screened and then dried in a belt dryer to 97% dry solids content, followed by particle size reduction in a hammer mill. The dosing system includes a rotor weighfeeder.

4.2.8 Sunila

The Sunila mill has two lime kilns that were previously fired with natural gas. The capacity of each kiln is about 150 tonnes per day. In 2015, the mill built a plant for lignin extraction from black liquor and installed a fuel supply system to make it possible to use lignin powder as fuel in the lime kilns. The lignin is dried to 95% dry solids content in a ring dryer that uses flue gases from the lime kiln as drying medium. There is a storage silo for the dried lignin powder and the dosing system to the lime kilns consists of a volumetric cell feeder.

4.3 MILLS USING GASIFIED WOOD OR BARK

4.3.1 Varkaus

The Varkaus mill has one lime kiln with a capacity of 280 tonnes per day. It was converted to firing with syngas from a 12 MW bark gasifier in 2011. The gasifier had previously been used since 2009 in a demonstration project to produce syngas for conversion into synthetic liquid biofuels via the Fischer-Tropsch process. For use of the gas in the lime kiln, the gasifier was converted to air-blown operation instead of oxygen-blown. The feedstock is bark and sawdust, which are dried in a belt dryer.

4.3.2 Joutseno

The Joutseno mill has a lime kiln with a capacity of 600 tonnes per day and was converted in 2013 from natural gas firing to firing with gasified bark. Surplus heat from the mill is used to dry the bark which is then fed into the gasifier. Hot water and low pressure steam from the mill are used to heat air the dryer to about 95°C. Bark leaving the dryer has a moisture content of 4%. The dried feedstock is fed to the gasifier, which operates at 750-800°C. The gas produced by the gasification plant has replaced the natural gas used in the lime kiln, whose burner has been replaced by a new multi-fuel burner (Figure 6).

Figure 6. Multi-fuel burner used to fire gasified bark. (Source: ANDRITZ)

4.3.3 Äänekoski

The Äänekoski mill was built as a greenfield mill starting up in 2017. The lime kiln capacity is 1200 tonnes per day and the fuel is supplied as gas from a 87 MW circulating fluidized bed gasifier. The feedstock is bark from pine, spruce and birch. Before the gasification, the bark is dried in a belt dryer.

4.3.4 Kemi

A greenfield mill is being built in Kemi with planned start-up in 2023. The lime kiln will have a capacity of 1400 tonnes per day, and it will be fired with gas from a 100 MW bark gasifier. Before the gasification, the bark will be dried in a belt dryer.

4.4 MILLS USING TALL OIL PITCH

4.4.1 Aspa

The Aspa mill has one lime kiln with a capacity of 140 tonnes per day. The primary fuel is tall oil pitch, but fuel oil is still used before and after planned shutdowns. Stripper off-gases and strong gases are incinerated in the lime kiln. There are two stainless steel tanks for the tall oil pitch: a 200 m^3 tank for weekly storage and a 25 m^3 day tank. Both tanks have a pumparound loop. The pitch is preheated in a shell-and-tube heat exchanger. The tall oil pitch is pumped with two pumps, both of which are cogwheel pumps.

4.4.2 Gruvön

The Gruvön mill has one lime kiln with a capacity of 380 tonnes per day. The primary fuel is tall oil pitch, while fuel oil (EO5) is used as the supplementary fuel.

The tall oil pitch is stored in a 400 m^3 acid-proof steel tank heated with low pressure steam in a steam coil. The tall oil pitch is preheated with low pressure steam in a shell-and-tube heat exchanger and pumped to the kiln with a rotary piston pump.

Figure 7. Shell and tube heat exchanger used for preheating tall oil pitch (shell side) in the Gruvön mill. Low pressure steam is used as the heating medium (tube side).

4.4.3 Iggesund

The Iggesund mill built a new lime kiln in 2008. It was originally fired with fuel oil, but in 2013 converted to firing with tall oil pitch. Fuel oil (EO3) is still used as the supplementary fuel. The capacity of the kiln is 380 tonnes per day. Tall oil pitch is used also for steam production in the bark boiler and the recovery boiler, and the tall oil pitch is pre-heated and delivered in a common fuel supply system for the kiln and the boilers. The pitch is stored in an 800 m^3 acid-proof steel tank. The pre-heater is a shell-and-tube heat exchanger heated with medium pressure steam. There is a steam coil in the tank, but normally the temperature in the tank is controlled by a return flow that has passed the pre-heater and the remaining fuel supply system. The tall oil pitch is pumped with a wing rotor pump.

4.4.4 Gävle

The Gävle mill has three lime kilns, each with a capacity of about 150 tonnes per day. The main fuel is tall oil pitch in all three kilns, with fuel oil (EO5) as back-up. The tall oil pitch is stored in a 300 m^3 stainless steel tank heated with low pressure steam in a steam coil at the bottom of the tank. The tall oil pitch is preheated with medium pressure steam in two shell-and-tube heat exchangers and pumped to the kilns with two screw pumps. Methanol is co-fired in all three kilns.

Figure 8. Discharge end of the three lime kilns in the Gävle mill (left) and the unloading station for tall oil pitch (right).

5 Results

5.1 FUEL CONSUMPTION IN 2020

We conducted a survey of actual fuel consumption in lime kilns in Swedish mills in 2020, which was a year with high utilization rate in the pulp and paper industry. The results are shown in Figure 9 (by mill) and Figure 10 (by fuel).

The survey showed that the total fuel consumption in Swedish lime kilns was 3.8 TWh in 2020 and that 90% of this energy was supplied with biofuels. Tall oil pitch was the dominant fuel with 63% of the overall consumption, followed by wood and bark powder (24%) and fuel oil (9%). About 3% of the energy used originated in methanol. A few mills incinerate non-condensable gases in the lime kilns, but these NCGs have a very small net energy content (in the graphs they have been included in the methanol share).

In Figure 11, similar data is shown for the Finnish kraft mills. This data was not obtained directly from the mills but estimated by the University of Lappeenranta [28] from pulp production numbers, environmental permits and knowledge about primary and secondary fuels used at the different mills. It is thus less exact than the compilation of data for the Swedish mill, but still gives a good comparison.

The total fuel consumption in lime kilns was thus estimated to about 4.2 TWh in Finland in 2020 with about 45% of this energy supplied with biofuels (Figure 12). Natural gas was the most common fuel with 36% of the overall consumption, followed by fuel oil (18%). Gasified bark also represented 18% of the fuel consumption, and the other biomass fuels were tall oil pitch (13%), wood powder (4%) and lignin powder (4%). About 6% of the energy used originated in methanol and non-condensable gases that were incinerated in the lime kilns.

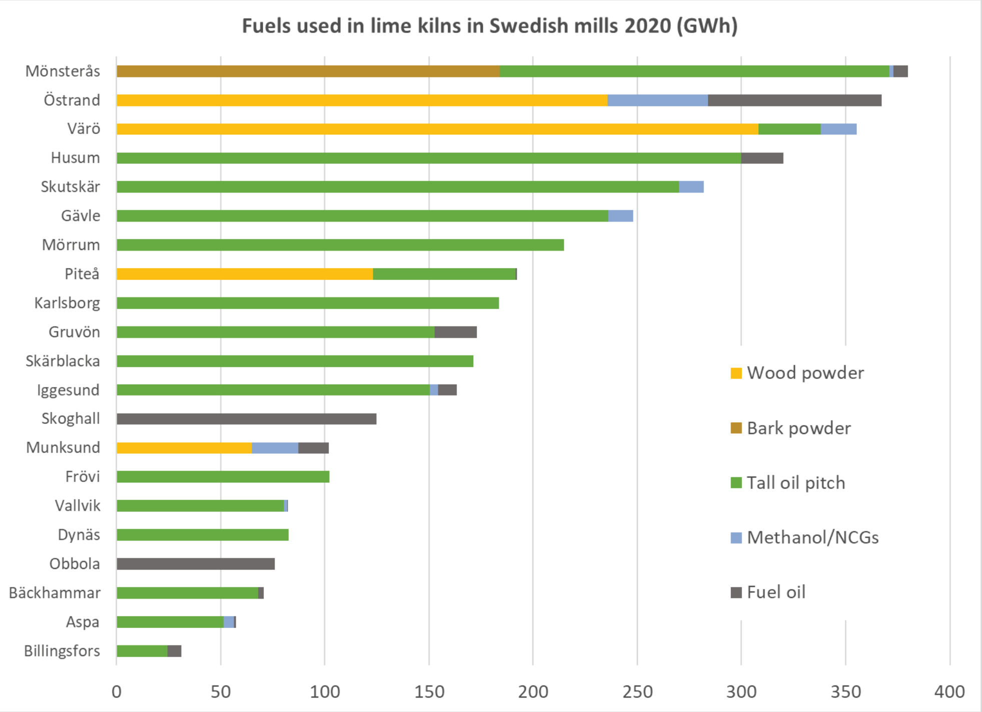

Figure 9. Fuel consumption in lime kilns in Swedish mills in 2020, expressed in GWh. Data collected directly from the mills in most cases (the consumption in Husum, Skoghall, Skutskär and Billingsfors was estimated from production data and environmental permits).

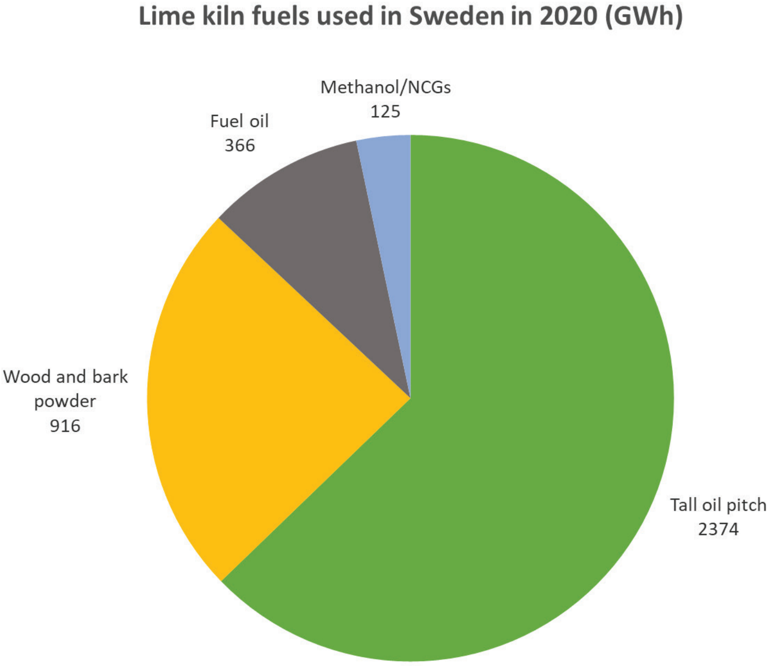

Figure 10. Energy input to lime kilns in Swedish mills in 2020, aggregated by type of fuel. The total fuel consumption, including methanol and non-condensable gases (NCGs) that were incinerated in lime kilns was 3.8 TWh.

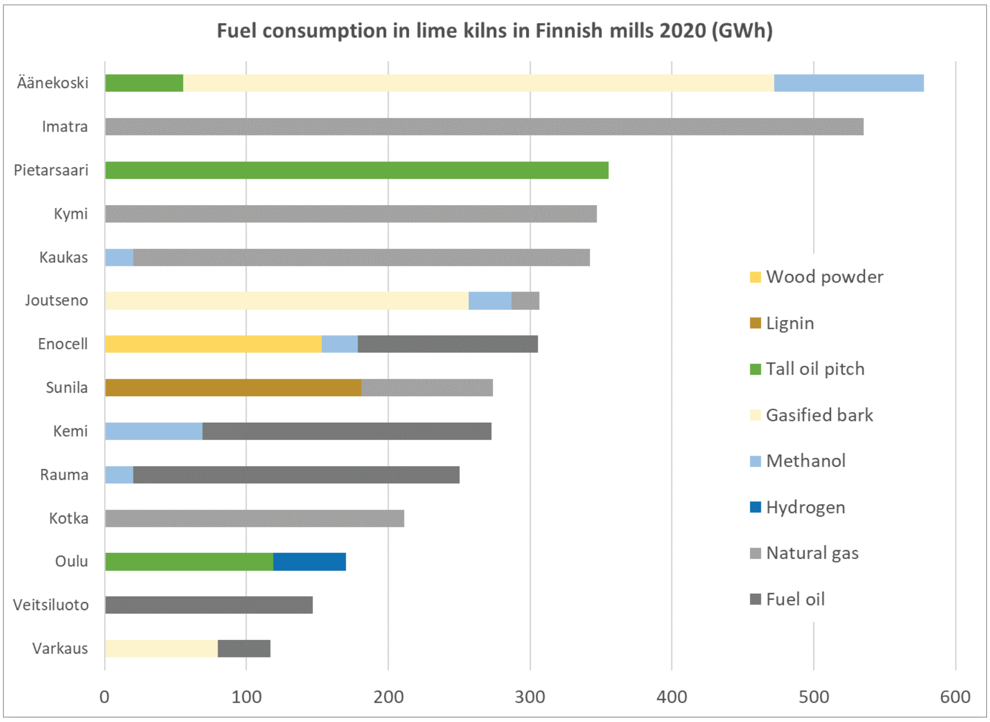

Figure 11. Fuel consumption in lime kilns in Finnish mills in 2020, expressed in GWh. Data estimated by Lipiäinen and Vakkilainen, University of Lappeenranta [28].

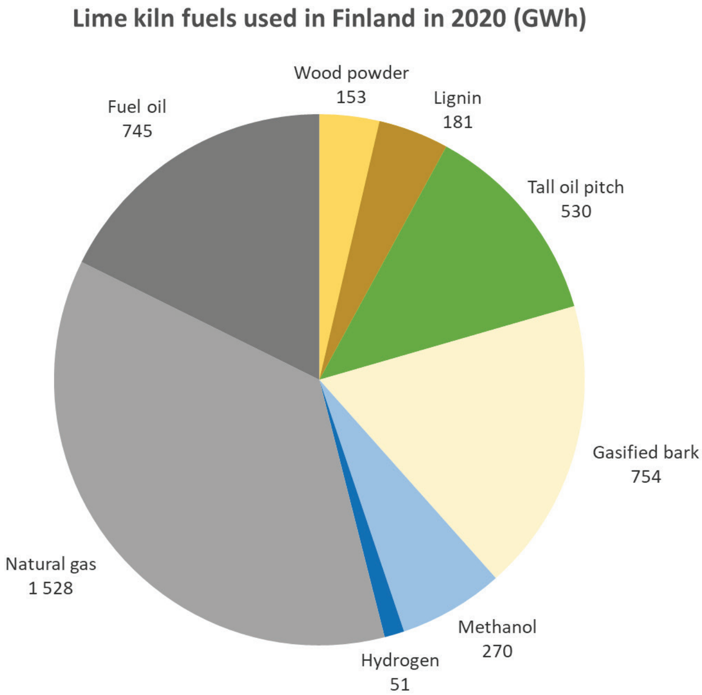

Figure 12. Energy input to lime kilns in Finnish mills in 2020, aggregated by type of fuel. The total fuel consumption, including methanol and non-condensable gases (NCGs) that are incinerated in lime kilns was 4.2 TWh. Data estimated by Lipiäinen and Vakkilainen, University of Lappeenranta [28].

5.2 RESULTS FROM INTERVIEWS

We were able to carry out 16 interviews with a total of 24 people in different positions at the mills, in corporate functions and with suppliers. Most of the interviewees at the mills were operations or process engineers with daily responsibilities related to the lime kiln operation. We were also able to make six mill visits where we could see and document major equipment and also talk to process operators when possible.

To facilitate comparisons, the results have been compiled on three levels:

- Operational experience from the biofuel system, including, e.g., drying, grinding and gasification.
- Operating experiences from the lime kiln
- Impact on lime and liquor cycle

Note that the mills firing tall oil pitch are described in a separate section (5.2.4).

The descriptions below naturally focus on the problems that exist or have existed. It should be pointed out that all mills have found it economically worthwhile to burn biofuels instead of oil or gas for a long series of years, despite challenges that have existed in operation and maintenance.

In this section, the mills have been slightly deidentified in order to be able to focus more easily on what are common experiences for the various facilities. A summary of the most important comparisons is presented in Table 5.

5.2.1 Operational experience from the biofuel system

The solid biofuels that are burned today are bark and sawdust, either delivered directly from the saw mill, or in the form of wood pellets. One mill uses kraft lignin separated from black liquor. Peat was used at one mill in the early 1980s. Some mills have gone from just bark to an increased proportion of sawdust or have completely switched to sawdust.

All plants use hammer mills, crushers, or a combination of the two to reduce the size of the biofuel before it is used as a powder directly in the lime kiln or gasified in an air-blown gasifier. Three of the powder fuel systems use flue gases from the recovery boiler or lime kiln as a heat source for the dryer. The remainder use steam heated dryers, sometimes complemented by hot water heating when excess low-temperature heat is available.

Two of the plants have vertical dryers with a wind screen that separates oversized material and returns it to an integrated hammer mill. Five plants have belt dryers. Experience does not show any general problems in achieving the desired dry matter content (usually below 5 % moisture content), or particle size (usually below 1 mm). The plant firing kraft lignin has a ring dryer, and the particle size of the precipitated and dried lignin is sufficiently small to make further milling unnecessary.

One plant that has a common dryer for producing wood powder and pellets has experienced a conflict regarding the moisture content from the dryer, which is preferred to be about 10% for pellets production and lower than 5% for use in the lime kiln.

One plant has had problems with transport and feed to the dryer in connection with the change of raw material from pine bark to spruce bark. The stringy spruce bark tends to clog transport screws. The plant later switched to sawdust as the only raw material.

In general, fires are a major problem in biofuel systems, especially in connection with drying. The dry powder is flammable and there is plenty of opportunity for sparking from contaminants in the form of sand and rock that accompanies the fuel. One key to avoiding fires is to keep the inert atmosphere in the system, but this is difficult because air leaks in easily. Most fires occur in connection with dry silos and bag filters. Three mills state a frequency of 1-2 dry silo fires per year.

Belt dryers employ lower temperatures and can therefore be designed to use air as the drying medium. The belt itself acts as a filter when air passes first through the bed and then through the belt, minimizing the amount of dry dust in the air stream.

In order to reduce the problems with fires, three measures in particular have been applied:

- Installation of spark indication systems.
- Extinguishing systems with medium pressure steam, water spray or CO_2
- Checking the O_2 content of the gases in flue gas heated dryers to avoid fires due to leaking air. The goal is to limit the content to 5-7% O_2.

Also with belt dryers, dried material can be ignited in the dry silo or during transport of the material. One mill has had incidents with clogging of bark conveyor belts that have led to overflow of dried bark, which has then caught fire when reaching hot surfaces in the gasification plant.

The experience of grinding is generally good. However, the exchange of hammers in the hammer mills (cf. Figure 13 and Figure 14) constitutes a relatively large share of the total downtime in some mills where hammers are changed at a frequency of 4-5 times per year. Other mills have used the same hammers for several years, so the variation is large. One of the mills states that more frequent changes would be preferable to get a more even quality of the fuel. The time required for the replacement is approximately one day.

Screens in the hammer mills determine the maximum particle size of wood powder that continues to the dry silo. As with hammers, the wear on screen plates varies and depends to some extent on contaminants entering the fuel supply system with the sawdust, bark or wood pellets. Small rocks, gravel and nuts and bolts are the worst threats in this respect, although metallic scrap is mostly removed with magnets in the feeding system to the hammer mill.

One long-term effect of the rotation of the hammers is that the hole where the hammer is mounted on the shaft tends to become oval over time, risking that the edge of the hammer damages the screen (cf. Figure 15).

Figure 13. Hammer mill opened for inspection.

Figure 14. Hammers replaced after normal maintenance interval.

Figure 15. Detail from a screen plate in a hammer mill where the screen has a tear from a dislodged hammer.

All mills underline the importance of an even flow of powder to avoid pulsation and to maintain a predictable amount of energy supply to the kiln. Historically the dosing systems have relied on volumetric dosing with screw feeders and cell feeders, but these make the fuel flow sensitive to density variations in the powder. A common problem is that material flows unevenly out of the dry silo and into a cell feeder, causing large short-term fluctuations in the amount of powder that is picked up by the transportation air to the burner. Newer installations have included a weighfeeder as an alternative to the volumetric dosing. One mill has also converted their existing system to include such a weighfeeder, which has resulted in a more even flow of biomass powder.

Table 5. Summary of operating experience from ten Nordic mills that use solid or gasified biomass as fuel in the lime kiln.

Mill	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*
Biofuel System										
Technology	powder	powder	powder	powder	powder	powder	powder	gasifier	gasifier	gasifier
Fuel	bark/chip rejects	sawdust	sawdust	pellets	pellets	sawdust	lignin	bark	bark	bark
Drying	recovery boiler flue gases	recovery boiler flue gases	belt dryer	no dryer	no dryer	belt dryer	ring dryer	belt dryer	belt dryer	belt dryer
Drying medium	recovery boiler flue gases	recovery boiler flue gases	air	-	-	air	lime kiln flue gases	air	air	air
Size reduction	hammer mill	hammer mill	hammer mill	hammer mill	hammer mill	hammer mill	no milling	crusher	crusher	crusher
Availability	80%	90%	>99%	>95%	>95%	n.a.	n.a.	n.a.	n.a.	95%
Fires and other causes of unavailability	replace hammers in mills, filter plugging, fires 1-2 per year, erosion	replace hammers in mills, plugging of mill, fires 3-4 times per year	only one fire (in hammer mill)	no fires, erosion	cell feeder leakage and seal replacemet, no fires	no fires	no fires	no fires	fires ca 1 time per year	fires ca 1 time per year
Lime Kiln										
Share of energy to kiln, max	100%	100%	100%	100%	100%	100%	100%	n.a.	100%	100%
Share of energy to kiln, annual average	55%	65%	85%	65%	65%	50%	70%	70%	75%	85%
Emissions compared to oil/NG										
- NOx	higher	unchanged	higher	higher	higher	higher	lower	higher	higher	higher
- CO	unchanged	higher	unchanged	unchanged	unchanged	unchanged	unchanged	unchanged	unchanged	unchanged
- TRS	unchanged	unchanged	unchanged	unchanged	unchanged	unchanged	unchanged	unchanged	unchanged	unchanged
- SO2	unchanged	unchanged	unchanged	unchanged	unchanged	unchanged	unchanged	unchanged	unchanged	unchanged
Capacity compared to oil/NG	lower	lower	unchanged	lower	unchanged	n.a.	unchanged	n.a.	lower	lower
Ring formation	not a problem, but dusting is	several times per year but not related to fuel	not a problem, but dusting is	not a problem but sometimes plugging of the feed end	problems initially but not now	n.a.	not a problem	n.a.	n.a.	n.a.
Repair of lining	ca 2 times per year	every 3-4 years	every 1-2 years	once per year, ca 20 m	none	n.a.	n.a.	n.a.	n.a.	n.a.
Flue gas temp compared to oil/NG	higher	higher	higher	higher	higher	higher	unchanged	higher	higher	higher
Other fuels to lime kiln										
- fuel oil	yes	yes	no	yes	yes	yes	no	yes	no	no
- natural gas	no	no	no	no	no	no	yes	no	no	yes
- tall oil pitch	yes	yes	yes	no	no	no	no	no	yes	no
- methanol	yes	no	yes	yes	yes	yes	no	no	yes	yes
- non-condensable gases	not normally	no	not normally	yes	yes	no	no	no	no	no
Liquor Cycle										
Lime mud dryness compared to oil	lower	lower	no experience	no experience	no experience	n.a.	n.a.	n.a.	n.a.	n.a.
Lime quality	no obvious effects	with bark green/black lime mud, greenish lime	no experience	no experience	no experience	unchanged	unchanged	n.a.	n.a.	greenish lime
Lime availability	90-93%	86-88%	87-93%	86-92%	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Residual carbonate	3-4%	4%	2-3%	2-4%	2-4%	n.a.	n.a.	3%	n.a.	n.a.
Lime mud dryness	66-72%	75-79%	80%	81%	77-80%	n.a.	n.a.	n.a.	n.a.	n.a.
Lime make-up	ca 5%	ca 2%	ca 1%	ca 5%	n.a.	n.a.	n.a.	2-5%	n.a.	n.a.
NPEs										
- P	increases	increases	increases	increases	monitored	increases	unchanged	monitored	monitored	monitored
- Mg	increases	monitored	monitored	monitored	monitored	increases	unchanged	monitored	monitored	monitored
- Si	monitored	monitored	monitored	monitored	monitored	small effects	unchanged	monitored	monitored	monitored
- Al	monitored	monitored	monitored	monitored	monitored	increases	unchanged	monitored	monitored	monitored
- K	high levels	not a problem	not a problem	not a problem	not a problem	not a problem	unchanged	monitored	monitored	monitored

The mill that extracts lignin from the black liquor uses a ring dryer to prepare the pulverized fuel. There is no need for milling, since the lignin powder has a sufficiently small particle size from the dryer. The dryer operates with an overpressure to decrease the risk of air leakage into the dryer. There is also a fire extinguishing system with CO_2 injectors.

5.2.2 Operating experiences from the lime kiln

The use of both powder and syngas gives a number of effects in the lime kiln itself. This applies to, e.g., temperature profile, flame length and appearance, emissions, dusting and capacity.

Two mills with powder firing state that the flame length increases with bark or wood powder compared to oil. The flame is yellowish, and sometimes more unstable and pulsating. The syngas flame is described as reddish and wider, and also as fluttering more and being less stable than an oil flame.

One effect of the longer flame is a flatter temperature profile. In turn, this leads to the need to increase the fuel flow in order to reach a sufficiently high temperature in the hot zone to sinter the lime, and to supply a sufficient amount of energy at temperatures above the calcination temperature. As a result, the flue gas flow also increases, which leads to reduced capacity, and the flue gas temperature increases, which leads to increased heat losses. Most mills state that they have a lower capacity when the furnace is fired with wood powder or gasified bark than when it is fired with oil, although several mills said it was hard for them to judge because the kiln is rarely fired with oil.

For wood powder fired kilns, the particle size distribution is important to ensure that all fuel is combusted. According to two mills, close to 100% should be below one mm in size and more than 50% should be less than 0.5 mm. Two mills have also worked extensively with suppliers to modify the introduction of swirl air in the burner for better control of air/fuel mixing and flame shape.

The most noticeable change in emissions is that the NOx content of the flue gases increases. This applies to both powder and gas firing for all mills except the one firing lignin. The increase in NOx emissions may in part be due to a higher nitrogen content in wood powder and bark than in oil and natural gas, but there may also be differences in thermal NOx formation.

Two mills indicate major problems with dusting. One mill states pulsation in the fuel flow as the primary cause. Another mill highlights low temperature with subsequent poor sintering as the main cause.

Two mills have moderate problems with ring formation, about once every two months. In one mill the measure is to cool the kiln until the rings crack. In another mill the problems have been greater with harder rings that required 24-hour stops to be removed.

One mill has recurring problems, similar to ring formation, with clogging of the entrance to the flue gas channel at the feed end of the kiln. It is more severe when the kiln is operated close to its design capacity. Sometimes, the mill switches from wood powder to fuel oil to retain capacity.

Maintenance of the refractory lining varies greatly between the mills. One mill indicates a three-year service life. Two mills replace bricks in parts of the burning zone several times a year. There is mostly no direct correlation to the way biofuels are burned, although one mill states that the zone where replacement of refractory is required correlates with the length of the powder flame.

A relatively large mechanical impact from the biofuels is erosion in burners and fuel lines due to entrained ash, sand, and bed material. The wear can be strong enough to cause deformation of the burner. Two mills state that parts of the burner can be so affected that it alters the flow pattern. One plant was designed with low gas velocities to minimize erosion, but even here it has not been possible to completely avoid this type of problem.

Overall, the operating experiences from the lime kiln are relatively good and the problems are fewer than in the systems for preparing the fuel to be used in the kiln.

A burner from one of the mills is shown in Figure 16. The bark powder and the primary air is supplied through separate concentrical slots. The primary air is supplied as swirl and axial air in separate slots. The secondary air is supplied via the lime product cooler. A part of the total combustion air is also supplied as powder transport air and flame stabilization air in the centre of the burner. The different air supplies are divided as; secondary air 84 %, primary air 8%, transport air 6 % and centre air 2 %.

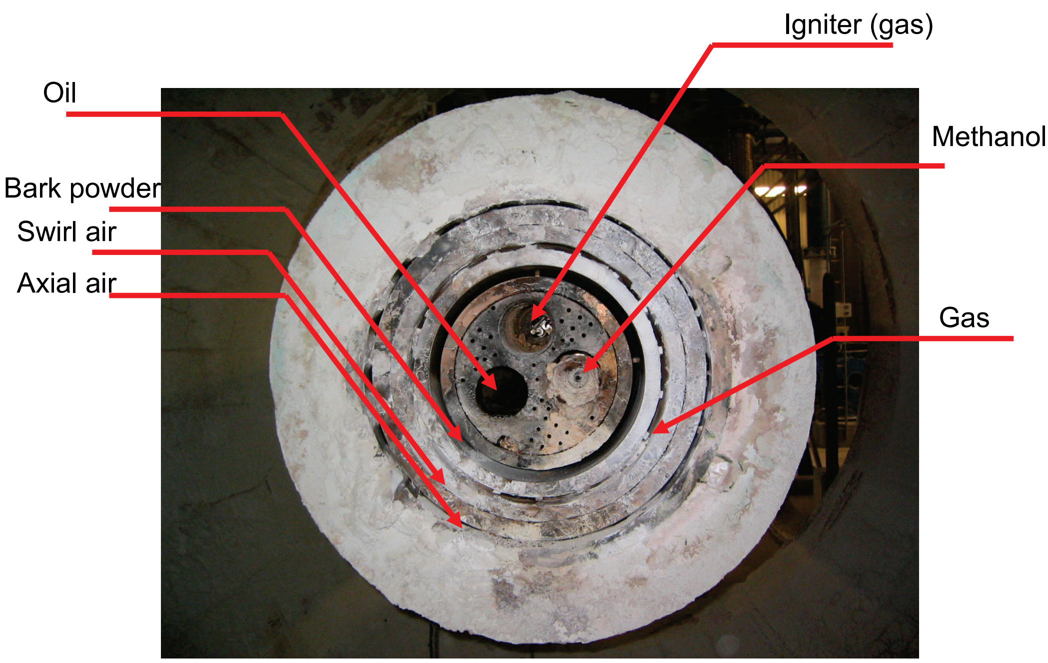

Figure 16. Combination burner for firing of bark and wood powder together with liquid and gaseous fuels.

The mill that uses lignin powder co-fired with natural gas notes that lignin gives a flame that is more similar to a flame when firing fuel oil. The temperature in the burning zone is higher than when firing natural gas only. The continuous co-firing rate has been up to 80% lignin and 20% natural gas, based on energy input. Feed-end flue gas temperature and O_2 content are not affected. Ring formation occurs occasionally both with and without co-firing of lignin, so there is no correlation to the change of fuel.

Emissions when co-firing lignin fall in the same range as for natural gas firing when it comes to SO_2 and TRS emissions. NO_x emissions are somewhat lower when co-firing lignin. Particulate emissions are higher but are mainly related to the dryer. An electrostatic precipitator has been installed to reduce particulate matter.

5.2.3 Impact on lime and liquor cycle

An increased level of non-process elements (NPE) is the most important effect that biofuel firing has in the chemical recovery cycle. The primary effect in the lime cycle is a reduced proportion of free CaO in the burnt lime. The secondary effect is an increased lime mud removal. Many mills monitor the levels of P, Mg, Si and Al in lime with a frequency of 1-2 times per month. Fe and Mn are also usually followed up at the same time. K is followed in the liquor cycle, by sampling on white liquor.

Phosphorus is the main contributor to the increased dead load in the lime cycle. This in turn creates a greater need for purchased lime to control free CaO - and thereby maintain capacity - and to keep the levels of NPE in the chemical cycle at acceptable levels. Several mills state that they control the lime mud extraction based on the phosphorus content. Some mills note that the electric precipitator dust from the kiln is enriched in phosphorus and therefore could be more suitable for purging than lime mud [17].

Several mills indicate a phosphorus content of 6-7 g/kg in lime as the upper limit, at which they increase purging of lime mud to reduce the dead load. An example of variations in NPE content of lime at one mill during one year is shown in Figure 17.

Silicon and aluminium contribute to the risk of precipitation in the evaporation plant. The mill that used peat quickly had very big problems with aluminium silicate crusts in the evaporation and therefore switched to bark. However, the bark also has high levels of Si and Al and the mill has over time converted to sawdust as the only raw material. Silicon in the form of calcium silicates does not seem to be a problem in the plants visited.

A few mills experience poorer filterability of the lime mud as a problem. They reach a lower dry matter content on average and have greater variations than when the kiln is fired with oil. One mill notes a sharp increase in the content of CaO in lime mud as one reason.

Magnesium forms hydroxides in the white liquor preparation, which also affects the dewatering properties of the lime mud. To a greater extent than for phosphorus, the Mg intake varies with the quality of the commercial lime. Several mills adjust the Mg/Al ratio to be able to purge magnesium as hydrotalcite. A certain aluminium intake can thus be positive because it helps to control the magnesium levels.

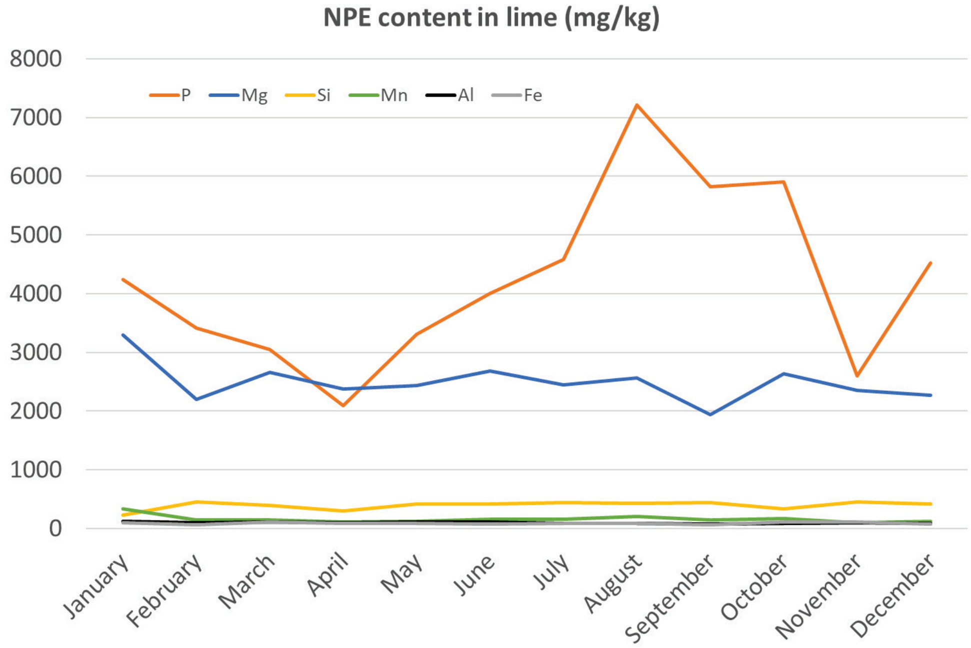

Figure 17. Monthly variations in the content of non-process elements (NPE) in lime in one mill.

Iron and manganese discolour the lime and lead to increased dusting in the lime kiln. Potassium causes problems first in the recovery boiler where it lowers the sticky temperature of dust in the flue gas path. One mill has had high potassium levels during periods when most of the oil was replaced with bark powder.

Sand is a problem in the plants that use bark powder. The sand accompanies the bark and lime and then accumulates in the trough to the lime mud filter. One mill states that the trough needs to be rinsed clean about once a week.

Ash separation after the gasifier is a major challenge and the potential advantage of gasification compared to powder firing is therefore difficult to exploit fully. In fact, much of the ash accompanies the fuel into the lime kiln and lime cycle even in the gasification cases.

Kraft lignin has a sulfur content of about 2%, and the mill that co-fires lignin thus sees an increase in the sulfur content of the lime compared to natural gas firing, resulting in some additional dead load in the kiln. The sulfur is dissolved in the causticizing operation, however, and does not show any tendency to accumulate in the lime cycle.

The sulfur in the kraft lignin is introduced during the pulping process and does therefore not result in any additional load in the liquor cycle due to the use of the lignin as a lime kiln fuel. During the lignin extraction process, however, the lignin is washed with sulfuric acid and this additional sulfur needs to be controlled to maintain the desired sulfidity in the liquor cycle. This is done by purging additional ESP ash from the recovery boiler.

5.2.4 Operational experience from mills using tall oil pitch

Out of the large number of mills using tall oil pitch, we interviewed four. The effects of using tall oil pitch instead of fuel oil were considered very small in the lime kiln, including emissions, and in the liquor cycle. The main considerations are related to the design of the fuel supply system with storage tanks, preheaters and pumps.

Two of the mills have storage tanks made from stainless steel SS2333 (EN 1.4301) and two mills have tanks made from acid-proof steel SS2343 (EN 1.4436). All mills use steam coils to keep the temperature of the tall oil pitch at 50-70°C. Normally, a pumparound is used to maintain mixing and avoid sedimentation.

All mills use positive displacement pumps to feed the tall oil pitch to the burner. All four mills had slightly different pumps: a piston rotor pump, a cogwheel pump, a screw pump, and a wing rotor pump. Common for all was that there were some challenges with leaking seals.

All mills also use shell-and-tube heat exchangers to preheat the tall oil pitch before it is fed to the burner, typically to 105-115°C. Two mills use low-pressure steam and two mills use medium pressure steam.

One mill reported an incident with corrosion in the preheater, leading to the steam condensate being contaminated with tall oil pitch. This resulted in an oil spill to the recipient. The measures that were taken included plugging of the failed tube and conductivity measurement in the steam condensate trap to prevent discharge of contaminated condensate.

5.3 RESULTS FROM SURVEY OF KILNS USING BOTH FOSSIL FUELS AND BIOFUELS

A broader survey was distributed to all mills in the Nordic countries, regardless of which fuel they used. The main objective was to collect data on issues that are faced frequently by operators, and to see to what extent these may have changed since a previous survey was done in 2008 [21]. The current survey is part of an effort to examine lime kilns globally, but within this report we focus on the mills in the Nordic countries.

There were 19 respondents among Swedish and Finnish lime kiln operators, out of a total of 45 lime kilns in operation in 2020. The operators were asked to rank problems on a 0-4 scale, where 0 indicates no problem at all and 4 indicates severe problems. In Figure 18, we have aggregated the fractions of respondents listing a certain issue as 3 (“occurred often, a nuisance, needs attention”) or 4 (“occurred often, very severe, intolerable, caused frequent kiln downtimes”) on the scale.

Although the response rate (42%) does not allow for full understanding of the distribution of issues facing lime kiln operators, the data does indicate that operability and mechanical issues require more attention than product quality and emissions. Ring formation is listed as the top issue requiring attention, but also dusting is a relatively frequent issue.

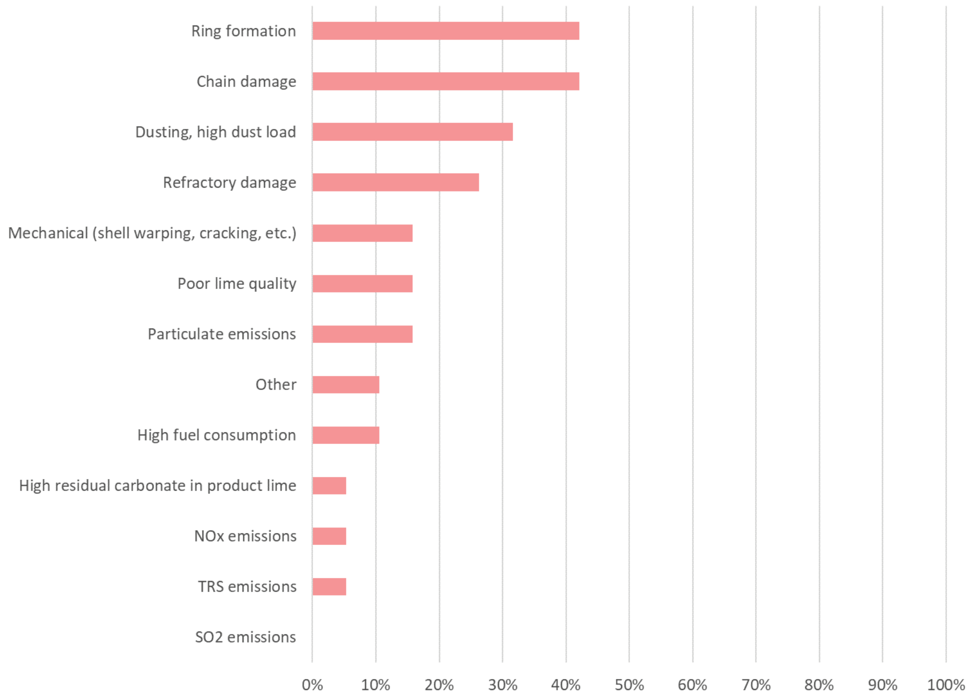

Figure 18. Fraction of respondents indicating an issue as occurring frequently. The total number of lime kilns was 19, five of which were fired with wood powder or gasified bark, nine with tall oil pitch, and the remainder with fuel oil or natural gas.

It was not possible to find significant differences between kilns firing different biofuels and those firing fossil fuels, due to the limited number of respondents using a certain type of fuel (Figure 19). An exception was the large fraction of mills that use tall oil pitch which also indicated refractory damage as a frequent issue. However, these mills did not suspect that this was related to the use of tall oil pitch specifically.

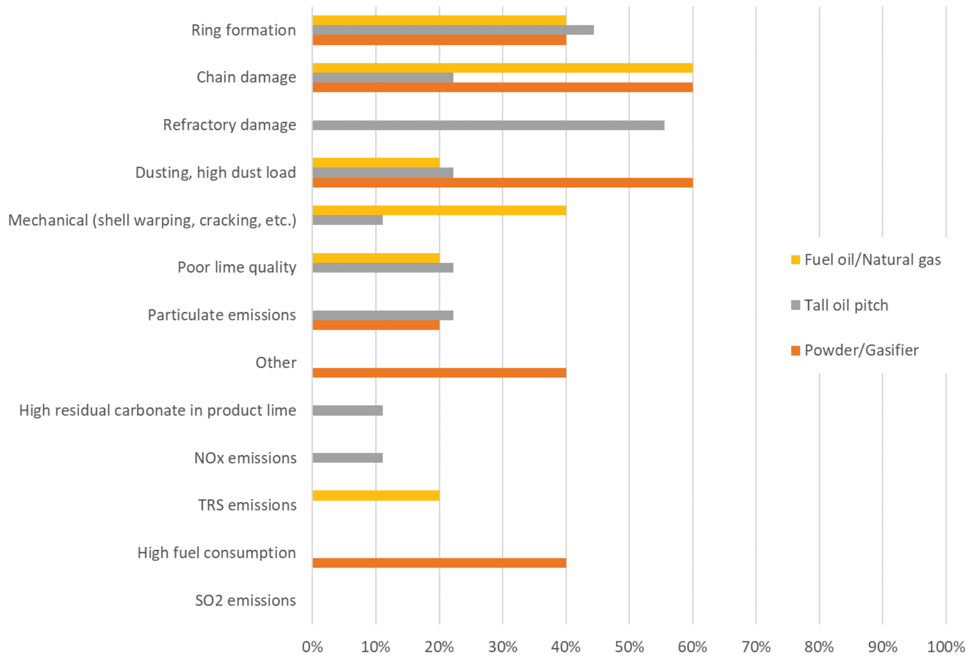

Figure 19. Fraction of respondents indicating an issue as occurring frequently, with data aggregated by main fuel used in the kiln. The total number of lime kilns was 19, five of which were fired with wood powder or gasified bark, nine with tall oil pitch, and the remainder with fuel oil or natural gas

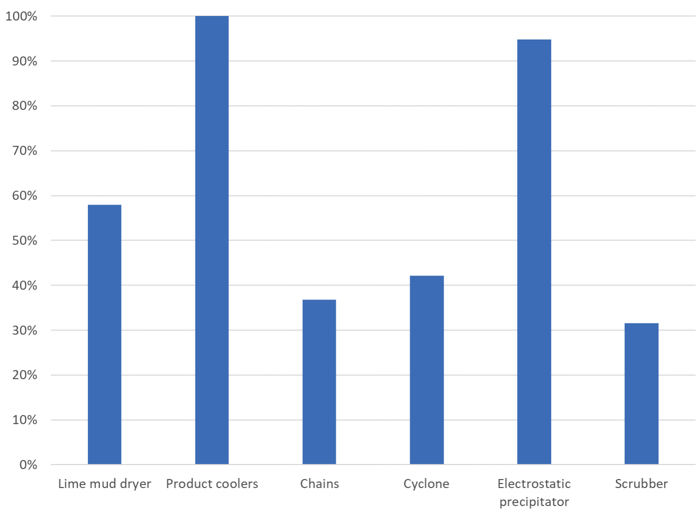

Figure 20. Fraction of respondents that have different types of equipment installed in or around the lime kiln.

Installed equipment, as summarized in Figure 20, shows that lime mud dryers are now very common and that the use of chains for heat transfer in the feed end of the kiln are less common. Electrostatic precipitators are installed in almost all mills since this is part of the European best available techniques (BAT) requirements [27]. Product coolers are used in all mills to maximize energy efficiency.

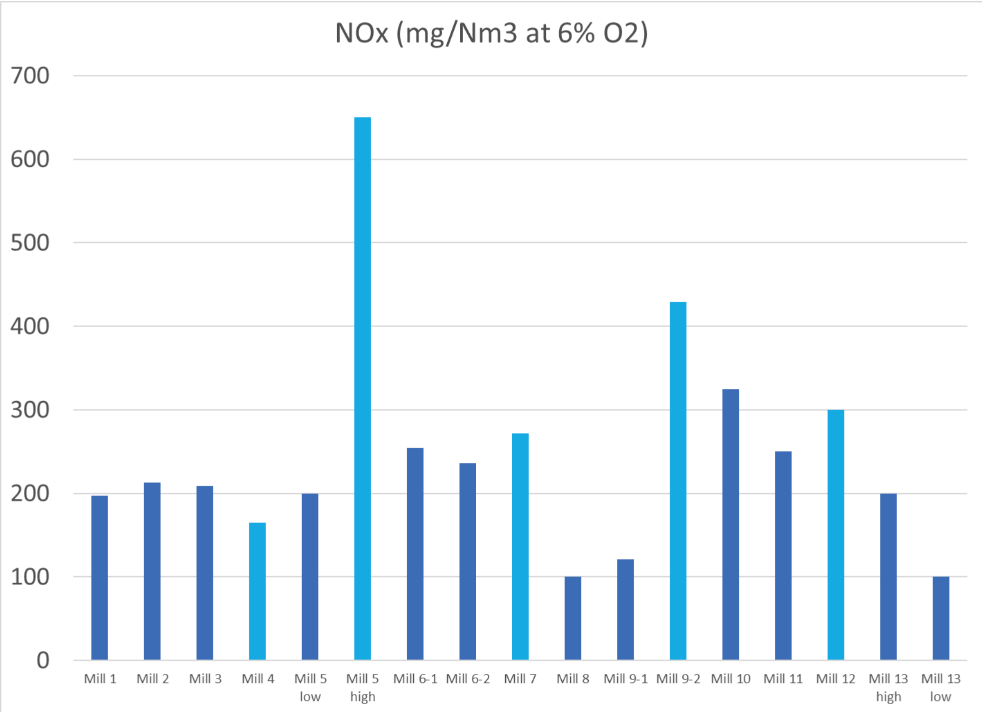

Figure 21. NOx emissions in 15 lime kilns among the survey respondents in the Nordic pulp and paper industry. Columns in light blue color indicate kilns where methanol and/or non-condensable gases are co-fired with the main fuel.

NO_x emissions are mostly around 200 mg/Nm^3 (at 6% O_2 content in the flue gas), with some low values around 100 mg/Nm^3 and some high at 400-600 mg/Nm^3 (Figure 21). Mills that use wood powder, bark powder or gasified bark as the main fuel are generally in the higher end of the normal interval. Kilns where also methanol or non-condensable gases are fired have the highest NOx emissions. This is especially clear for the mills that have indicated two operating modes or have two kilns where NCGs are fired in only one of the kilns.

6 Discussion

We have compared the results from the current study to those of the 2006 study [18] when it comes to the process design and operation of the fuel supply systems as well as on the operation of the lime kiln itself and the impact on the lime and liquor cycle.

A general observation is that the systems in operation when the 2006 study was carried out had all been installed in the 1980s, largely driven by a desire to reduce increased costs caused by the sharp increases in oil prices during the late 1970s and early 1980s. The systems currently in operation are mostly part of a “second wave” of deployment that started around 2010, also driven at first by high oil and gas prices, but now more and more by a desire to further reduce the climate impact of pulp production and minimize the carbon footprint of the products.

6.1 BIOFUEL SUPPLY SYSTEMS

The most notable difference in the process design of the fuel supply systems is that pneumatic dryers have been replaced almost completely by belt dryers when designing new systems. An important advantage is that this has reduced the risk of fires in the dryer considerably since lower temperatures are used. In the older gasification systems, a partial flow of the fuel gas was used to generate hot flue gases to a drum dryer or pneumatic dryer. Fires in the dryer represented a large part of the unavailability of these systems.

One of the mills with gasifiers in the 2006 study stated that fires on the outside of the transport line for the gas had been a frequent problem. The line was equipped with expansion bellows to absorb the thermal expansion in the longitudinal direction and leakage in these led to the hot gas easily catching fire. The other mill with the corresponding system had installed a ceramic lined gas duct and had no problems with fires.

The risk of dust explosions is also significant and can have potentially much more serious consequences than fires [10-16]. The greatest risk of explosions is not during operation but when the plant is stopped. Great care must be taken before welding, cutting or other work that can cause sparks. There is always a risk that dry powder has accumulated on horizontal surfaces and can swirl up in the form of dust. Two of the mills in the 2006 study had experience of serious explosions with long stops and extensive repairs as a result. Some mills use a technology with fiber optics to inspect the plant's interior before maintenance work.

Sintering of the bed in the gasifier occurred in the older installations. Carryover of coke and tar that condensed out of the gas led to fouling of heat exchangers and valves. One mill handled this by burning coke out of the air preheater by temporarily running under oxidizing conditions. Another mill had significant problems with tar clogging the gas valve.

The total availability of biofuel systems in the older installations was low compared to other parts of a modern sulphate pulp mill. The facilities with gasifiers indicated an availability of 65-75%. Those with powder firing had a higher availability, 80-90%. In the current study the availability in newer systems was in general 95% or above for both powder firing and gasification systems.

Another difference between newer and older systems is the incorporation of mass flow metered dosing systems for wood and bark powder. A drawback of volumetric dosing systems using cell feeders and screw feeders is that they are sensitive to density variations in the wood powder flow and to uneven flow from the powder silo to the feeder. Newer installations include rotor weighfeeders as part of the original design to reduce variations in the mass flow of powder to the kiln, and one mill has retrofitted its system to achieve the same objective.

There are some differences in the choice of technologies between different markets. Currently, powder firing dominates in Sweden, while bark gasification is more common in Finland and outside Europe. One reason that more mills in Sweden use wood powder is that they are more often co-located with saw mills, and therefore have good access to sawdust that does not need to be transported. Some mills are integrated pulp and paper mills and the bark is then used for steam production and not available for use in the lime kiln. An important reason for the choice of bark gasification in new very large mills in Asia and South America (and to some extent in Finland) is that they are normally market pulp mills with an energy surplus and the use of bark in the lime kiln is a way of valorizing the bark without the need to ship it long distances.

Tall oil pitch (TOP) has become an important lime kiln fuel in Sweden in particular. It is an option with relatively low investment costs and minor effects on operation compared to the firing of fuel oil. TOP is however a limited resource and would therefore not be an option for all mills in a global context. Sweden is already an importer of TOP, since the tall oil distilled in Sweden does not generate enough TOP as a by-product to meet the demand.

6.2 LIME KILN OPERATION

All mills that use wood or bark powder also fire small amounts of a liquid fuel at the same time, either tall oil pitch or methanol.

As in the 2006 study, mills firing solid or gasified biofuels indicated that the capacity was lower than when firing fuel oil. This is expected, based on the larger flue gas flow per unit of heat released when firing wood or bark. Several mills could not comment on capacity changes with any certainty since the kilns were built at the same time as the conversion to biofuels firing and the kilns are rarely fired with fuel oil. An illustration by one of the suppliers (Figure 22) shows the relatively large differences in flame energy (MJ/Nm^3 combustion gas) as function of flue gas flow (absolute m^3) of various fuels.

Softwood bark and birch bark have slightly different composition. The birch bark typically has a heating value 5-15% higher than softwood bark [37], which is favorable both when bark powder is fired directly and when bark is gasified.

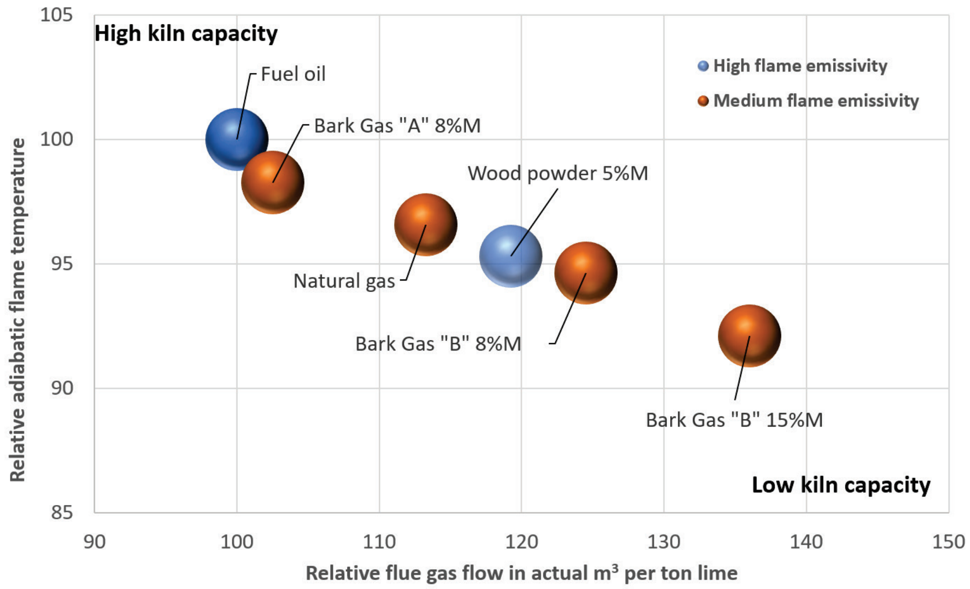

Figure 22. Illustration of relative capacity for a lime kiln when fired with fuel oil or natural gas, vs firing with gasified bark of varying composition and moisture content. Source: Valmet [36].

Ring formation is a common challenge in many lime kilns but there is no direct correlation to the choice of fuel, although uneven fuel supply is a possible contributing factor. This is known, e.g., from firing of non-condensable gases with varying flow and energy content [3-5]

Emissions of carbon monoxide, SO_2 and TRS are in general not affected by a switch to biofuels. NO_x emissions can be affected, depending on what fuel is used. With fuel oil and biofuels, NOx formation is more related to the nitrogen content of the fuel, whereas natural gas firing in general leads to more thermal NOx production. Also locally poor mixing of wood powder and air in the flame can lead to increases in thermal NOx formation [32].

The nitrogen content of biofuels varies considerably, from tall oil pitch having a nitrogen content only slightly higher than fuel oil, to bark, which may have a significantly higher nitrogen content. In addition, hardwood bark has about twice the nitrogen content of softwood bark. Sawdust, which originates from stemwood, has a considerably lower nitrogen content, and the mills firing wood pellets or dried sawdust directly did therefore not experience any major challenges related to NOx emissions.

BAT-associated emission levels (BAT-AEL) for NOx in lime kiln flue gases are given as 100-200 mg/Nm^3 (at 6% O_2) for liquid fuels and 100-350 mg/Nm^3 for gaseous fuels [27]. Footnotes indicate, however, that levels of up to 350 mg/Nm^3 for liquid biofuels (“fuels originating from vegetable matter”) and up to 450 mg/Nm^3 for gaseous biofuels may occur.

6.3 EFFECTS IN THE LIME AND LIQUOR CYCLES

The greatest impact on lime and liquor cycle operation is from non-process elements (NPE) that enter the lime cycle with the biofuel. Magnesium, silicon, aluminium, iron, manganese, potassium and phosphorus all have effects in different parts of the lime and liquor cycles (cf. 5.2.3) [6-9].

Phosphorus is the dominant NPE that determines dead load in the lime cycle, mainly because it forms phosphates like $Ca_3(PO_4)_2$ [8]. It is the NPE that most of the mills firing biofuels focus on when determining the amount of lime mud that needs to be purged. A common target for maximum P content in the lime is 6-7 g/kg.

An observation is that since the 2006 study was carried out it has become common in many mills to burn biosludge in the recovery boiler, something that also increases the NPE content of the lime, in particular the phosphorus content.

In general, the use of bark poses more challenges than if sawdust is used, because of the higher ash content of the bark. This is exemplified Figure 23, which shows that the levels of non-process elements are considerably higher with bark firing when compared at approximately the same level of lime mud purge. A rule-of-thumb indicated by the suppliers is that the required lime mud purge is approximately doubled with bark firing compared to using a fossil fuel with low or no ash content [31].

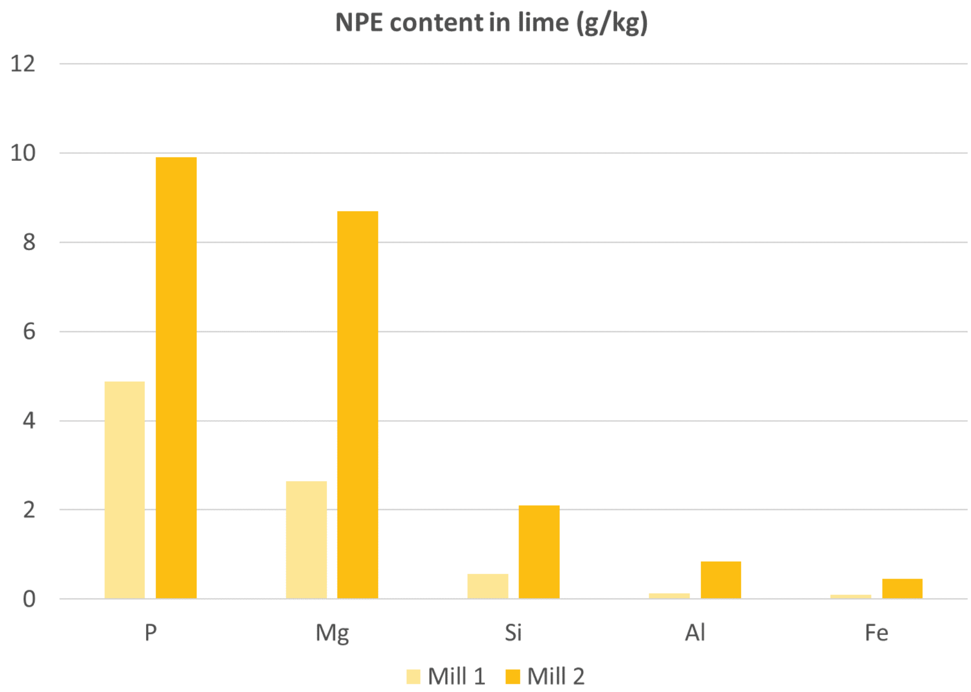

Figure 23. Measured content of some non-process elements (NPE) in lime. Data are two-year averages from one mill using a large share of sawdust ("Mill 1") and one using a large share of bark ("Mill 2") as fuel in the lime kiln.

Lignin was not yet used as lime kiln fuel by any mills when the 2006 study was carried out, but it was demonstrated on full scale in one kiln in 2008 [19] and has been used commercially since 2015 in two kilns at one mill [29, 30]. Commercial operation has confirmed the results of the initial demonstration that sulfur from the lignin does not accumulate in the lime cycle. Sulfur does still contribute to dead load, since some CaO is used to capture the sulfur inside the kiln. There is no effect on NPEs, since the lignin is taken out of the liquor cycle in the same mill as where it is used.

6.4 OTHER CONCEPTS THAN BIOFUELS

Besides biofuels there are a few other solutions being discussed and developed to reduce CO_2 emissions from lime kilns.

Hydrogen is already used as a co-firing fuel in one of the Finnish mills and in one mill in Uruguay. As a fuel, hydrogen gives very high flame temperatures and rapid flame propagation. The burner needs to be designed for high exit velocities to avoid overheating of the burner tip [24].

To have a positive effect on climate impact, the hydrogen would be prepared via electrolysis of water using renewable electricity. With the advent of many applications that use renewable hydrogen for industrial processes, the lime kiln application may benefit from cost reductions resulting in development in other industry branches. Industrial gas suppliers that are familiar also with the pulp and paper industry are scaling up electrolysis for this purpose. They also have technology available for use of oxygen in lime kilns as a means of increasing capacity and improving combustion. One mill in Sweden is currently evaluating the combination of wood powder firing and oxygen lancing [34].

Another possibility of using renewable electricity as the heat source for lime reburning is plasma technology similar to what is used in the metallurgical industry. One such process where the calcination takes place in a type of plasma arc furnace is being developed in Sweden. The developer recently received public co-funding to test the concept on pilot scale [35].

7 Conclusions

We can conclude from the survey of fuel consumption that the use of biofuels in lime kilns has become the norm in Sweden, where 90% of the energy used in 2020 was supplied with liquid or solid biofuels. In Finland, the use of biofuels has reached 45% of the energy supply in lime kilns.

An overall conclusion from the study of operating experience is that lime kiln firing with solid biofuels, either as wood powder or after gasification, is a much more mature technology now than when the 2006 study was carried out.

Availability and reliability have improved to a point where there is little difference between using biofuel systems and conventional fuel oil or natural gas fired systems. The choice of fuel for a new lime kiln has thus become a relatively straightforward trade-off calculation between capex related to the investment in the fuel supply system and opex related to the cost of the feedstock.

Some developments in the design of the fuel supply system that are notable:

- Belt dryers are used in all new installations.
- Mass flow metered dosing systems are used in most new pulverized fuel installations.
- Bark gasifiers have increased considerably in size, from about 25 MWth in earlier installations to above 100 MWth for a single gasifier in recent installations.
- Lignin powder firing has been established as a proven option.

Factors to be considered when operating a fuel supply system with solid biofuels include:

- Erosion in systems for pulverized fuels, which may lead to increased maintenance of pipe bends and burner nozzles. This is more of a concern for bark powder than for wood powder.
- Uneven flow of powder due to density variations in intermediate storage or other fluctuations resulting from volumetric dosing systems or from accumulation of powder in the pneumatic conveying system.
- Preventive maintenance to ensure proper operation of spark detection and fire extinguishing systems and to prevent air leakage.
- High standards of housekeeping to prevent accumulation of biomass powder around the fuel supply system, in order to minimize the risk for dust explosion.

Factors to be considered in the operation of the lime kiln itself include:

- The flue gas flow from biofuels is larger than from fuel oil for the same heat release, and the capacity of a lime kiln is therefore most often lower when firing biofuels.
- Good control of the particle size distribution when powder is fired directly in the lime kiln.
- It is important to optimize swirl air vs. axial air in the burner to maximize combustion efficiency and control of the flame.

- NO_X emissions may increase, both as a result of higher nitrogen content in the fuel and due to poor local air/fuel mixing

Factors related to the lime and liquor cycle include:

- Phosphorus is the primary non-process element that determines the purging rate of lime mud to control dead load.
- With sawdust, other NPEs than P are of little concern, but with the use of bark there needs to be a focus also on Si, Al, Mg, Mn, Fe and K because of their possible effects in the evaporation plant and the recovery boiler.

An intermediate solution for many Swedish and Finnish mills is the use of tall oil pitch as a replacement for fuel oil. Also these systems are characterized by high availability, but there needs to be focus on prevention of seal leakage in pumps. Corrosion is acceptable provided that stainless steel or acid-proof steel is used in storage tanks and preheaters.

8 References

[1] Olauson L, ”Biomass gasification at the Värö pulp mill”, EUCEPA 1990

[2] Lyytinen H, ”Biomass gasification as a fuel supply for lime kilns: description of recent installations”, Tappi Journal 70(7), 77-80, 1987.

[3] Dhak J; ”Ringbildning i mesaugnar II”, Värmeforskrapport 945, 2005.

[4] Tran H, X Mao, H Barham, ”Mechanisms of ring formation in lime kilns”, International Chemical Recovery Conference, Seattle, WA, USA, vol 1, p169-179, 1992.

[5] Björk M, ”Effects of process variation on ring formation in lime kilns”, International Chemical Recovery Conference, Charleston, SC, USA, vol 1, p115-120, 2004.

[6] Aksnes Ö, Andersson U, Ulmgren P, Wellmar M, ”Fabriksförsök:kartläggning av processfrämmande grundämnen i mixeri och kalkcykel”, STFI-rapport D 256, 1986.

[7] Ulmgren P, “Processfrämmande grundämnen i vitlutsberedning och kalkcykel. Del 2. Slutsatser från fabrikskarteringar och försök med fabrikskalker.” SCAN-Forsk 519 , 1988.

[8] Ulmgren P, Rådeström R, “The build up of phosphorus in a kraft pulp mill and the precipitation of calcium phosphate from green and white liquors”, J. Pulp. Pap. Sci., vol 23, 2, pJ52-J58, 1997.

[9] Eriksson J-E, Maripuu M, Theliander, H; ”Simulation of the lime mud kiln”, Proceedings AIChE Annual Meeting, Los Angeles, CA, November 17-22, p. 178f, 1991.

[10] Lindman E-K, Ingvarsson P, “Konvertering till pulvereldning med biobränslen”, Värmeforskrapport 498, 1994.

[11] Malmgren A, Tao L, Wennström M, “Konvertering av befintliga oljepannor till pulvereldning för spetslast”, Värmeforskrapport 686, 2000.

[12] Wiklund S-E, Levén P, Eriksson L, Lundin T; “Malningsteknik för biopulver”, Värmeforskrapport 650, 1998.

[13] Knudsen A, Persson H; “Brandsäkerhet vid torkning av biobränsle”, Värmeforskrapport 709, 2000.

[14] Dyrke J, Lindberg M, Morelius P; “Problematik vid lagring och hantering av biobränslen - en förstudie”, Värmeforskrapport 661, 1999.

[15] Shen K, Persson H, Knudsen A; “Riskanalys för torkning av biobränslen”, Värmeforskrapport 633, 1998.

[16] Bigün H, Bodlund G, Dahllöf L, Pettersson L, "Tillgänglighets- och riskbedömning av system för hantering och beredning av biobränsle i förbränningsanläggningar", Värmeforskrapport 922, 2005.

[17] Häggström R, "Gengasanläggning – Tillgänglighet och ekonomi. Påverkan på processfrämmande grundämnen i kalkstock", AssiDomän Karlsborg, KM 99.45, 1999.

[18] Wadsborn R, Berglin N, Richards T, "Konvertering av mesaugnar från olje- till biobränsleeldning – drifterfarenheter och modellering", Värmeforskrapport 1040, projekt S5-606 (2007).

[19] Berglin N, Tomani P, Olowson P, Hultberg T, Persson S, "Experiences from Feeding and Co-firing of Lignin Powder in a Lime Kiln", *International Chemical Recovery Conference*, Williamsburg, March 29-April 1 (2010).

[20] Berglin N, Tomani P, Salman H, Herstad-Svärd S, Åmand L-E, "Pilot-scale combustion studies with kraft lignin in a powder burner and a CFB boiler", *Tappi J* 9(6):24-30 (2010).

[21] Francey S, Tran H, Berglin N, "Global Survey on Lime Kiln Operation, Energy Consumption and Alternative Fuel Usage", *Tappi J* 10(8):19-26 (2011).

[22] Notidis E, Tran H, "Survey on Lime Kiln Operation and Ringing Problems", *Tappi J* 76(5):(1993).

[23] Hart P, "Alternative 'green' lime kiln fuels: Part I – pulping/recovery byproducts", *Tappi J* 19(5):263-269 (2020).

[24] Hart P, "Alternative 'green' lime kiln fuels: Part II – woody biomass, bio-oils, gasification and hydrogen", *Tappi J* 19(5):271-278 (2020).

[25] Tao L, Nordgren D, Blom R, " Development of a three-dimensional CFD model for rotary lime kilns", Värmeforskrapport 1158, S09-207 (2009).

[26] Manning, Tran, "Impact of cofiring biofuels and fossil fuels on lime kiln operation", *Tappi J* 14(7):474-480 (2015).

[27] European Commission, "Establishing the best available techniques (BAT) conclusions, under Directive 2010/75/EU of the European Parliament and of the Council, for the production of pulp, paper and board", 2014/687/EU (2014).

[28] Lipiäinen S and Vakkilainen E, personal communication, November 2021.

[29] Beddows M, Manning R, Rennie C, Björk M, Korhonen V, Kotilainen A, Moilanen J, Nikunen K, "Lignin Firing in Lime Recovery Kilns", *6th Nordic Wood Biorefinery Conference*, Helsinki, October 20-22 (2015).

[30] Björk M, Nikunen K, Savia M, Henriksson T, Andersson P, "Renewable Lineo™ by Stora Enso – A step towards the bio-based society", *PAPTAC International Lignin Conference,* Edmonton, Alberta, September 18-20 (2018).

[31] Taillon J, Horvath A, Oksman A, "Replacement of fossil fuel with biomass in lime kilns", *O Papel* 79(3):85-89 (2018).

[32] Wind S, Nielsen H, Havu A, Jensen C, Jensen-Holm C, Martinsson A, ”Wood powder as fuel in lime kilns”, *TAPPI Peers Conference*, Portland, Oregon, October 28-31 (2018).

[33] Salo K, ”Gasification helps mill go fossil fuel-free”, Spectrum – Andritz customer magazine, Issue 28, pp 6-9 (2014).

[34] Sellerholm P, Linde Gas, personal communication, November (2021).

[35] Lundqvist R, LimeArc Process, personal communication, November (2021).

[36] Valmet sales presentation, ”Lime kilns and biofuels – proven solutions”, (Graph inspired by AFRY Forum webinar, 2020), March (2021)

[37] Alakangas E, Hurskainen M, Laatikainen-Luntama J, Korhonen J, ”Suomessa käytettävien polttoaineiden ominaisuuksia”, VTT Technology Report 258 (2016).

Keywords

Lime kiln, biofuels, powder burner, gasifier, maintenance, bark, tall oil pitch, sawdust, non-process elements, capacity

BIOFUELS IN LIME KILNS

The lime kiln is a central process in the chemical pulp mill. The process is energy intensive and consumes large amounts of fossil fuel. Conversion to operation with biofuel is interesting both to reduce carbon dioxide emissions and to reduce costs. Globally, about 50 TWh of fuel is used per year (in Sweden about 4 TWh/year). Fossil fuel dominates, but in Sweden and Finland there is a relatively large proportion of biofuels. The documented experience gained from mills that use biofuels will facilitate the possible conversion of other mills.