

Biofuels in lime kilns – Operating experience in the Nordic pulp and paper industry

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ABSTRACT: The lime reburning process is a central part of the chemical pulp mill. It is energy intensive and consumes large amounts of fossil fuel, globally consuming about 50 terawatt-hours (TWh) of fuel per year. Conversion to operation with biofuel is interesting, both to reduce carbon dioxide emissions and to reduce costs.

Researchers interviewed managers in mills that use solid, liquid, or gasified biofuels to replace fuel oil or natural gas in their lime kilns, and they conducted surveys related to fuel consumption and operations and maintenance. In Sweden and Finland, there were ten mills in 2020 using biomass powder or gasified biomass as the primary fuel, and two more installations were under construction. There were also nine installations in operation or under construction outside the Nordic countries. Fourteen mills in Sweden and two mills in Finland used tall oil pitch as the main fuel. Fuel consumption in Swedish lime kilns was 3.8 TWh in 2020, and 90% of this energy was supplied with biofuels. Of about 4.2 TWh used in Finnish lime kilns, approximately 45% was supplied with biofuels. Developments in the design of the fuel supply system include belt dryers being used in all new installations and mass flow metered dosing systems being used in most new pulverized fuel installations. Bark gasifiers have increased considerably in size. Lignin powder firing has been established as a proven option. A solution for many Swedish and Finnish mills is the use of tall oil pitch as a replacement for fuel oil.

Application: The documented experience gained from the studied mills using biofuels will facilitate the possible conversion in other mills.

The lime kiln is a central unit operation in the chemical pulp mill, where burning of lime mud (CaCO_3) 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 metric tons of lime are produced per year in lime kilns, and fuel consumption corresponds to approximately 50 terawatt-hours (TWh) per year. In many pulp mills, lime reburning is the only remaining use of fossil fuels, apart from small amounts used during startup and shutdown.

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 with tall oil pitch, wood powder, bark powder, gasified bark, and lignin powder. Biofuels 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 that accumulate in the liquor and lime cycle. Temperature profile, flame stability, and emissions in the kiln also tend to change. Differences in availability and maintenance needs for alternative technical solutions affect the real savings of fossil fuel that can be obtained over a longer period.

The number of lime kilns operating with biofuel has increased in the past ten years and most probably will fur-

ther increase in the future. Therefore, the aim of our study was to provide an overall picture of experiences of using fuels other than oil and natural gas in the lime kiln in order to provide a better basis for investment decisions aimed at reducing fossil carbon dioxide emissions. This paper summarizes the findings described in more detail in [1].

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 using renewable fuels have been added during the last 10-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 [2]. Three of the mills had systems with biomass gasifiers, and two used powder burners. The in-depth interviews showed several challenges when converting to solid biofuels. 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 at 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. The



1. Belt dryer for sawdust (left) and storage silo (right) at the Värö mill in Sweden.

main reason was the use of hot flue gas for biomass drying.

A longer flame is obtained with some biofuels, causing a flatter temperature profile in the kiln. This leads to a need to increase the fuel flow, and thus also the flue gas flow, to maintain sufficient temperatures in the hot end of the kiln. All in all, this leads to somewhat reduced capacity and increased heat losses. Four out of five mills stated that they had lower capacity when the furnace was fired with bio-fuel than when it was fired with oil. Computational fluid dynamics (CFD) calculations have also shown similar effects in simulations [3].

The most noticeable change in emissions in the 2006 study was that the nitrogen oxide (NO_x) content of the flue gases increased. Two mills reported major problems with dusting, i.e., dust formation inside the kiln. 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 bio-fuels instead of oil for a long series of years, despite the challenges that have existed in operation and maintenance.

All facilities with gasifiers in Sweden have been closed,

but new facilities 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 [4].

TECHNOLOGIES

There are several technologies in use for supply of solid, liquid, or gaseous biofuels to lime kilns:

- *Direct firing with wood or bark powder.* 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 a belt dryer and a storage silo in a typical system.
- *Gasification of bark or wood followed by gas firing.* Gasification is carried out by partially oxidizing the biomass with air, producing a gas that consists mainly of hydrogen, carbon monoxide, and various hydrocarbons as active components. It has a much lower heating value than natural gas, but additional energy is transferred to the lime kiln by maintaining the gas at a high temperature and by allowing entrained biochar to accompany the gas into the kiln. Bark leaving the dryer normally has a moisture content of 4%–8%, and the gasifier operates at 750°C–800°C. The gas produced by the gasification plant often replaces natural gas used in the lime kiln, whose burner is then replaced by a multi-fuel burner, as depicted in **Fig. 2** [5].
- *Firing with bio-oils.* Tall oil pitch is the dominant liquid biofuel used for this purpose, but other bio-oils have also been used by some mills, e.g., mixed fatty acids. 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. Typically, fuel oil is used



2. Multi-fuel burner used to fire gasified bark [5].



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

Company	Mill	Country	Technology	Capacity	Feedstock	Supplier	Startup
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	2023

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

Company	Mill	Country	Technology	Capacity	Feedstock	Supplier	Startup
Bracell	Lencois Paulista	Brazil	Gasifier x 2	2 x 87 MW	Bark and wood residues	Valmet	2021
Klabin	Ortigueira	Brazil	Gasifier	51 MW	Wood chips (eucalyptus)	Andritz	2021
Suzano	Cerrado	Brazil	Gasifier x 2	2 x 67 MW	Wood chips	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	China	80 MW	Chip screening fines	Andritz	2019
Liansheng	Zhangzhou	China	China	115 MW	Bark and fines (eucalyptus/acacia)	Andritz	2024
APP	OKI	Indonesia	Gasifier x 2	2 x 110 MW	Bark and fines	Valmet	2017
Sun Paper	Xepon	Laos	Powder burner		Wood chips (acacia)	Valmet	2017

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

as supplementary fuel. The tall oil pitch is normally stored in 200–400 m³ acid-proof steel tanks 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, as shown in **Fig. 3**.

PLANTS IN OPERATION

We have focused on the Nordic mills that use either biomass powder or gasified biomass, but we 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. **Table I** shows the 10 mills in Sweden and Finland that in 2020 used biomass powder or gasified bio-

mass as the main fuel in the lime kiln. Some mills have two kilns, and the total number of biomass-fired kilns is therefore 13. One more mill in Sweden converted to wood powder firing and started up the new kiln in late 2021. One mill in Finland started up a new kiln with a bark gasifier in 2023.

There are also nine installations in operation or under construction outside the Nordic countries, as may be found in **Table II**. All of these are located in Asia or South America. Eight of the plants are based on gasification, with gasifiers operating on a 100 MW scale per gasifier.

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 [6,7]. They are listed in **Table III**. The Karlsborg mill decommissioned its gasifier in 2000 when there was a need for major reinvestments. Instead, they converted to tall oil pitch. The Wisaforest mill chose to invest in a new larger oil-fired lime kiln in 2004 when a new

Company	Mill	Country	Technology	Capacity	Feedstock	Supplier	Startup
Wisaforest	Pietarsaari	Finland	Gasifier	35 MW	Bark and sawdust	Ahlström (Sumitomo)	1983
Stora Enso	Norrsundet	Sweden	Gasifier	25 MW	Bark and sawdust	Ahlström (Sumitomo)	1985
Billerud	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

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

Company	Mill	Country	Use of tall oil pitch
Ahlström-Munksjö	Aspa	Sweden	Main fuel
Ahlström-Munksjö	Billingsfors	Sweden	Main fuel
Billerud	Gruvön	Sweden	Main fuel
Billerud	Karlsborg	Sweden	Main fuel
Billerud	Skärblacka	Sweden	Main fuel
Billerud	Frövi	Sweden	Main fuel
Billerud	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	Mörå	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

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

recovery plant was built. The Norrsundet mill operated its gasifier until 2008 when the mill was shut down. The Värö mill operated its bark gasifier until 2014 when a new lime kiln was built for firing with wood powder.

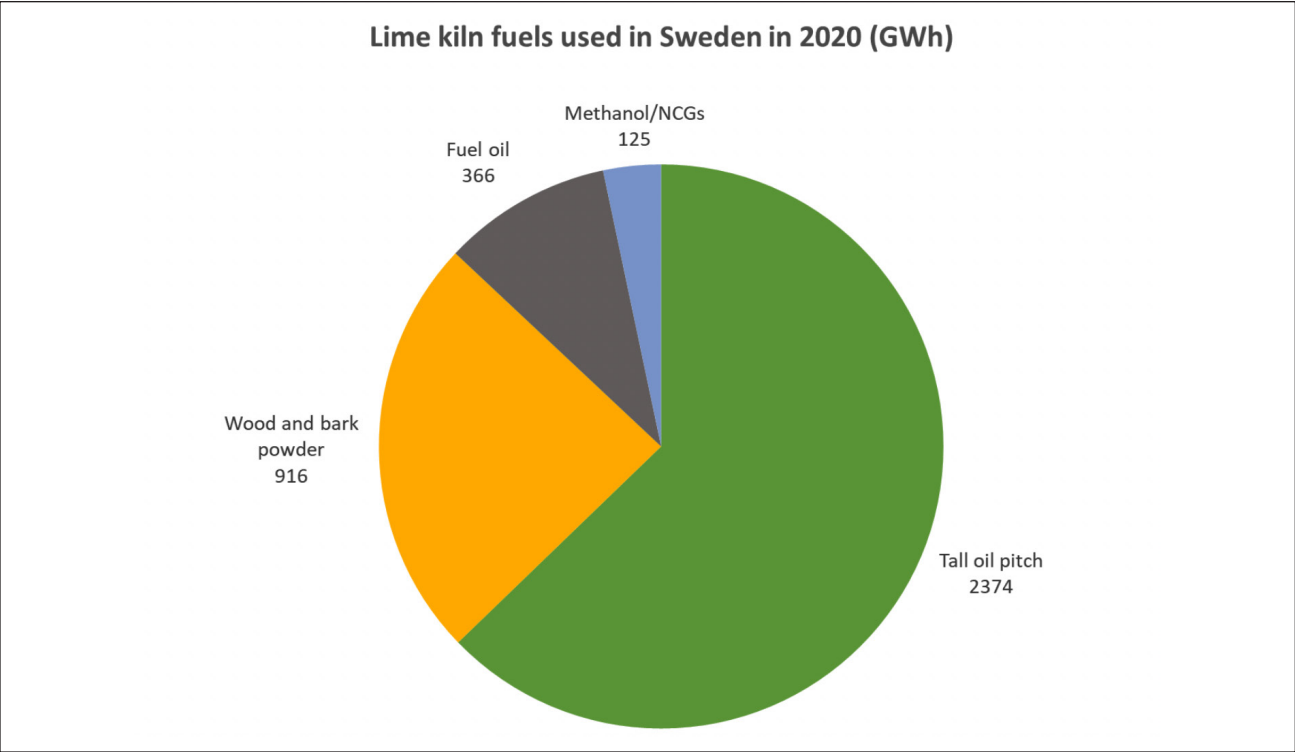
In addition, there were 20 mills using tall oil pitch as a liquid biofuel in the Nordic countries in 2020 (**Table IV**). Fourteen mills in Sweden and two mills in Finland used tall oil pitch as the main fuel.

RESULTS

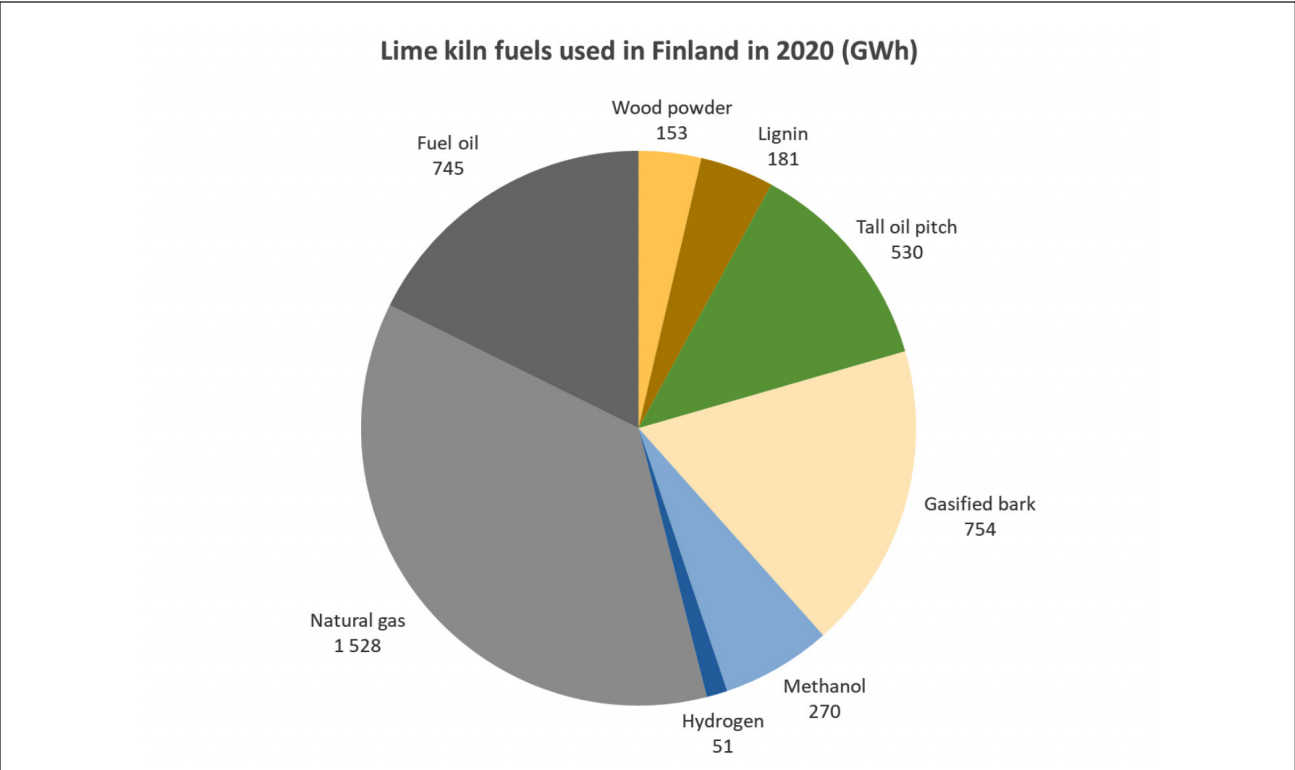
We conducted a survey of actual fuel consumption in lime kilns in Swedish mills in 2020, which was a year with high

utilization rate in the pulp and paper industry. The results are shown in **Fig. 4** (by fuel) [1].

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 (NCGs) 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).



4. Energy input to lime kilns in Swedish mills in 2020, aggregated by type of fuel (GWh: gigawatt hours). The total fuel consumption, including methanol and non-condensable gases (NCGs) that were incinerated in lime kilns was 3.8 terawatt hours (TWh). Data is sourced from [1].



5. Energy input to lime kilns in Finnish mills in 2020, aggregated by type of fuel (GWh). The total fuel consumption, including methanol and NCGs that are incinerated in lime kilns was 4.2 TWh. Data is sourced from [1].

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 from pulp production numbers, environmental permits, reported fossil CO₂ emissions, 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 mills, 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 (**Fig. 5**) [1]. 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 NCGs that were incinerated in the lime kilns.

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 talk to process operators.

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.

A summary of the most important comparisons is presented in **Table V**. The mills are anonymized and only referred to as Mill A, etc., to focus more easily on the common experiences for the various facilities.

Operational experience from the biofuel system

The solid biofuels that are burned today are bark and sawdust, either delivered directly from the sawmill 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 solid 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 inte-

grated 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).

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 feedstock.

In general, fires are a major problem in biofuel systems, especially in connection with drying [8]. The dry wood 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 hot 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.

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 CO₂.
- Checking the oxygen (O₂) 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% O₂.

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 has led to overflow of dried bark, which 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 (**Fig. 6** and **Fig. 7**) 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

Mill	A	B	C	D	
BIOFUEL SYSTEM					
Technology	Powder	Powder	Powder	Powder	
Fuel	Bark/chip rejects	Sawdust	Sawdust	Pellets	
Drying	Recovery boiler flue gases	Recovery boiler flue gases	Belt dryer	No dryer	
Drying medium	Recovery boiler flue gases	Recovery boiler flue gases	Air	-	
Size reduction	Hammer mill	Hammer mill	Hammer mill	Hammer mill	
Availability	80%	90%	>99%	>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	
LIME KILN					
Share of energy to kiln, max	100%	100%	100%	100%	
Share of energy to kiln, annual average	55%	65%	85%	65%	
Emissions compared to oil/NG					
- NO _x	Higher	Unchanged	Higher	Higher	
- CO	Unchanged	Higher	Unchanged	Unchanged	
- TRS	Unchanged	Unchanged	Unchanged	Unchanged	
- SO ₂	Unchanged	Unchanged	Unchanged	Unchanged	
Capacity compared to oil/NG	Lower	Lower	Unchanged	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 is	
Repair of lining	ca. 2 times per year	Every 3–4 years	Every 1–2 years	Once per year, ca. 20 m	
Flue gas temperature compared to oil/NG	Higher	Higher	Higher	Higher	
Other fuels to lime kiln					
- Fuel oil	Yes	Yes	No	Yes	
- Natural gas	No	No	No	No	
- Tall oil pitch	Yes	Yes	Yes	No	
- Methanol	Yes	No	Yes	Yes	
- Non-condensable gases	Not normally	No	Not normally	Yes	
LIQUOR CYCLE					
Lime mud dryness compared to oil	Lower	Lower	No experience	No experience	
Lime quality	No obvious effects	With bark green/black lime mud, greenish lime	No experience	No experience	
Lime availability	90%–93%	86%–88%	87%–93%	86%–92%	
Residual carbonate	3%–4%	4%	2%–3%	2%–4%	
Lime mud dryness	66%–72%	75%–79%	80%	81%	
Lime makeup	ca. 5%	ca. 2%	ca. 1%	ca. 5%	
NPEs					
- P	Increases	Increases	Increases	Increases	
- Mg	Increases	Monitored	Monitored	Monitored	
- Si	Monitored	Monitored	Monitored	Monitored	
- Al	Monitored	Monitored	Monitored	Monitored	
- K	High levels	Not a problem	Not a problem	Not a problem	

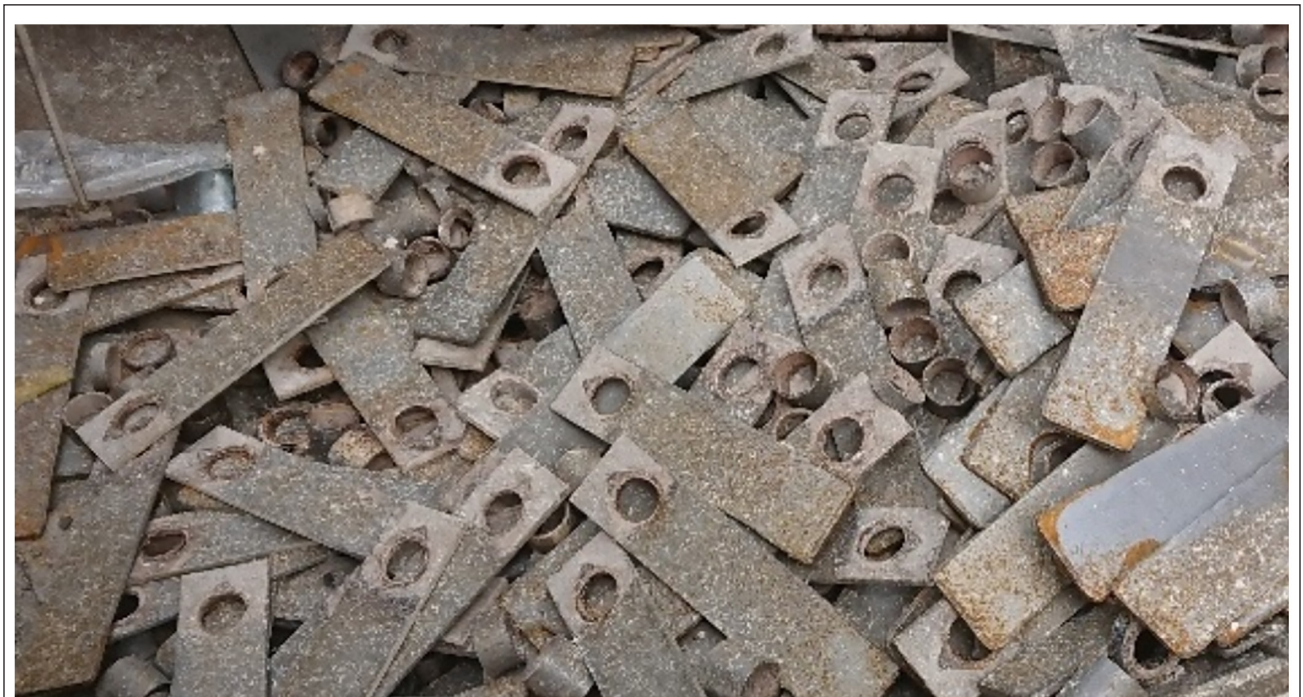
NG: natural gas; NO_x: nitrogen oxide; CO: carbon monoxide;TRS: total reduced sulfur; SO₂:- sulfur dioxide; NPEs: non-process elements; P: phosphorus; Mg: magnesium; Si: silicon; Al: aluminum; K: potassium; n.a.: not applicable.

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

	E	F	G	H	I	J
	Powder	Powder	Powder	Gasifier	Gasifier	Gasifier
	Pellets	Sawdust	Lignin	Bark	Bark	Bark
	No dryer	Belt dryer	Ring dryer	Belt dryer	Belt dryer	Belt dryer
	-	Air	Lime kiln flue gases	Air	Air	Air
	Hammer mill	Hammer mill	No milling	Crusher	Crusher	Crusher
	>95%	n.a.	n.a.	n.a.	n.a.	95%
	Cell feeder leakage and seal replacement, no fires	No fires	No fires	No fires	Fires ca. 1 time per year	Fires ca. 1 time per year
	100%	100%	100%	n.a.	100%	100%
	65%	50%	70%	70%	75%	85%
	Higher	Higher	Lower	Higher	Higher	Higher
	Unchanged	Unchanged	Unchanged	Unchanged	Unchanged	Unchanged
	Unchanged	Unchanged	Unchanged	Unchanged	Unchanged	Unchanged
	Unchanged	Unchanged	Unchanged	Unchanged	Unchanged	Unchanged
	Unchanged	n.a.	Unchanged	n.a.	Lower	Lower
	Problems initially, but not now	n.a.	Not a problem	n.a.	n.a.	n.a.
	None	n.a.	n.a.	n.a.	n.a.	n.a.
	Higher	Higher	Unchanged	Higher	Higher	Higher
	Yes	Yes	No	Yes	No	No
	No	No	Yes	No	No	Yes
	No	No	No	No	Yes	No
	Yes	Yes	No	No	Yes	Yes
	Yes	No	No	No	No	No
	No experience	n.a.	n.a.	n.a.	n.a.	n.a.
	No experience	Unchanged	Unchanged	n.a.	n.a.	Greenish lime
	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	2%–4%	n.a.	n.a.	3%	n.a.	n.a.
	77%–80%	n.a.	n.a.	n.a.	n.a.	n.a.
	n.a.	n.a.	n.a.	2%–5%	n.a.	n.a.
	Monitored	Increases	Unchanged	Monitored	Monitored	Monitored
	Monitored	Increases	Unchanged	Monitored	Monitored	Monitored
	Monitored	Small effects	Unchanged	Monitored	Monitored	Monitored
	Monitored	Increases	Unchanged	Monitored	Monitored	Monitored
	Not a problem	Not a problem	Unchanged	Monitored	Monitored	Monitored



6. Hammer mill opened for inspection.



7. Hammers replaced after normal maintenance interval.



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

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, as illustrated in **Fig. 8**.

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 its existing system to include such a weighfeeder, which has resulted in a more even flow of biomass powder.

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 CO₂ injectors.

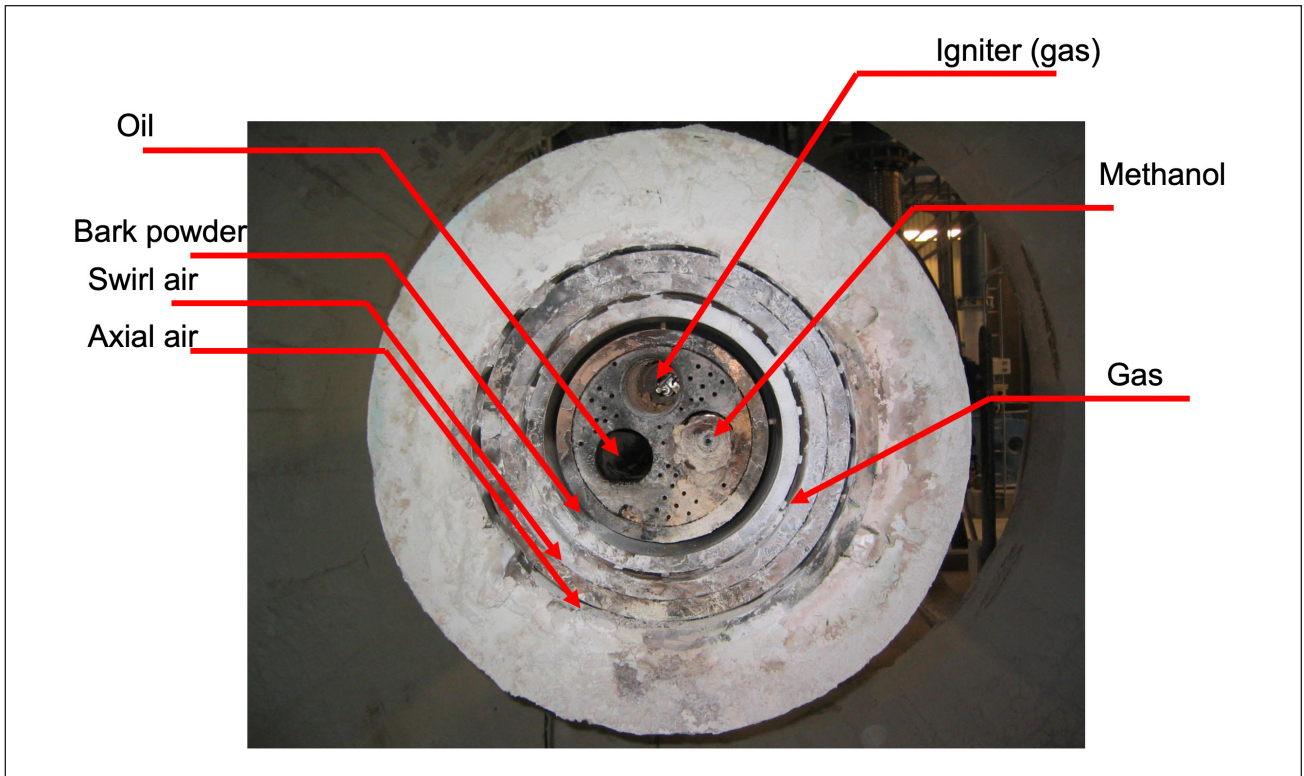
Operating experiences from the lime kiln

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 1 mm in size and more than 50% should be less than 0.5 mm. Two mills have also worked extensively with suppliers to mod-



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

ify 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 NO_x content of the flue gases increases, which is also reported in the EU IPCC BAT BREF document [9]. This applies to both powder and gas firing for all mills except the one firing lignin. The increase in NO_x 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 NO_x formation due to different flame shapes.

Two mills indicate major problems with dusting. Dusting refers to fine lime particles being entrained in the gas phase, visibly changing the gas phase from “clear” to “dusting”. It usually also increases the load on the electrostatic precipitator [10]. One mill states pulsation in the fuel flow as the primary cause. Another mill highlights low temperature, with subsequently poor sintering, as the main cause.

Two mills have moderate problems with ring formation of 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-h 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.

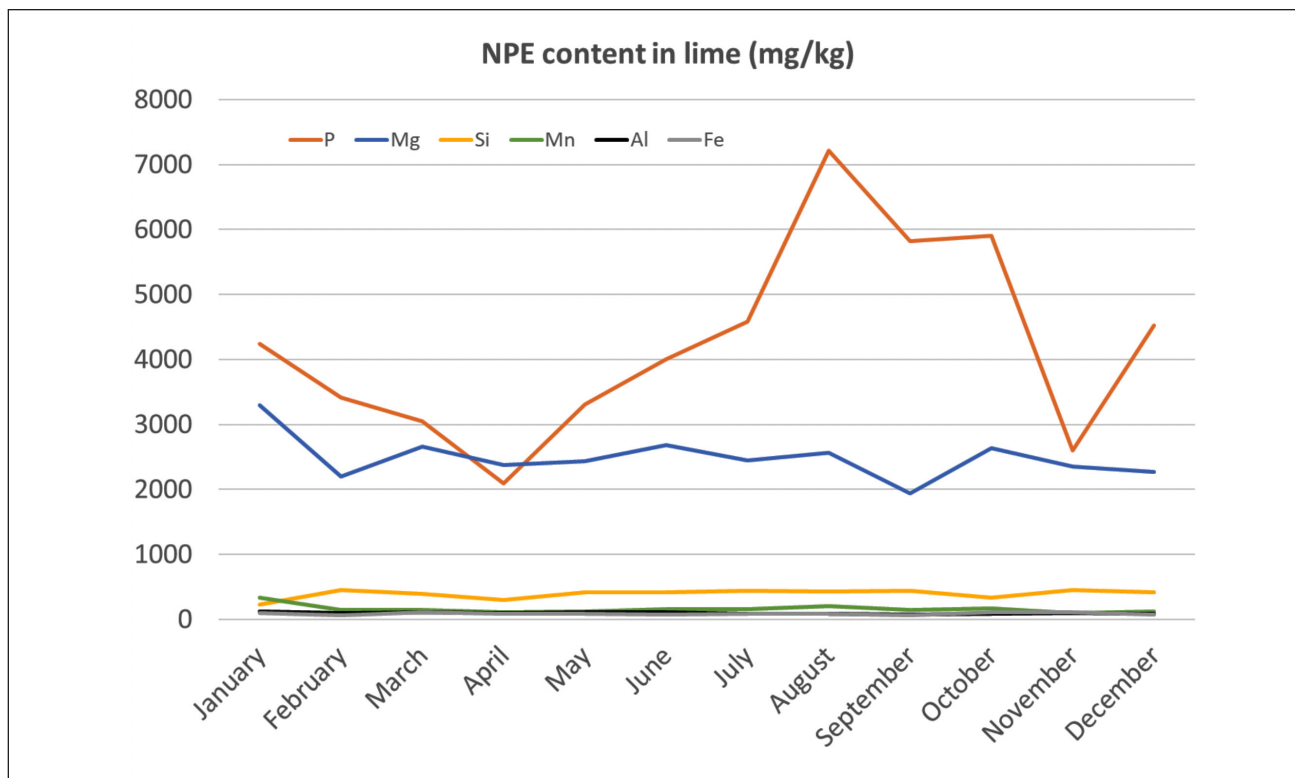
Maintenance of the refractory lining varies greatly between the mills. One mill indicates a three-year service life. Two mills replace bricks in parts of the burning zone several times a year. There is mostly no direct correlation to the way biofuels are burned, although one mill states that the zone 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 **Fig. 9**. The bark powder and the primary air is supplied through separate concentric 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 center of the burner. The different air supplies are divided as secondary air 84%; primary air 8%; transport air 6%; and center air 2%.

The mill that uses lignin powder co-fired with natural



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

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 O₂ 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 sulfur dioxide (SO₂) and total reduced sulfur (TRS) emissions. The 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 from the dryer and the kiln.

The results from modern gasifiers have been mostly positive. One mill reported that the need to control the biomass dry solid content before the gasifier, to get even operation, requires attention. The same mill also had bark supply problems that resulted in fluctuating product gas flow. During gasification, there is tar formation, and this tar tends to stick to the inside of the product gas duct to the kiln. The presence of hot tar requires safety measures, such as inertization with nitrogen, during shutdown to avoid fires. Another installation has reported operating problems, such as more frequent disturbances, at reduced loads, but states that at full load the operation is fine. Higher NO_x than with fossil fuel was reported by two mills operating gasifiers.

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 [11]. The secondary effect is an increased lime mud removal. Many mills monitor the levels of phosphorus (P), magnesium (Mg), silicon (Si), and aluminum (Al) in lime at a frequency of 1–2 times per month. Iron (Fe) and manganese (Mn) are usually followed up at the same time. Potassium (K) is monitored in the liquor cycle by sampling 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. The P compounds also make reaching low water content in the lime mud feed problematic. Several mills state that they control the lime mud extraction based on the P content. Some mills note that the electrostatic precipitator dust from the kiln is enriched in P and therefore could be more suitable for purging than lime mud [12].

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 **Fig. 10**.

Silicon and Al contribute to the risk of precipitation in the evaporation plant. The mill that used peat quickly had

very big problems with aluminum silicate crusts in the evaporation plant 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 filtration rate 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 P, the Mg intake varies with the quality of the commercial lime. Several mills adjust the Mg/Al ratio to be able to purge Mg as hydro-talcite. A certain Al intake can thus be positive, because it helps to control the Mg levels.

Iron and Mn discolor the lime and lead to increased dusting in the lime kiln. Potassium causes problems in the recovery boiler, where it lowers the sticky temperature of dust in the flue gas path. One mill has had high P 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 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 (S) content of about 2%, and the mill that co-fires lignin thus sees an increase in the S content of the lime compared to natural gas firing, resulting in some additional dead load in the kiln. The S is dissolved in the causticizing operation, however, and does not show any tendency to accumulate in the lime cycle.

The S 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 S needs to be controlled to maintain the desired sulfidity in the liquor cycle. This is done by purging additional electrostatic precipitator (ESP) ash from the recovery boiler.

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 EN 1.4301, and two mills have tanks made from acid-proof steel EN 1.4436. All mills use steam coils to keep the temperature of the tall oil pitch at 50°C–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 pre-heat the tall oil pitch before it is fed to the burner, typically to 105°C–115°C. Two mills use low-pressure steam, and two mills use medium-pressure steam.

One mill reported an incident with corrosion in the pre-heater, 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.

DISCUSSION

We have compared the results from the current study to those of the 2006 study [2] 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. It was 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. Globally, there are numerous liquid and solid biofuels used, and also other fuels that may be alternatives to fuel oil and natural gas, such as hydrogen [13,14]

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. 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 technology with fiber optics to inspect the equipment 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 sulfate 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 sawmills, 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 is 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 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. Tall oil pitch 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 tall oil pitch, since the tall oil distilled in Sweden does not generate enough tall oil pitch as a by-product to meet the demand.

Lime kiln operation

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

As in the 2006 study, mills firing solid or gasified biofuels indicated that the kiln 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.

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

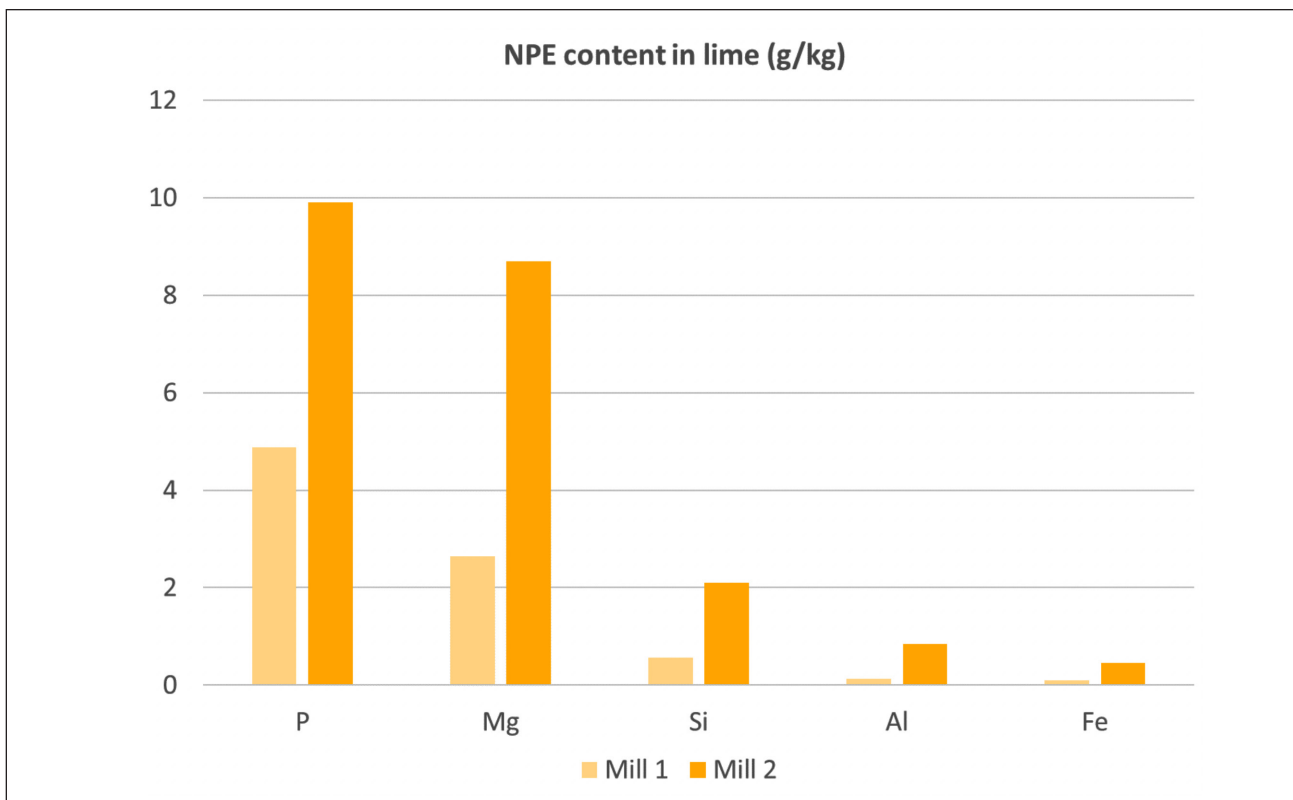
Ring formation is a common challenge in many lime kilns, but there is no direct correlation to the choice of fuel, although uneven fuel supply is a possible contributing factor. This is known, e.g., from firing of non-condensable gases with varying flow and energy content [16,17].

Emissions of carbon monoxide (CO), SO₂, and TRS are in general not affected by a switch to biofuels. The NO_x emissions can be affected, depending on what fuel is used. With fuel oil and biofuels, NO_x formation is more related to the nitrogen content of the fuel, whereas natural gas firing in general leads to more thermal NO_x production. Also, locally poor mixing of wood powder and air in the flame can lead to increases in thermal NO_x formation [18].

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 NO_x emissions.

Effects in the lime and liquor cycles

The greatest impact on lime and liquor cycle operation is from NPE that enter the lime cycle with the biofuel. The Mg, Si, Al, Fe, Mn, K, and P all have effects in different parts of the lime and liquor cycles [12].



11. Measured content of some 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.

Phosphorus is the dominant NPE that determines dead load in the lime cycle, mainly because it forms phosphates like $\text{Ca}_3(\text{PO}_4)_2$ [11]. 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 P 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 in **Fig. 11**, which shows that the levels of NPEs 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 [19].

Lignin was not yet used as lime kiln fuel by any mills when the 2006 study was carried out, but it was demonstrated at full scale in one kiln in 2008 [4] and has been used commercially since 2015 in two kilns at one mill [20,21]. 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 reacts 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.

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 capital expenditures related to the investment in the fuel supply system and operating expenditures related to the cost of the feedstock.

Some developments in the design of the fuel supply system 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 megawatt thermal (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.
- As with all biomass fuel systems, careful attention should be placed on selecting properly sized, durable, and proven components for biomass transportation, e.g., screws, belts, and silos.

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.
- Paying attention to safety systems to prevent fires.

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 somewhat lower when firing biofuels.
- Good control of the particle size distribution is important 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.
- The 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 NPE 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 acceptably low provided that stainless-steel or acid-proof steel is used in storage tanks and preheaters. **TJ**

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ABOUT THE AUTHORS

Reducing fossil fuel use in manufacturing processes is a prime objective in the decarbonization of the industry, including reduction of fossil fuel use in lime kilns. This study complements research done by us and others in the way that it summarizes the actual operating experience with biofuels in lime kilns, and in a way where it is possible to see a development over a longer time period.

The most difficult aspect of this study was getting access to information that reflected the true experience of mill operators. This was handled by building trust over time, as well as clarifying the value of understanding the experience of others.

Through our study, we discovered large differences in biofuel use between different geographies and a number of different strategies used by companies. A surprising finding was the very large replacement of fossil fuels that has already taken place in Sweden (90%).

We think this study will support decision-making when choosing between different routes to reduce the carbon footprint of kraft pulp production. A good next step for this research would be to further ex-



Berglin



von Schenck



Vakkilainen

plore the operating experience outside of Nordic countries.

At the time of writing, Berglin was managing partner and von Schenck was managing partner at NiNa Innovation AB in Täby, Sweden. Berglin and von Schenck are now with AFRY Management Consulting in Stockholm, Sweden. Vakkilainen is professor at Lappeenranta University of Technology in Lappeenranta, Finland. Email Berglin at niklas.berglin@ninainnovation.com.