

The lime industry in South Africa developed initially with vertical kilns, but from the 1950s new kiln capacity has been based almost entirely on rotary kilns with coal used as fuel for kiln firing. Dependence on both rotary kiln technology and coal as fuel presents challenges, in terms of operation and process equipment, in addressing and managing CO₂ emissions.

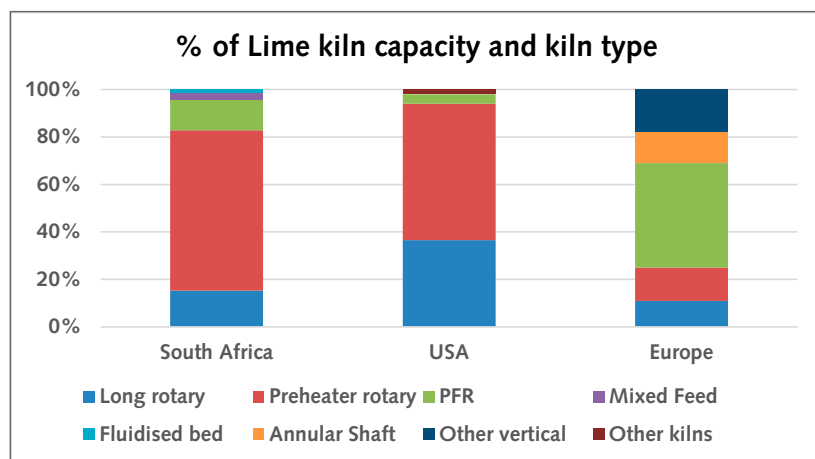
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CO₂ emissions: meeting the challenges for the lime industry in South Africa

1 Introduction

From the early 1900s, development of the lime industry in South Africa was driven by the needs of the mining and metallurgical industries, with production based on mixed-feed shaft kilns of traditional design. The first major lime plant was in the Northern Cape Province, at Taung, which, in 1924, received international recognition following discovery of the skull of the “Taung Child” embedded in the limestone.



1 Capacity and lime kiln type in South Africa [2] compared with USA and Europe [3]

By 1949, it was evident that the rapid development of the new uranium industry would be a major consumer of lime and that a new, extensive limestone source would be required to meet this demand. This led to the establishment of the Lime Acres plant, located 160 km west of Kimberley in the Northern Cape Province, and a switch to rotary kiln technology to meet the requirements of large-scale production [1].

Following the commissioning of the first rotary kiln in 1954, subsequent plant expansion at Lime Acres was based entirely on rotary kilns. Production at the nearby Ouplaas plant, located at Danielskuil, commenced in 1973 and was also built

up on rotary kiln technology. However, in the most recent expansion at the Ouplaas plant, two modern Parallel Flow Regenerative (PFR) vertical kilns have been installed. The size of the Lime Acres and Ouplaas plants has resulted in South Africa's lime production capacity being concentrated in the Northern Cape Province, with the two plants forming more than 85% of total installed kiln capacity.

Overall, it is estimated that rotary kilns currently make up 82% of installed lime kiln capacity in South Africa [2]. This is similar to the industry structure in the USA, but significantly different from the situation in Europe [3], as illustrated in Figure 1.

Owing to the significant investment in existing rotary kilns, these kilns are expected to form South Africa's major lime production base for the foreseeable future. While consuming more heat than shaft kilns, rotary kilns have several beneficial features that can be utilised in operating a competitive lime production facility:

- » Processing of smaller quarried stone sizes resulting in increased utilisation of available limestone resources
- » Meeting specific product quality demands, particularly in terms of lime reactivity
- » Operating with a variety of fuels, either as a single fuel, or a combination of fuels, to take advantage of biomass – a non-fossil fuel – and other alternative fuels, when available.

A carbon tax was introduced in South Africa in 2019, at a base rate of US\$ 7.06 per ton CO₂ emitted (Exchange rate: US\$ 1.00 = SA R 17.00), with the effective tax reduced by several initial allowances. The current base rate is US\$ 8.47. Tax-reduction allowances are to be phased out by the end of 2025, and from 2026, increases will be more rapid with the tax projected to reach US\$ 30 per t by 2030 [4].

The carbon tax will therefore become a significant liability unless measures are taken to reduce

the level and type of CO₂ emission, through improvements in operating efficiency as well as a switch to fuels with lower environmental impact, including the possible use of biomass.

2 A structured approach to reducing and managing CO₂ emissions from rotary lime kilns

2.1 Fuel combustion emissions

2.1.1 Energy efficiency at optimum level

Over the past 40 years, the heat consumption of a rotary lime kiln equipped with a preheater has improved from a reported level of 5350 kJ/kg [5] to a generally accepted best performance level of 5100 kJ/kg [6].

Improvements to process equipment and control of plant operation should have the objective of running as close to this value as possible, with key focus areas being preheater operation and heat recovery from lime cooling.

2.1.2 CO₂ emission reduction through kiln fuel selection

Carbon intensity is a measure of CO₂ emitted in relation to the energy obtained from fuel combustion: a switch to a fuel with lower carbon intensity is therefore one option for reducing combustion emissions. Natural gas, with a carbon intensity of 56.1 kg CO₂/GJ [7] has been used extensively as a replacement for bituminous coal (94.6 kg CO₂/GJ).

The use of biomass is an environmentally sound operating practice because its application, in meeting process fuel requirements and with renewable harvesting, is greenhouse neutral. This is due to complete recycling of carbon with no net increase of greenhouse gases in the atmosphere. Additional benefits of biomass combustion are low emissions of sulfur and nitrogen which result in minor levels of acid precipitation [8]. In some instances, the cultivation of extensive plantations may be required to meet biomass fuel demand: supply and growth need to be balanced for this to be sustainable.

2.2 Process emissions

In the production of lime, the major portion of CO₂ emissions arises from the CO₂ contained in the limestone used as kiln feed (process emissions). In the cement industry, the impact of process CO₂ emission can be reduced in the final cement and concrete application through the use of pozzolanic extenders. These extenders effectively result in less kiln-produced cement clinker being used, while cement strength and durability is not adversely affected.

In the case of lime, its wide-ranging chemical use requires application in pure form, thus preventing any form of extension or dilution with a corresponding reduction in the contribution to emissions from the CO₂ in the limestone. The only

option for managing process CO₂ emissions from lime production is to modify the kiln process in order to generate a high CO₂ concentration in the kiln exhaust gas, suitable for downstream carbon capture and storage. This can be achieved through oxyfuel combustion for kiln firing.

In oxyfuel combustion, oxygen replaces air for combustion of the kiln fuel. Nitrogen from air is therefore excluded from the kiln gas flow, resulting in an increased level of CO₂ in the kiln exhaust gas stream. Combustion with oxygen raises the kiln flame temperature and kiln exhaust gas can be re-circulated to regulate the temperature at normal levels.

Lime kiln oxyfuel status has been reported as follows:

- » “No lime kilns are known to be operating in oxyfuel mode” [9]
- » “No technology has been developed so far to equip existing lime kilns with an oxyfuel system” [10].

However, Maerz PFR kilns of the current design are considered to be “oxyfuel ready” as the addition of equipment for oxyfuel combustion and flue-gas recirculation, when required, is straightforward [10].

In the cement industry, kiln conversion for oxyfuel operation has reached an established design stage. A key feature of particular relevance to rotary lime kiln operation is the modification of a grate cooler to 2-stage operation, where the first (hot) cooling stage uses oxygen combined with recycled kiln exhaust gas, while the second stage uses air for clinker cooling.

3 Rotary lime kiln energy efficiency

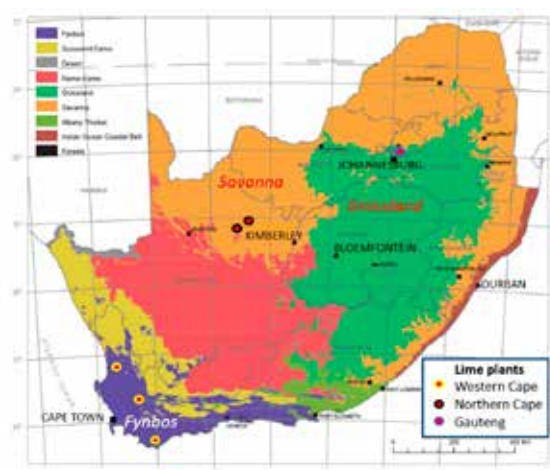
For solid fuel firing, a multi-channel burner provides scope for improving energy efficiency as well as the introduction of biomass in a fuel switch. With indirect firing, the burner is able to operate with a primary air flow of 8–12% of total combustion air requirement [11]. A reduction in burner primary air enables more preheated air from the cooler to be utilised for fuel combustion with a resulting improvement in kiln heat consumption.

Norbom reported a preheater exit gas temperature of 315 °C, and stack gas heat loss (including dust) of 1459 kJ/kg which makes up 27.3% of kiln heat consumption [5]. Comparative figures for a PFR kiln are a heat loss of 429 kJ/kg in the exhaust gas, corresponding to 11.3% of kiln heat consumption [12]. In assessing preheater operation in relation to exit gas temperature, the effect of leakage air which lowers the temperature needs to be taken into account [13].

Cement industry best practice for reducing kiln exit gas losses includes improving preheater operation or adding preheater capacity [11]. Although these principles may apply, a lime kiln preheater, however, operates with a bed of stone in a graded



2 Lime plant location in South Africa and gas pipeline network [17]



3 Map of the biomes of South Africa [22] with location of lime plants added

size range whereas a cement kiln preheater suspends the kiln feed material in the gas stream.

While kiln feed stone size is largely dictated by lime product size grading requirements, consideration should be given to stone shape in optimising preheater operation and gas-to-stone heat transfer. Channeling of gas flow – with a resulting uneven heat distribution – is minimised by the presence of stone which is more cubically shaped than laminar, in addition to close size grading [14]. This may, in turn, require evaluation of crushing equipment selection. For example, an impact crusher – utilised either as a primary or secondary crusher – is suitable for producing a high proportion of cubical stone [15].

4 Fuel switching: options in South Africa

South Africa’s industrial energy needs have historically been based on coal right up to the present. In the non-metallic minerals industry, coal and gas make up 68% and 21% respectively of energy supply, with the balance from electricity. If electricity is excluded, the contribution of coal increases to 76.4% [16].

Coal is therefore used almost exclusively as the fuel for lime kiln firing. As a consequence, rotary kiln burners in use are generally designed for single-fuel firing, with both indirect and direct firing

systems in use.

4.1 Natural gas

In Europe, one of the first steps taken by the lime industry in reducing CO₂ emissions has been to switch to natural gas, a less carbon-intensive fuel. In 2014, natural gas was used to meet about 33% of the required energy demand for lime production in Europe [6].

In South Africa, natural gas is supplied from Mozambique via an 865 km pipeline from Temane to the Sasol petrochemical plant at Secunda, (see Figure 2). Gas is then distributed over a limited area through the Sasol Gas pipeline network: it is not accessible to the main lime producing areas.

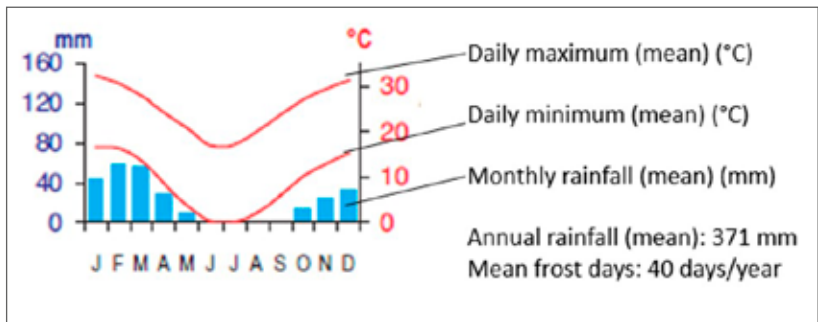
4.2 Biomass

In Africa, energy derived from biomass makes up a significant amount of the total energy used. The majority of this is, however, used for non-commercial applications, such as through the burning of wood and tree branches for cooking and heating [18].

In kiln firing applications, biomass can be used in solid form or after gasification. In pulp and paper plants in the Nordic countries, lime kiln firing with biomass is considered a mature technology. As an example, a survey of fuel consumption of lime reburning kilns in Sweden indicated that bio-fuels made up 90% of fuel requirements [19]. In contrast, in the European lime industry, biomass usage in the kiln fuel mix was reported to be 2% in 2014 [6].

Woody biomass can be described as the solid portion of stems and branches from trees or the residue products made from trees. Sources include [20]:

- » Removal of unwanted trees
- » Vegetation management covering the removal of excess woody plants and shrubs
- » Plantations with fast-growing trees grown spe-



4 Kuruman Mountain Bushveld – climatic conditions [22]



5 Kuruman Mountain Bushveld – between Danielskuil and Kuruman in the Northern Cape (altitude 1680 m) [22]

- cifically for biomass supply
- » Residues from sawmill operation and the manufacture of wood-based products

In South Africa, there is an established supply of woody biomass in the south Western Cape. This is based mainly on the harvesting of invasive alien vegetation and trees along the Breede, Berg and Zonderend rivers [21].

4.2.1 Biomass availability and distribution in South Africa

The distribution of vegetation in South Africa is defined by nine biomes which cover a variety of habitats. These include the moist winter-rainfall Fynbos biome in the south west, and the summer-rainfall Savanna and Grassland biomes in the north and east, and in the cooler higher-altitude interior.

The Savanna biome is the largest, covering over 30% of the area of South Africa, and representing the southern extent of the largest biome in Africa (see Figure 3) [22]. A characteristic feature of the savanna biome is a grassy ground layer with a separate upper layer of woody plants.

Biomass availability in the Western Cape is supported by the climatic conditions and extensive agricultural activity including wheat farming, wine production and fruit growing, together with associated food processing. The amount of available river biomass – from the removal of invasive alien vegetation – has been estimated at 700 000 t in total [23]. The invasive plants are trees or woody plant species, and therefore differ completely from the indigenous fine-leaved fynbos vegetation. These trees have the capacity to modify catchment hydrology and water availability through higher evapotranspiration rates, and use up to 20% more water than the native fynbos [24].

4.2.2 Potential in the savanna biome in the Northern Cape

In 1982, Shaw and Phillips [25] noted the unfavourable conditions being faced in re-establishing indigenous plant species on limestone mine and quarry waste and overburden dumps. In particular, severe climatic conditions that include long dry periods as well as poor soil quality were highlighted. As an example, data for the Kuruman Mountain Bushveld region of the Northern Cape, in the area of the Danielskuil lime plant, are shown in Figure 4, with an example of typical vegetation in this region illustrated in Figure 5.

An indigenous shrub which grows to a height of 2-7m, and which could possibly provide a key component in a biomass supply chain in the area near the Northern Cape lime plants, is *Dichrostathys cinerea*, commonly known as sickle bush (see Figure 6). It is an invasive species causing bush encroachment or bush thickening, with

6 Sickle bush (*Dichrostathys cinerea*) – Waterberg, Limpopo Province [28]



an adverse effect on grass cover in cattle ranching and wild game rangelands. The dense growth of these invader species also restricts animal access in affected areas.

A study in Namibia identified *Dichrostathys cinerea* as one of the problematic species causing bush thickening, and reported high biomass potential [26]. An earlier study [27] covering thornbush invasion in the savanna at Olifants Drift in Eastern Botswana, bordering on South Africa's Limpopo Province, with a study area of 100 km², identified *Dichrostathys cinerea* as one of the major species present.

The sickle bush is a leguminous plant and its root system has the capacity to fix atmospheric nitrogen [29] thereby improving soil fertility. The plant is drought resistant and is found in areas with wide-ranging temperatures, but is susceptible to frost [30]. In a study of cold weather damage to woody plants [31], it was found that plants in a certain height range were damaged: *Dichrostathys cinerea* shrubs with a height of 1–3 were affected in this way. With denser tree cover the effect of cold is reduced.

The energy potential of sickle bush [30] is illustrated quantitatively in the comparison of composition and calorific value with corresponding data for wood [32] and bark [33] in Table 1.

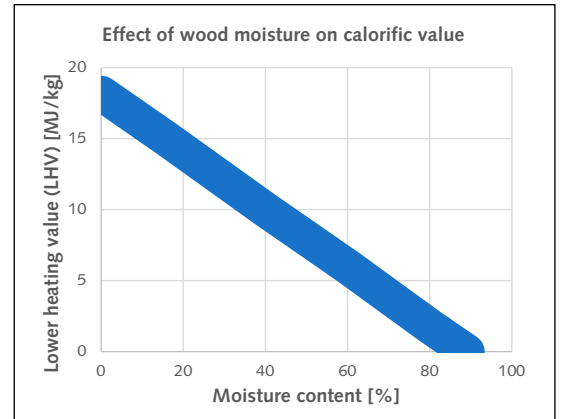
4.2.3 Woody biomass properties and processing for use as a kiln fuel

For combustion in a rotary kiln burner, woody biomass material must be dried and then milled or shredded to a suitable fineness. The moisture content is a critical aspect of both size reduction and subsequent kiln operation.

Wood has viscoelastic properties which result in the application of stress causing either temporary deformation (where the stress is removed after a short time) or permanent deformation (where the stress is maintained). Owing to these properties, a rotor impact mill of the hammer mill type is suitable for wood processing to produce the required fineness for kiln firing [34].

Table 1 Comparison of sickle bush (*Dichrostathys cinerea*) composition and calorific value with data for wood and bark

Composition (dry)	Sicklebush (with bark)	Wood	Bark
[wt %]			
C	49.25	48.00	48-52
H	5.38	6.50	4-8
N	0.44	0.10	0.1-0.5
O	42.48	45.20	36-42
S	0.06	trace	< 0.05
Ash	2.35	0.20	2-4
Calorific value			
MJ/kg (gross)	19.84	19.72	
MJ/kg (net)	18.69		17-19



7 Reduction in wood calorific value (LHV) with increasing moisture [8]

Drying is an essential requirement prior to milling: high wood moisture content affects the mechanical properties of wood and ease of shredding, resulting in a significant increase in the power consumption required for milling. With high moisture levels, fine and moist wood blocks the screens in hammer mills. Moisture lowers the wood calorific value significantly (see Figure 7). This indicates that wood should be dried to a moisture level of about 10% to produce a suitable process fuel, while addressing potential safety and fire risks.

The handling of biomass can present potential fire and explosive hazards due to self-heating, particularly in the bulk storage of wood chip or sawdust [35]. Maintenance systems should therefore include scheduled checks to ensure correct operation of protection systems covering spark detection and fire extinguishing [19]. For the transport of prepared biomass fuel, plant design detail must also allow for erosion wear in conveying lines and in burner components [33].

In order to reduce fire risk, belt dryers are commonly used [19] because of their effective operation at low temperatures. In a typical installation, drying high-moisture RDF (Refuse Derived Fuel) as a cement kiln fuel, a belt dryer operates at 90 °C [36]. A biomass processing line, with the inclusion of a belt dryer, is shown in Figure 8.

The operation with biomass as a kiln fuel, in a staged replacement for solid fuels, will result in an expansion of fuel preparation activities in a rotary lime kiln plant, as illustrated in Figure 9. Fuel preparation and the effective use of fuels in combination becomes critical for optimum kiln performance together with an effective reduction in CO₂ emissions.

5 Oxyfuel operation

Process emissions of CO₂ – arising from the calcination of limestone – can only be managed through a carbon capture and storage system, for which a process stream with a high concentration of CO₂ is required. This can be achieved through the use of



8 Wood biomass processing for lime kiln firing [19]

oxygen instead of air (with 79% nitrogen) for kiln fuel combustion. With nitrogen excluded, the resulting kiln exhaust gas has a CO_2 content which can potentially exceed 90% [10].

5.1 Simulation of oxyfuel combustion

The impact of oxyfuel combustion on a long rotary lime kiln has been assessed in a simulation study with limestone (97.4% CaCO_3) and coal as the input streams. The study was based on the prediction of process conditions using multicomponent chemical equilibrium calculations, following validation of a generic model for a rotary lime kiln against actual operating data, as well as published information [9]. The results showed that an oxyfuel process to produce a high quality lime product is feasible. The authors acknowledged, however, that further study is required.

Examples from the simulation study indicating the CO_2 content in the exhaust gas which can be achieved are illustrated in Table 2.

Fuel combustion with pure oxygen results in an elevated flame temperature. The temperature can be regulated satisfactorily by mixing the oxygen stream with recirculated kiln exhaust gas. The simulation results also showed that the recirculation of hot kiln exhaust gas may provide an opportunity for reducing kiln heat consumption, as indicated by the reduction of coal in the oxyfuel (2) case above.

Chlorides enter the kiln system at trace levels in the limestone feed and kiln fuel, with most being removed in the kiln product through reaction with calcium oxide. The resulting emission levels of hydrogen chloride are in the range of $<5 - <20 \text{ mg HCl/Nm}^3$ for rotary lime kilns with a preheater [38]. Recirculation of kiln exhaust gas will result in an accumulation of certain components in the kiln system. From their simulation results, Eriksson et al [9] noted an accumulation of chlorides due to the recirculation of kiln exhaust gas which might be significant for kiln operation.

5.2 Plant and equipment requirements: lime cooling

For cooling of the product from a rotary lime kiln, a shaft or contact cooler is commonly used (see Figure 10). The cooler is based on the Niems design, developed during the 1960s [39].

Hot lime, discharged from the kiln, passes through an angled grate (to separate oversized material) and falls into the cooler. The cooling medium is ambient air which is introduced by a forced draught fan, and flows upwards through the bed of hot lime, recovering heat and providing hot secondary air for fuel combustion. Cooled lime is discharged intermittently to maintain the level of the lime bed within pre-set limits.

With oxyfuel combustion, the stoichiometric volume of oxygen required is substantially less than the volume of air with an equivalent amount of oxygen, and is therefore insufficient for the required cooling duty. The oxygen flow is therefore supplemented with additional air for cooling. The

9 Rotary lime kiln layout [37] with biomass and solid fuel preparation systems for indirect firing replacing the original direct-fired system

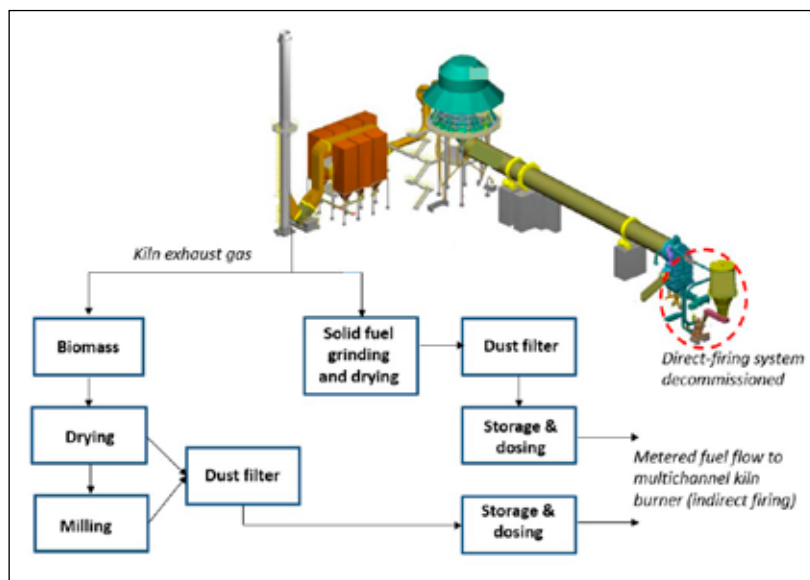
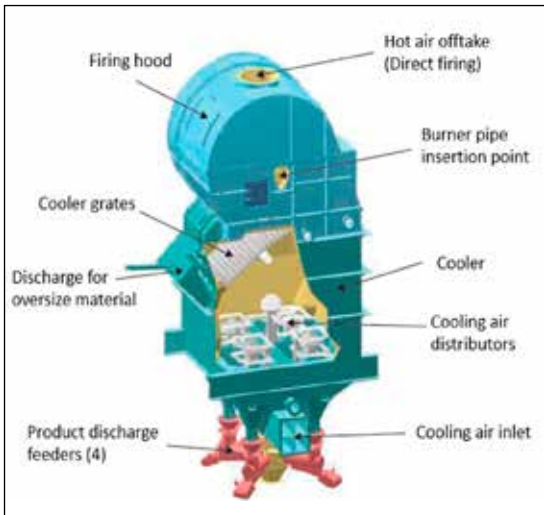


Table 2 Rotary kiln simulation results comparing standard and oxyfuel operation [9]

	Combustion gas	Exhaust gas recirculation [%]	Coal [kg/h]	O_2 [kg/h]	Kiln exhaust gas [%]				Dry gas [%]
					N_2	O_2	CO_2	H_2O	CO_2
Base case	Air	0	2366	5610	62.3	1.6	28.6	7.5	30.9
Oxyfuel (1)	Oxygen	80	2366	5610	0.2	4.4	75.6	19.9	94.4
Oxyfuel (2)	Oxygen	60	2129	5049	0.2	8.2	73.0	18.6	89.7



10 Pebble lime contact cooler [40]

cooler, however, needs to be partitioned in order to prevent the cooling air stream from entering the kiln and introducing nitrogen into the flue gas.

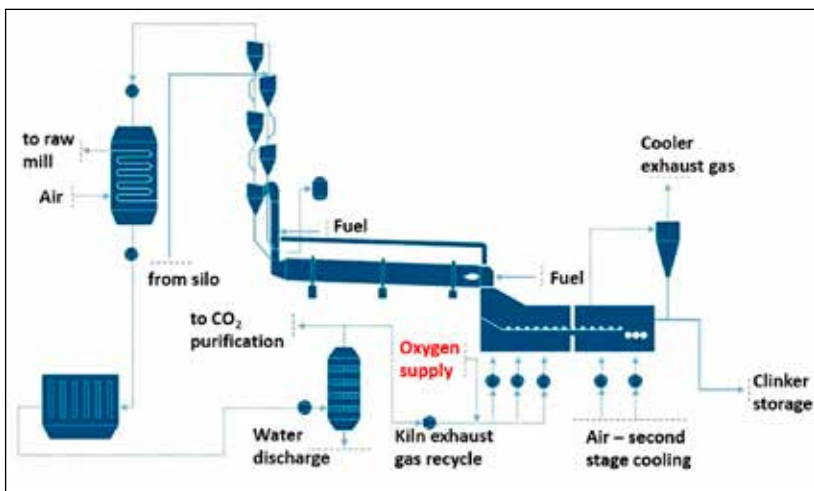
5.2.1 Cement kiln cooler for oxyfuel operation

In the cement industry, where grate coolers are generally used for clinker cooling, an accepted design for oxyfuel operation utilises a cooler layout arranged in two separate stages (see Figure 11). Oxygen, combined with re-circulated kiln exit gas, is used in the first stage while air is used in the second stage. The preheated oxygen stream is used for fuel combustion in the kiln, while the air exhaust from the cooler can be used for process heating.

5.2.2 Two-stage contact cooler for lime

The Niems-type cooler is an integrated vertical unit, from the inflow of hot lime at the top to the discharge of cooled lime at the bottom. In comparison, a grate cooler is a horizontal unit which readily enables separation into two distinct zones.

For conversion to oxyfuel operation of an existing rotary lime kiln with contact cooler, the cooling process will need to be split into two stages with-



out air or gas flow between the stages. The high temperature first stage will use oxygen mixed with recycled kiln gas and the possible recarbonation of lime will have to be considered. The gas stream leaving the first stage would be used for fuel combustion in the kiln.

A possible 2-stage layout could utilise a short grate cooler section as the first stage, discharging into a flow control hopper which would also function as the seal between the two stages. The lower section would operate as the familiar contact cooler, with air cooling, exhausted separately. A compact cooler arrangement will, however, be required in order to accommodate a retrofit within an existing plant layout. In many cases, the height required for the contact cooler has resulted in cooler installations extending below ground level.

With conventional kiln operation, the kiln exhaust gas – with a low level of oxygen – is used to provide heat for drying in the fuel preparation section. With oxyfuel operation, kiln exhaust gas is recirculated to the kiln, while a new exhaust gas stream – heated air from the cooler second stage – will be available. While this can be utilised for fuel drying, additional control and safety measures will be required due to the oxygen level in the cooler exhaust air.

6 Conclusion

With the South African lime industry's dependence on rotary kiln technology, increasing tax pressures can be expected to drive a reduction in CO₂ emissions from kiln fuel combustion, through optimised process efficiency and a reduced dependence on coal.

Biomass utilisation presents a fuel switch option, but will require the installation of suitable material handling equipment and firing system upgrades, utilising the fuel flexibility presented by rotary kilns. The diverse vegetation in South Africa could potentially support a biomass supply chain, but local climate conditions will have to be taken into consideration.

For managing process emissions, a major change in kiln operation will be required, with conversion to Oxyfuel combustion as a potential solution, following pioneering development work in the global cement industry. The contact shaft cooler – for many years the industry standard for the cooling of lime produced by a rotary kiln – will require a major modification or replacement for an oxyfuel application.

11 Cement kiln for oxy-fuel firing with 2-stage grate cooler operation [41]

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