

THE PURGE CREDIT: SORBENT MAKE-UP OPTIMISATION AND CONSISTENT CARBON ACCOUNTING FOR A CALCIUM LOOPING-UREA COMPLEX HOSTED BY A CEMENT KILN

Abubakar, H.^{1*}, Kareem, S.A.¹, Kwende, F.M.² and Okoye, S.¹

¹Department of Chemical Engineering, Modibbo Adama University, P.M.B. 2076, Yola, Adamawa State, Nigeria

²Department of Chemical Engineering, American University of Nigeria, Yola, Adamawa State, Nigeria

*Corresponding email: hayatuddeen.abubakar@mau.edu.ng

ABSTRACT

Statement of the problem: In every published assessment of calcium looping (CaL), the deactivated sorbent purge is treated as a waste that must be disposed of, and the make-up rate is consequently minimised. Where the host is a cement kiln this premise is inverted: the purge is a calcined raw meal that the kiln can consume. *Aim of the research:* This paper aims to quantify the purge credit for a CaL-urea complex retrofitted to the Ashaka cement plant, Nigeria, derive the economically optimal make-up ratio, and establish a consistent carbon-accounting framework that separates transferred, temporarily stored and permanently avoided emissions. *Methodology:* A marginal-cost model was developed incorporating raw-meal displacement, avoided kiln calcination fuel per BS EN 197-1:2011 and NIS 444-1:2003, recovered purge sensible heat, and carbon-closure sizing from the companion study. Sorbent deactivation was described by the Grasa-Abanades expression, with mean carrying capacity weighted over the particle age distribution. *Results obtained:* The purge credit reduces the marginal cost of make-up from US\$47.2 per tonne of limestone at a power-plant host to US\$3.5 per tonne at a cement host, a 93% reduction. The optimal make-up ratio rises from the conventional $F_0/FCO_2 = 0.115$ to 0.30, increasing mean CaO carrying capacity from 0.172 to 0.315 and cutting solids circulation by 35% (247 to 162 t d⁻¹). The kiln can absorb twenty times the purge generated (0.50% of CaO demand at ratio 0.30), with sulphur load at 1.3% of clinker allowance. Raising make-up increases endogenous carbon fraction from 31.5% to 52.3%, contracting required flue-gas slipstream from 1.17% to 0.42% of the kiln. *Recommendation:* It is recommended that CaL retrofits hosted by cement kilns adopt $F_0/FCO_2 = 0.30$, return the purge to the raw-meal circuit, and fire the calciner with biogenic fuel and decarbonised power to achieve carbon neutrality, as the complex is otherwise a net permanent emitter of 12.1 t d⁻¹ despite temporarily storing 36.5 t d⁻¹ in urea.

Keywords: Calcium looping, Carbon accounting, Cement kiln integration, Process economics, Sorbent deactivation, Sorbent purge

1 INTRODUCTION

Calcium looping captures carbon dioxide by cycling calcium oxide between a carbonator and an oxy-fired calciner. Its central material problem is well known: the sorbent loses carrying capacity with each cycle through pore closure and sintering, so a continuous make-up of fresh limestone must be charged and an equivalent purge withdrawn [1, 2, 3]. Every techno-economic assessment of the process therefore treats make-up as a consumable and purge as a waste, and optimises the make-up ratio downwards until the loss of activity is just tolerable. Reported make-up ratios cluster

between $F_0/FCO_2 = 0.05$ and 0.15 for this reason [4, 5]. That optimisation is correct for a power-plant host. It is not correct for a cement host. The purge from a CaL island is calcium oxide produced by calcining limestone at $900\text{ }^{\circ}\text{C}$, which is precisely what a cement kiln makes in its own precalciner before combining it with silica, alumina and iron to form clinker. Returning the purge to the raw-meal stream therefore displaces limestone, displaces the fuel that would have calcined it, and delivers sensible heat at $900\text{ }^{\circ}\text{C}$ into a process that needs heat at that temperature. The synergy is acknowledged qualitatively in the cement CaL literature [4, 6, 7], and the CEMCAP and CLEANER programmes assumed purge utilisation in their cost bases, but its consequence for the make-up optimum has not been quantified. If make-up is nearly free, the entire trade-off that sets the sorbent inventory changes. A second and less comfortable question arises when the captured carbon is used rather than stored. In a companion study the present authors showed that an oxy-fired CaL island delivers carbon to a downstream urea plant from three sources, the flue gas, the calcination of the make-up and the combustion of the calciner fuel, and that sizing the slipstream on flue-gas carbon alone oversizes the capture island by 46% [8]. Make-up therefore does not only affect sorbent activity; it injects carbon into the product stream. At a fixed utilisation-plant capacity, increasing make-up must displace flue gas. Beyond some ratio the complex is no longer capturing the host's emissions at all but merely calcining fresh limestone and burning fuel to make urea, which is worse than doing nothing. Any make-up optimisation for a capture-and-utilisation complex must therefore be constrained by carbon accounting, and that accounting must not credit the same tonne of carbon twice. The objectives of this work are (i) to formulate a purge-credit model for a CaL island hosted by a cement kiln and to obtain the marginal cost of sorbent make-up; (ii) to determine the make-up ratio that minimises solids circulation subject to capture integrity; (iii) to establish the absorption limit of the host kiln for the purge; and (iv) to develop a carbon ledger that distinguishes transferred, temporarily stored and permanently avoided carbon, and to identify the conditions under which the complex is a genuine abatement measure.

2 MODELLING FRAMEWORK

2.1 Reference kiln and capture island

The host is the Ashaka cement plant, Gombe State, taken as a dry-process kiln of 3000 t d^{-1} clinker, 65 wt% CaO per BS EN 197-1:2011 [9] and NIS 444-1:2003 [10], requiring 3480 t d^{-1} of calcium carbonate in the raw meal and emitting 2318 t d^{-1} of carbon dioxide, of which 1530 t d^{-1} is process carbon from calcination. Specific thermal energy is 3.4 GJ per tonne of clinker. The capture island treats a slipstream and feeds a 50 t d^{-1} urea plant. Table 1 collects the basis.

Table 1. Basis for the host kiln and the calcium looping island.

Parameter	Value	Unit
Clinker production	3000	t d^{-1}
CaO in clinker	65	wt%
CaCO_3 in raw meal	3480	t d^{-1}
Kiln CO_2 emission (process + fuel)	2318	t d^{-1}
Kiln specific thermal energy	3.4	GJ t^{-1} clinker
Precalciner thermal efficiency, η_{kiln}	0.85	-
CaL calciner thermal efficiency, η_{cal}	0.72	-
Carbonator capture efficiency, E_c	0.945	-
Residual CaO conversion, X_r	0.075	-
Deactivation constant, k	0.52	-
CO_2 demand of urea plant	36.53	t d^{-1}
Limestone delivered and ground	11.0	$\text{US\$ t}^{-1}$
Raw meal preparation avoided	9.0	$\text{US\$ t}^{-1}$
Fuel (natural gas)	8.0	$\text{US\$ GJ}^{-1}$
Electricity	0.12	$\text{US\$ kWh}^{-1}$

2.2 Sorbent activity and circulation

Cyclic decay of the carrying capacity is described by the Grasa-Abanades expression, in which the conversion attainable at cycle N approaches a residual value X_r , [1, 2, 3].

$$X_N = \frac{1}{\frac{1}{1-X_r} + kN} + X_r \quad (1)$$

Under continuous make-up F_0 and circulation F_R the inventory contains particles of every age, distributed as

$$r_N = \frac{F_0 F_R^{N-1}}{(F_0 + F_R)^N}, \quad \sum_{N=1}^{\infty} r_N = 1 \quad (2)$$

So that the mean carrying capacity of the circulating solids is

$$X_{ave} = \sum_{N=1}^{\infty} r_N X_N \quad (3)$$

The carbonator carbon balance fixes the circulation required to carry the captured load.

$$F_R = \frac{E_c F_{CO_2}}{X_{ave}} \quad (4)$$

and the make-up ratio conventionally reported in the calcium looping literature follows as

$$\frac{F_0}{F_{CO_2}} = \frac{F_0}{F_R} \frac{E_c}{X_{ave}} \quad (5)$$

Equations (1) to (5) are solved simultaneously because X_{ave} and F_R are mutually dependent; convergence is obtained by successive substitution in fewer than ten iterations.

2.3 The purge credit

At steady state the calcium withdrawn in the purge equals the calcium charged as make-up, so the purge delivers to the kiln a mass of calcium oxide.

$$\dot{m}_{purge} = \frac{M_{CaO}}{M_{CaCO_3}} \dot{m}_{mk} \quad (6)$$

Each tonne of make-up limestone therefore displaces one tonne of limestone in the raw meal, avoids the calcination enthalpy that the precalciner would have supplied, and carries sensible heat from the calciner outlet temperature into the preheater. The three credits, expressed per tonne of make-up, are

$$b_{meal} = p_{meal}, \quad b_{fuel} = \frac{\Delta H_{calc}}{\eta_{kiln}} p_f, \quad b_{sens} = \frac{M_{CaO}}{M_{CaCO_3}} c_p (T_{cal} - T_{meal}) p_f \quad (7)$$

A fourth credit arises only when the island feeds a utilisation plant. The carbon released by calcining the make-up, together with the carbon from the additional calciner fuel it demands, enters the purified product stream and displaces an equal quantity of flue-gas capture, whose specific energy is e_{cap} ,

$$b_{cap} = \frac{\delta}{\eta_p} e_{cap} p_f, \quad \delta = \frac{M_{CO_2}}{M_{CaCO_3}} + \frac{\Delta H_{calc}}{\eta_{cal} LHV} \frac{M_{CO_2}}{M_{CH_4}} \quad (8)$$

where δ is the carbon dioxide entering the product stream per tonne of make-up. The costs incurred per tonne of make-up are the limestone itself, the calcination fuel burned in the CaL calciner, the oxygen that fuel requires from the air separation unit, and the compression of the additional carbon dioxide,

$$c_{tot} = p_{lime} + \frac{\Delta H_{calc}}{\eta_{cal}} p_f + m_{O_2} w_{ASU} p_e + \delta w_{comp} p_e \quad (9)$$

so that the marginal cost of sorbent make-up is

$$c_{mk} = c_{tot} - (b_{meal} + b_{fuel} + b_{sens} + b_{cap}) \quad (10)$$

For a host that cannot use the purge, the three kiln credits vanish and a disposal charge p_{disp} is added instead.

2.4 Coupling to carbon closure

The calciner must decompose both the sorbent carbonated in the carbonator and the make-up, so its fuel demand is

$$\dot{m}_f = \frac{\Delta H_{\text{calc}}(\dot{m}_{\text{carb}} + \dot{m}_{\text{mk}})}{\eta_{\text{cal}} \text{LHV}} \quad (11)$$

and the carbon delivered to the urea plant, following the closure framework of the companion study [8], must equal the stoichiometric demand. Solving that constraint for the flue-gas slipstream at fixed urea output gives.

$$\dot{m}_{\text{fg}} = \frac{\dot{m}_{\text{CO}_2, \text{st}}/\eta_p - \dot{m}_{\text{mk}}(M_{\text{CO}_2}/M_{\text{CaCO}_3}) - \dot{m}_f(M_{\text{CO}_2}/M_{\text{CH}_4})}{E_c Y_{\text{CO}_2}} \quad (12)$$

Equation (12) is the constraint that bounds make-up from above: as make-up rises the numerator falls, and when it reaches zero the urea plant is supplied entirely by fresh limestone and fuel, and the complex captures nothing from the kiln. The endogenous carbon fraction θ and the slipstream fraction ϕ defined in [8] are used to report this behaviour.

2.5 Carbon accounting rules

Three categories of carbon must be kept separate to avoid double counting. Carbon that would have been calcined in the kiln and is instead calcined in the CaL calciner is transferred: it leaves the system in the product rather than at the stack, but no additional abatement occurs, and it must be counted once only. Carbon fixed in urea is temporarily stored, since urea hydrolyses in soil within weeks of application and returns its carbon to the atmosphere; it is therefore excluded from the permanent ledger. Only fuel and power effects are permanent. The permanent balance is [8, 11, 12].

$$\Delta E_{\text{perm}} = \frac{\Delta H_{\text{calc}}}{\eta_{\text{kiln}}} \dot{m}_{\text{mk}} \varepsilon_f + \frac{b_{\text{sens}}}{p_f} \times \varepsilon_f - \dot{m}_f \frac{M_{\text{CO}_2}}{M_{\text{CH}_4}} - W_e \varepsilon_e \quad (13)$$

Where ε_f and ε_e are the emission factors of fuel and electricity. Credits for displacing conventionally produced urea are deliberately excluded, because the counterfactual is indeterminate: if the ammonia supplier vents the carbon dioxide by-product of its own steam reforming, no fossil carbon is left in the ground and the credit is zero, whereas if the displaced urea plant would have consumed that by-product the credit approaches the full stoichiometric requirement. The range is reported rather than a point value.

3 RESULTS AND DISCUSSION

3.1 Sorbent activity and circulation

Figure 1(a) shows the decay of carrying capacity computed from Eq. (1). Conversion falls from 0.70 in the first cycle to 0.14 by the twenty-fifth, and the mean value weighted over the age distribution is 0.172 at the conventional make-up ratio of 0.115. This is an order of magnitude below the values sometimes assumed in equilibrium-based flowsheet models of cement-plant capture, and it is the quantity that sets the solids inventory: by Eq. (4) the circulation required to carry 25.5 t d⁻¹ of captured carbon dioxide is 247 t d⁻¹ of solids. Figure 1(b) traces the effect of raising make-up. Mean carrying capacity rises steeply at first, reaching 0.315 at F₀/F_{CO2} = 0.30 and 0.44 at 0.60, and the circulation falls correspondingly from 247 to 162 and then 132 t d⁻¹. The curve flattens beyond about 0.4: trebling make-up again buys only a further 12% reduction in circulation. Table 2 lists the operating points. [1, 3, 6].

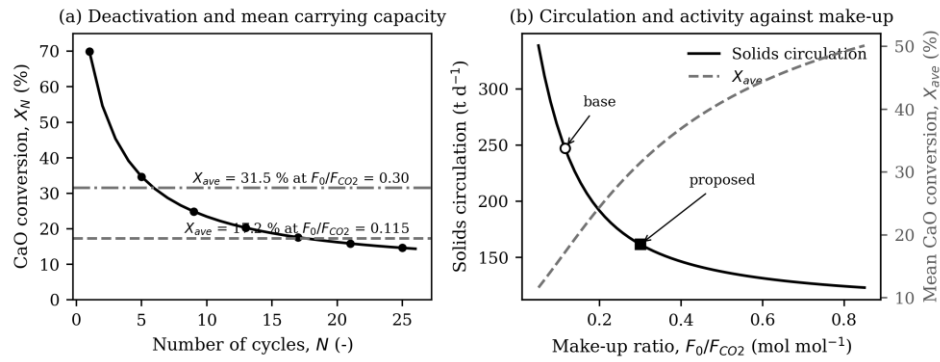


Figure 1. (a) Cyclic decay of CaO conversion from Eq. (1) with the age-weighted means at two make-up ratios; (b) solids circulation and mean carrying capacity against make-up ratio.

Table 2. Sorbent activity, circulation and purge at four make-up ratios.

F_0/F_{CO_2} ($mol\ mol^{-1}$)	0.115	0.20	0.30	0.60
Mean carrying capacity, X_{ave}	0.172	0.244	0.315	0.444
Make-up limestone ($t\ d^{-1}$)	6.7	11.6	17.4	34.9
Solids circulation ($t\ d^{-1}$)	247	192	162	132
Purge to clinker line ($t\ d^{-1}$)	3.7	6.5	9.8	19.5
Purge as share of kiln CaO demand (%)	0.19	0.33	0.50	1.00
Calcliner fuel ($t\ d^{-1}$)	3.22	3.46	3.75	4.61
Endogenous carbon fraction, θ (%)	31.5	36.4	41.3	52.3
Flue-gas slipstream ($t\ d^{-1}$)	120.0	106.6	90.9	43.6
Slipstream fraction, ϕ (%)	1.17	1.04	0.88	0.42
Flue-gas CO_2 captured ($t\ d^{-1}$)	25.5	22.7	19.3	9.3

3.2 The marginal cost of make-up

The purge credit is quantified in Figure 2 and Table 3. Charging one tonne of limestone to the CaL island costs US\$44.4: US\$11.0 for the stone, US\$19.8 for the calcination fuel at 72% calciner efficiency, US\$6.0 for the oxygen that fuel requires, and US\$7.6 to compress the 0.58 t of additional carbon dioxide it releases. Against this, the tonne of calcium oxide returned to the clinker line displaces a tonne of raw-meal limestone (US\$9.0), removes 2.10 GJ of precalciner duty (US\$16.8) and carries 0.45 GJ of sensible heat into the preheater (US\$3.6), while the carbon it injects into the product stream removes an equal duty from the flue-gas capture section (US\$11.5). The net marginal cost is US\$3.5 per tonne. At a host that must landfill the purge the same tonne costs US\$47.2. The purge credit therefore removes 93% of the cost of sorbent make-up. [4, 7, 13].

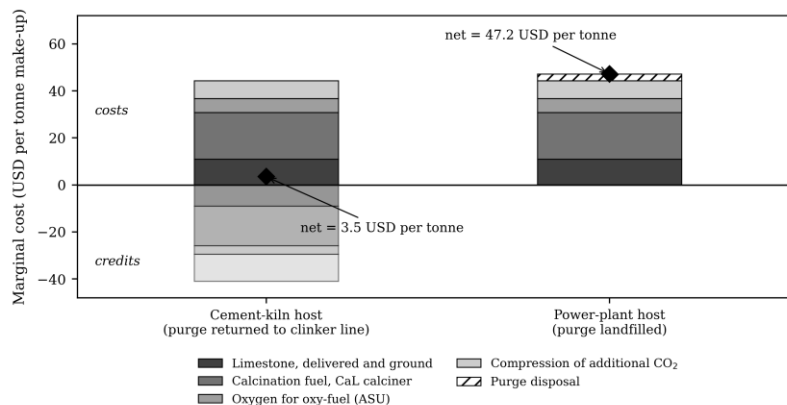


Figure 2. Marginal cost of sorbent make-up at a cement-kiln host and at a power-plant host. Bars above the axis are costs, bars below are credits, and the diamonds mark the net values.

Table 3. Marginal cost of sorbent make-up, per tonne of limestone charged.

Item	Cement host (US\$ t ⁻¹)	Power host (US\$ t ⁻¹)
Limestone, delivered and ground	11.0	11.0
Calcination fuel, CaL calciner	19.8	19.8
Oxygen from air separation unit	6.0	6.0
Compression of additional CO ₂	7.6	7.6
Purge disposal	-	2.8
Raw meal displaced at the kiln	-9.0	-
Kiln calcination fuel avoided	-16.8	-
Purge sensible heat recovered	-3.6	-
Flue-gas capture duty avoided	-11.5	-
Net marginal cost	3.5	47.2

3.3 Absorption limit of the host kiln

A make-up ratio of 0.30 produces 9.8 t d⁻¹ of purge against a kiln demand of 1950 t d⁻¹ of calcium oxide, or 0.50%. Even at a ratio of 1.0 the purge would supply only 1.7% of the kiln's calcium. Sulphur, the usual objection to returning capture residues to a clinker line, is equally undemanding here: the 0.8 t d⁻¹ of calcium sulphate formed by sulphation of the sorbent carries 0.47 t d⁻¹ of sulphur trioxide into a clinker stream that can accept roughly 36 t d⁻¹ at a 1.2 wt% limit, and the sulphation load falls rather than rises with make-up because a smaller slipstream is treated. The kiln can therefore absorb some twenty times the purge generated at the design point. Purge disposal is not the binding constraint on make-up at a cement host, which is the essential difference from the power-plant case that has shaped the published optimum. [4, 6, 13].

3.4 Capture integrity as the binding constraint

What does bind is carbon. Figure 3(a) shows the endogenous fraction rising from 31.5% at the conventional make-up to 52.3% at a ratio of 0.60, while the slipstream required to close the balance at 50 t d⁻¹ of urea contracts from 1.17% to 0.42% of the kiln. Beyond a ratio of about 0.85 the required slipstream is negative: the calcination of make-up and the combustion of calciner fuel alone would oversupply the urea plant, and the island would have ceased to be a capture plant. Figure 3(b) presents the same information as a trade-off between the solids inventory and the quantity of kiln carbon actually captured. The knee of that curve lies between ratios of 0.20 and 0.35, where a 35% reduction in circulation costs a 24% reduction in flue-gas carbon captured; beyond it the exchange rate deteriorates sharply, and a further 19% reduction in circulation costs more than half the remaining capture. A ratio of 0.30 is therefore proposed, giving $X_{ave} = 0.315$, a circulation of 162 t d⁻¹ and 19.3 t d⁻¹ of kiln carbon captured, at an incremental operating cost of US\$38 per day. [8, 11, 14].

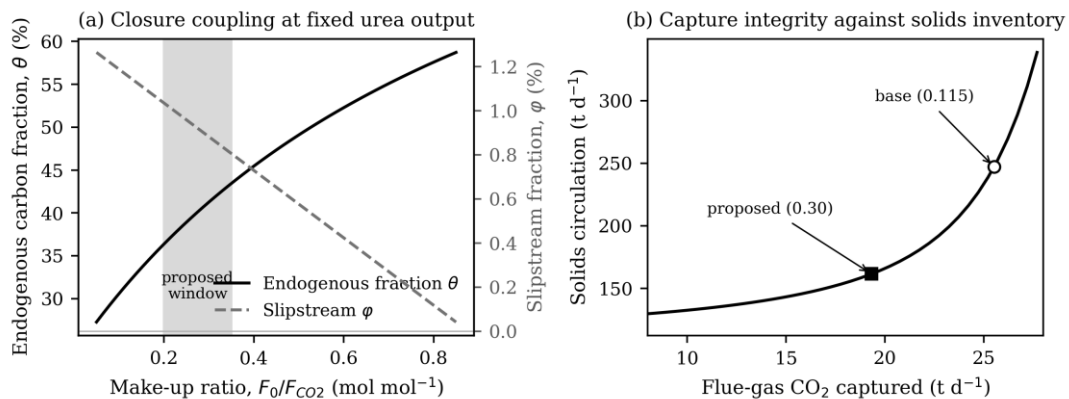


Figure 3. (a) Endogenous carbon fraction and required flue-gas slipstream against make-up ratio at fixed urea output, Eq. (12); (b) trade-off between solids circulation and flue-gas carbon captured, with the base and proposed operating points.

The capital consequence is material. Solids circulation sets the riser cross-section, the cyclone duty, the loop-seal aeration and the standpipe inventory of a dual fluidised-bed system. Scaling the solids-handling portion of the capture island, taken as 45% of its capital cost, with circulation to the 0.65 power, the 35% reduction in circulation returns a 24% saving on that portion, or approximately US\$0.8 million of the US\$7.2 million capture island. This is obtained for an operating cost increase of about US\$14 000 per year.

3.5 The carbon ledger

Figure 4(a) sets out the permanent ledger at the base case under the rules of Section 2.5. The purge returns 1.09 t d⁻¹ of avoided kiln fuel emissions and 0.23 t d⁻¹ from recovered sensible heat. Against these, the CaL calciner burns 3.2 t d⁻¹ of natural gas, emitting 8.82 t d⁻¹, and the 10.2 MWh d⁻¹ of electricity for the air separation unit, compression and utilities emits a further 4.57 t d⁻¹ at a captive gas-fired emission factor of 0.45 t MWh⁻¹. The permanent balance is therefore negative at -12.1 t d⁻¹, against 36.5 t d⁻¹ of carbon temporarily stored in the urea. This result should not be read as a verdict against the concept, but as a correction to the way its benefit is usually stated. The complex does not sequester carbon; urea returns its carbon to the atmosphere within weeks of field application, as every nitrogen-fertiliser pathway does. Its defensible benefits are the displacement of imported fertiliser, the security of domestic supply, and the delay of 36.5 t d⁻¹ of kiln emissions by the residence time of the product. Where a genuine permanent abatement is sought, Figure 4(b) shows the two levers that deliver it. Firing the calciner with biogenic fuel, for which Nigeria has abundant agricultural residue, removes 8.82 t d⁻¹ of the debit and brings the balance to -3.3 t d⁻¹; decarbonising the electricity supply removes a further 4.06 t d⁻¹ and brings the complex marginally positive at +0.81 t d⁻¹. Neither lever affects the urea output, the purge credit or the economics of make-up developed above. [12, 15, 16].

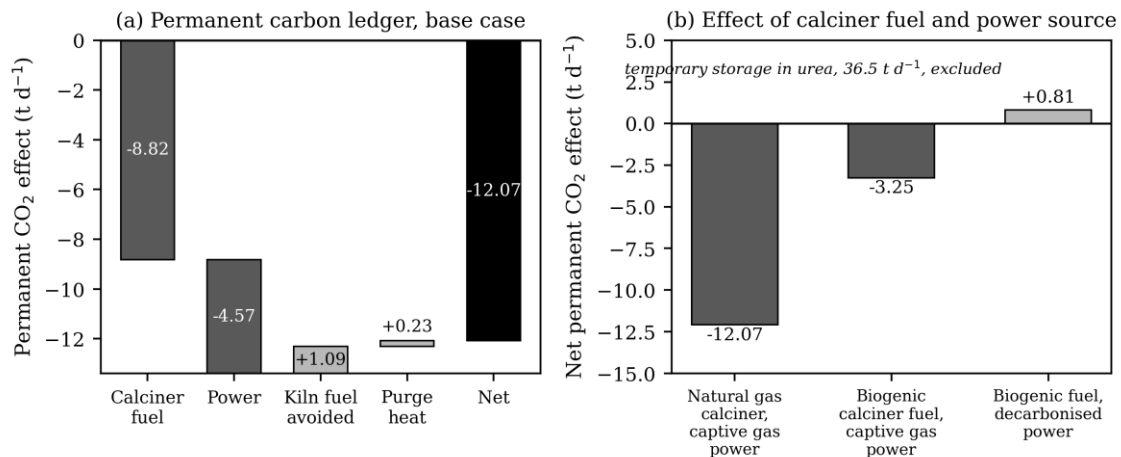


Figure 4. (a) Permanent carbon ledger of the complex at the base case, excluding the 36.5 t d⁻¹ temporarily stored in urea; (b) net permanent balance under three calciner-fuel and power-supply scenarios

Two comparisons place these figures in context. First, the counterfactual credit excluded from Eq. (13) ranges from zero to 36.5 t d⁻¹ depending on whether the displaced urea production would otherwise have drawn its carbon dioxide from a source that is now vented; the honest statement is that the permanent balance lies between -12.1 and +24.4 t d⁻¹ and that resolving it requires a defined counterfactual, not a further simulation. Second, the permanent debit is dominated by the calciner, which is precisely the unit whose fuel a cement host is best placed to substitute, since alternative-fuel firing is already established practice in the industry [17, 18, 19, 20, 21].

4 CONCLUSIONS

The treatment of the sorbent purge as a waste, inherited from power-plant studies, misstates the economics of calcium looping at a cement host and leads to a make-up ratio that is too low. The following conclusions are drawn. (1) Returning the purge to the clinker line reduces the marginal cost of sorbent make-up from US\$47.2 to US\$3.5 per tonne of limestone, a reduction of 93%, through raw-

meal displacement, avoided precalciner fuel, recovered sensible heat and reduced flue-gas capture duty. (2) Because make-up is effectively free, the make-up ratio should be raised from the conventional 0.115 to 0.30. Mean CaO carrying capacity rises from 0.172 to 0.315 and solids circulation falls by 35%, from 247 to 162 t d⁻¹, worth about US\$0.8 million of capture-island capital for an operating cost increase of US\$14 000 per year. (3) The host kiln can absorb about twenty times the purge generated, and the sulphur load is 1.3% of the clinker allowance, so purge disposal does not constrain make-up at a cement host. (4) The binding constraint is capture integrity. At fixed urea output, raising make-up displaces flue gas: the slipstream contracts from 1.17% to 0.88% of the kiln between ratios of 0.115 and 0.30, and reaches zero at 0.85, beyond which the complex captures nothing. (5) Consistent accounting requires transferred, temporarily stored and permanently avoided carbon to be distinguished. On this basis the complex is a net permanent emitter of 12.1 t d⁻¹ with a gas-fired calciner, reaching -3.3 t d⁻¹ on biogenic calciner fuel and +0.81 t d⁻¹ with decarbonised power, while temporarily storing 36.5 t d⁻¹. Experimental determination of the deactivation constant and residual conversion for Ashaka limestone, and a firing trial of the calciner on locally available agricultural residue, are recommended as the immediate next steps.

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NOMENCLATURE

b_{cap}	Credit for flue-gas capture duty avoided, US\$ t ⁻¹
b_{fuel}	Credit for kiln calcination fuel avoided, US\$ t ⁻¹
b_{meal}	Credit for raw meal displaced, US\$ t ⁻¹
b_{sens}	Credit for purge sensible heat recovered, US\$ t ⁻¹
C_{mk}	Marginal cost of sorbent make-up, US\$ t ⁻¹
C_p	Specific heat capacity of the purge, GJ t ⁻¹ K ⁻¹
E_c	Carbonator CO ₂ capture efficiency, -
e_{cap}	Specific energy of the capture section, GJ t ⁻¹ CO ₂
F_0	Sorbent make-up molar flow of calcium, kmol d ⁻¹
F_{CO_2}	Molar flow of CO ₂ to the carbonator, kmol d ⁻¹
F_R	Sorbent circulation molar flow of calcium, kmol d ⁻¹
ΔH_{calc}	Calcination enthalpy, 1.786 GJ t ⁻¹ CaCO ₃
k	Sorbent deactivation constant, -
LHV	Lower heating value of the calciner fuel, GJ t ⁻¹
M_i	Molar mass of species i , kg kmol ⁻¹
m_i	Mass flow rate of stream i , t d ⁻¹
N	Number of carbonation-calcination cycles, -
p_e, p_f	Price of electricity and of fuel, US\$ kWh ⁻¹ , US\$ GJ ⁻¹
r_N	Age-distribution weighting at cycle N , -
T_{cal}	Calciner outlet temperature, °C
W_e	Electrical energy demand of the complex, MWh d ⁻¹
$W_{\text{ASU}}, W_{\text{comp}}$	Specific work of air separation and of compression, kWh t ⁻¹
X_{ave}	Mean CaO carrying capacity of the circulating solids, -
X_N	CaO conversion at cycle N , -
X_r	Residual CaO conversion, -
y_{CO_2}	CO ₂ mass fraction in the flue gas, -

GREEK SYMBOLS

δ	CO ₂ entering the product stream per tonne of make-up, t t ⁻¹
ΔE_{perm}	Net permanent CO ₂ effect, t d ⁻¹
ϵ_e, ϵ_f	Emission factor of electricity and of fuel, t MWh ⁻¹ , t GJ ⁻¹
$\eta_{\text{cal}}, \eta_{\text{kiln}}$	Thermal efficiency of the CaL calciner and of the precalciner, -
η_p	Recovery of the purification and compression train, -
θ	Endogenous carbon fraction, -
ϕ	Flue-gas slipstream fraction, -

ABBREVIATIONS

ASU	Air separation unit
CaL	Calcium looping
CCU	Carbon capture and utilisation
CEMCAP	European project on CO ₂ capture from cement production
CLEANKER	Clean clinker production by calcium looping process