CONGRESO
Cemento & Concreto Verde 2050

Organiza: FICEM

Decarbonizing Clinker – Low $ & High Gains

- John Kline – Kline Consulting

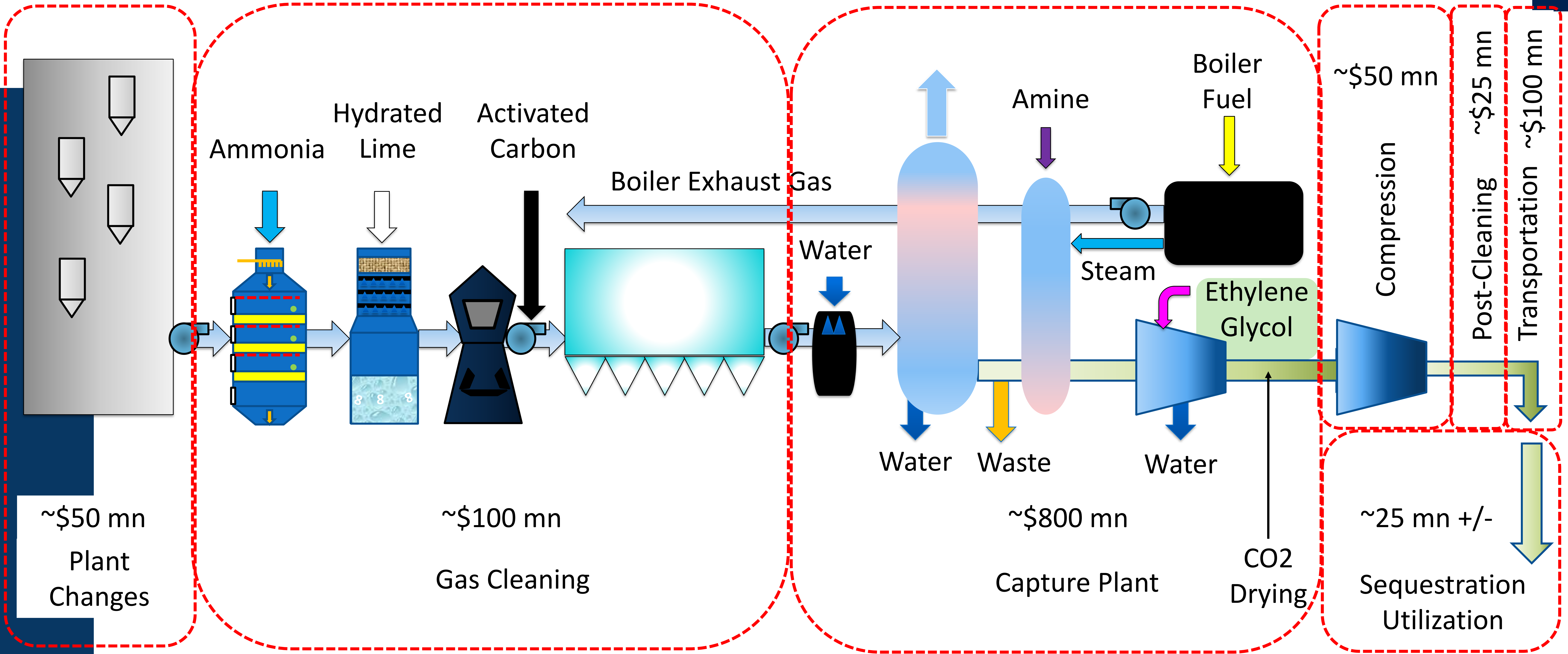
Agenda

- Cost of Capture
- CO_2 Capture Cost Drivers
- Kiln Feed Uniformity
- Raw Mix Composition
- Decarbonated Raw Materials
- Recycled Concrete Paste
- Clinker Composition
- Summary

Introduction

- Carbon capture is complex
  - Need to have a place for the CO_2 to go
  - Need to have a means of transportation
  - Need to purify the CO_2
  - Need to capture the CO_2
- Carbon capture is expensive
  - Equal to the cost of a new plant
    - ~Double the heat consumption
    - ~Double the power consumption

Carbon Capture Capex



Costs based on 1 mn ton CO_2 per year, amine capture plant in the US

How Much Would Your CCS Plant Cost ?

- Most CC Capex numbers you hear cover just the Carbon Capture plant
- Full project costs require a full project definition
  - Where is the CO2 going
  - How will it get there
  - What **pre-transport** treatment is required
    - Purity
    - Pressure
    - Temperature
  - Based on the above, what is the best technology for capture
  - What are the **pretreatment** (purity) requirements for the input gases
  - How does the cement plant have to be modified to supply flue gas and integrate the carbon capture plant
- Essentially, working backward from the use (sequestration / utilization) point to the capture technology selection and necessary plant modifications

How Much Would Your CCS Plant Cost ?

- Capex Calculation

- Cost to reproduce your plant as a green field today
- Divided by the annual tons of CO_2 emitted today

- Opex Calculation
- Today's Opex + $ 200 / ton CO_2 captured

- For a typical plant the CO_2 emitted ranges between 700 and 800 kgs per annual ton of clinker production

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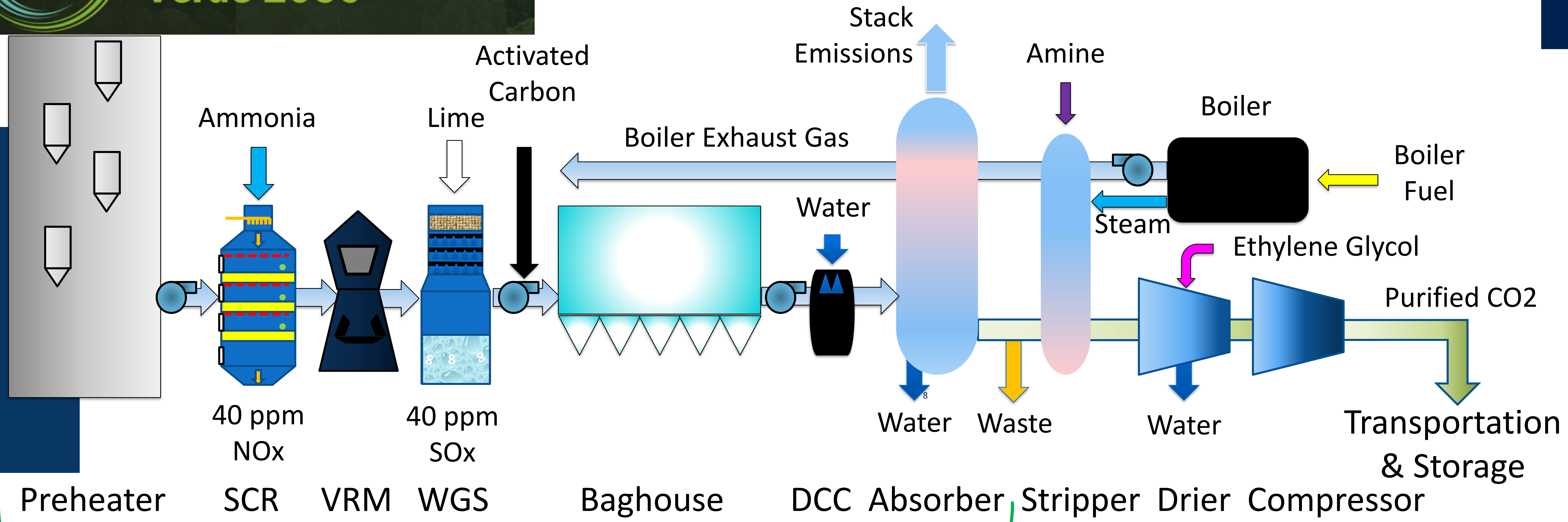
My Example

- 1 mn tonne per year CO_2 from clinker plant with greenfield cost \$500 mn

- CC Capex = \$500,000,000 = \$500 / annual ton of CO_2

- Current Opex = \$50 / t-clk
- CC Opex = Current Opex + \$200 = \$250 / t-clk
  - (Includes amortization)

Carbon Capture System
2 Main Cost Factors



1st Factor – Total Volume of Gas

f (Heat Consumption, Fuel Type, Elevation, & Inleakage)

25~34% of Costs

2nd Factor – Total Volume of CO2

f (CO2 from fuel, calcination, & boiler)

66~75% of Costs

$ Impact of Reducing CO2 Emissions (US$)

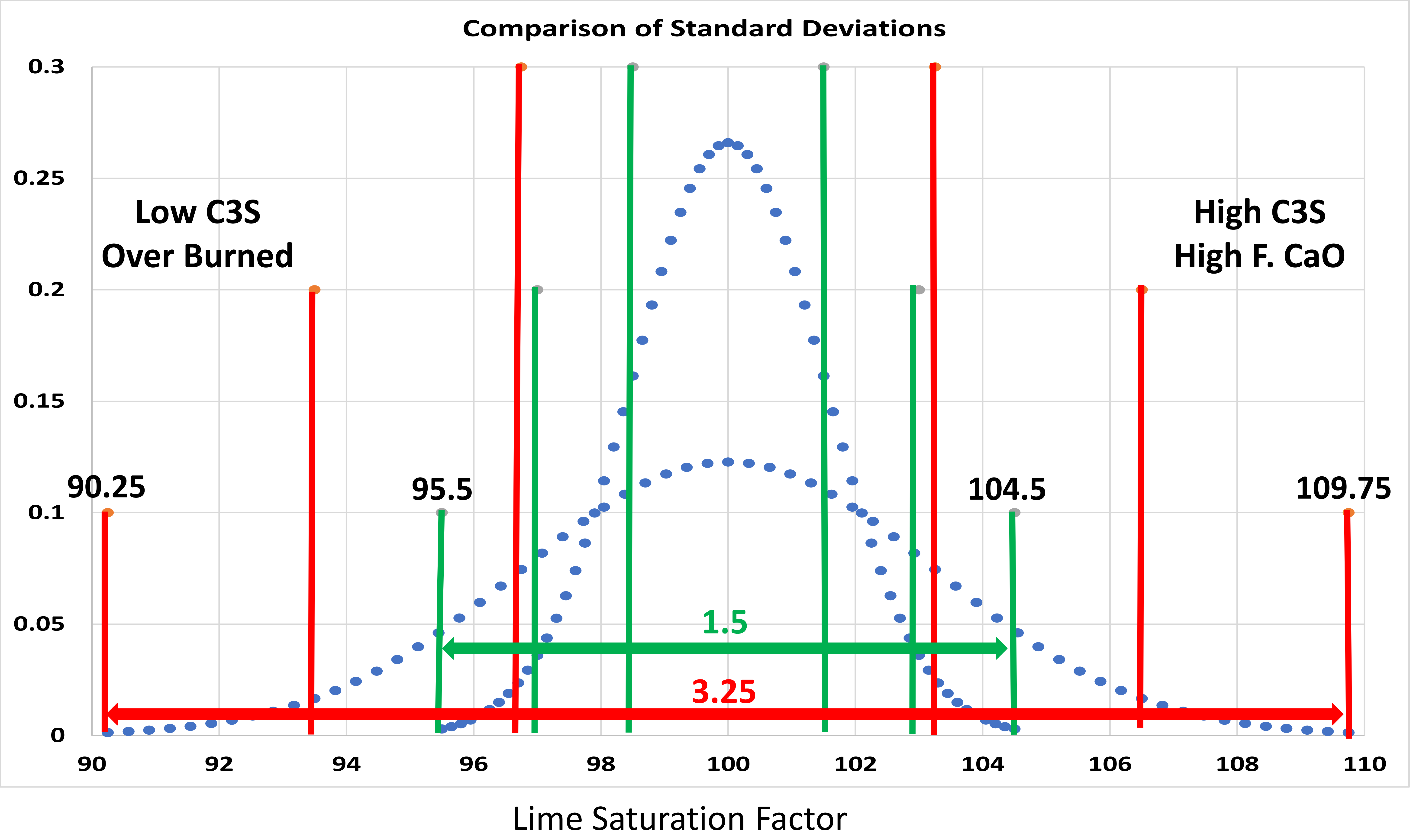
- US$1,000 in Capex per annual tonne of CO_2 emitted
- US$100 to US$400 in Opex per tonne of CO_2 captured and sequestered
- 10% reduction in CO_2 saves:
  - $100 million in CCUS Capex
  - $10~40 per ton-clk in CCUS Opex
- Based on McKinsey Cement Plant CO_2 Balance:
  - 10% reduction in raw material CO_2 = 47.9 kg-CO_2/t-clk
  - 10% reduction in fuel CO_2 = 31.9 kg-CO_2/t-clk
  - 10% reduction in power consumption CO_2 = 10.2 kg-CO_2/t-clk

Kiln Feed Uniformity

- Kiln feed uniformity or homogeneity is important for stable kiln operations and maintaining an optimum heat consumption
- A target uniformity can be expressed in several ways
- Here we will use the standard deviation of the lime saturation factor (LSF)
- Plant target LSF SD should be below 1.5
- The following charts demonstrate the difference between a LSF of standard deviation of 1.5 and 3.25

Standard Deviation – Target 100 LSF at 1.5 & 3.25 SD

Kiln goes Liquid



Kiln goes Raw

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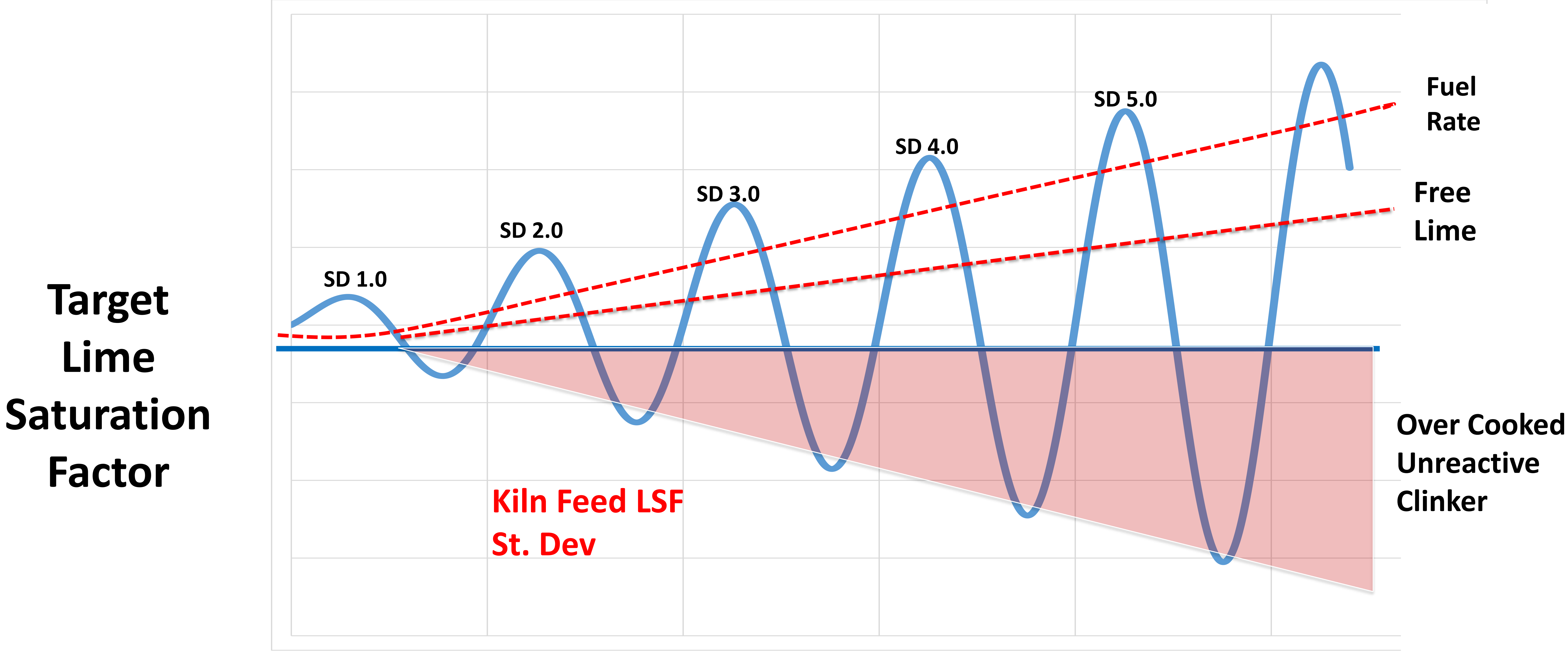
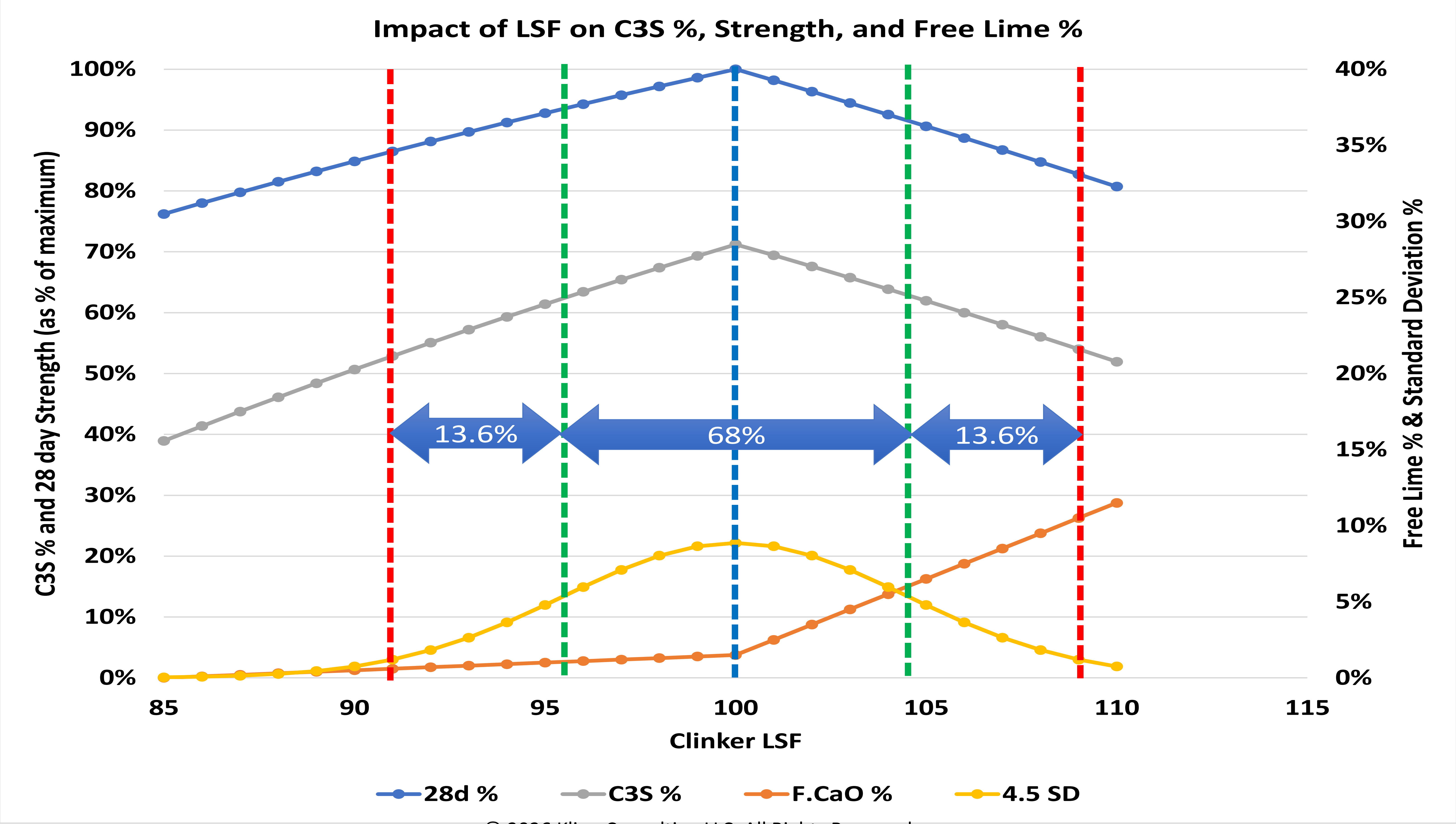
LSF Impact on Clinker



Increasing standard deviation of kiln feed chemistry from target (LSF)

LSF Impact on Clinker



Understanding the Spreadsheets

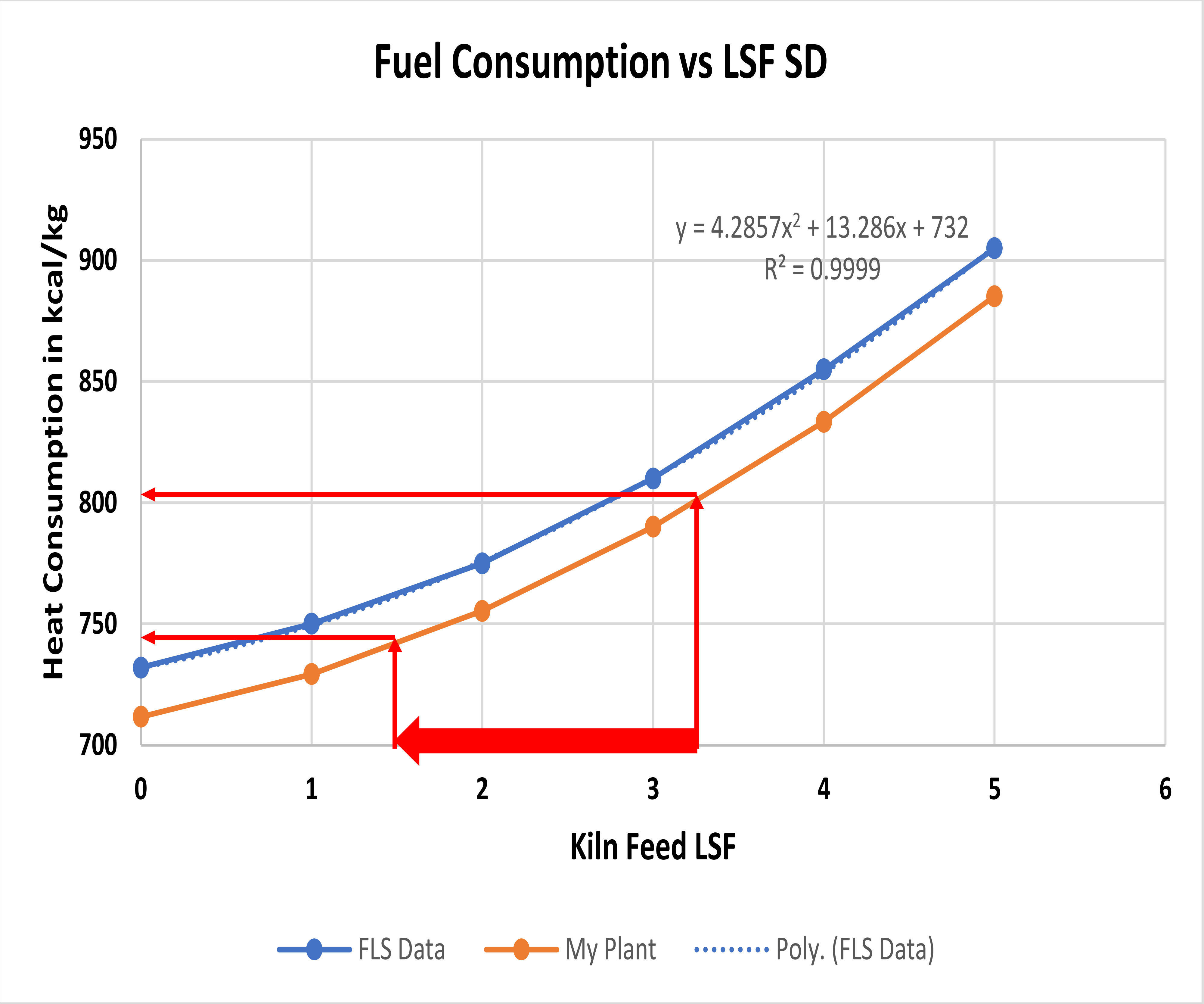
- Pale yellow indicates an input value
- Bright yellow indicates a constant value that should not be changed
- Green indicates a calculated value
- Blue cells are labels and unused cells

“Kiln Feed Uniformity” Spread Sheet

Impact of Kiln Feed Uniformity on Specific Heat Consumption

Fuel Savings Estimation - Improved Blending

Plant Name		My Plant	
Clinker Production Rate		1,000,000	tpy
Clinker Heat Consumption		800	kcal/kg
Fuel Cost		$9[illegible]	$/t-clk
Kiln Feed LSF Standard Deviation		[illegible]	
Target LSF Standard Deviation		[illegible]	
Fuel Carbon Factor		[illegible]	kg CO2/kCal
CO2 Target Price	$	40[illegible]	$/t-CO2
Improved Heat Consumption		741.0	kcal/kg
CO2 Reduction		22,302	t-CO2/year
Fuel Cost Savings	$	700,625	$/year
CO2 Cost Savings	$	892,080	$/year
Total Cost Savings	$	1.59	$/t-clk



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Chemical & Physical Impacts

Clinker Burnability Temperature for FCaO, plus Liquid

Inputs in Red Outputs in Green

BT	% A.I.R. +90u	Clk LSF
1454	5	96.0
% MgO	% Raw meal+150u	Clk A/F
2.0	5	2.2
% Clk FCaO	% Clk Fluorine	% Clinker SO3
1.2	0.1	1.61
% Clk Al2O3	% Clk Fe2O3	% Clk MgO
5.62	2.50	2.8
% Clk K2O	% Na2O	Clinker Sul/Alk
1.00	0.24	1.4
% TiO2	% LP Liquid at BT	% LP Liquid at 1338
0.4	25.8	18.5
	Kiln SHC kCal/kg	
	320.9	

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"Burning Zone Temperature" Spreadsheet

Keys:
% A.I.R. = Acid Insoluble Residue (Coarse Quartz)

Impacts:	Δ °C Factor
% A.I.R. +90u	= +21
LSF	= +10
RM + 150 u	= +3
A / F[1]	= +32
% F	= -250
F.CaO (>1.0)	= -23.3
F.CaO (< 1.0)	= +100
TiO2	= -180

[1]IF A / F > 1.5, then A / F used = actual
IF A/F < 1.5, then A / F used = (3 - Actual A / F)

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Decarbonated Raw Materials

Clinker Chemistry Design Impact on CO_2 Emissions

	Current	New	
Clinker Production Rate	1,000,000	1,000,000	Tonnes / Year
Specific Heat Consumption	3,420	3,097	kJ/kg-clk
Fuel CO2	0.092	0.092	kg-CO2/GJ
Fuel Costs	$ 3.00	$ 3.00	Monetary Units/GJ
CO2 Cost / tax	$ 75.00	$ 75.00	Monetary Units/tonne-CO2
Current Mix	%	%	
Raw Material Loss on Ignition	35.5%	32.1%	%
Raw Mix CaO from CaCO3	65.0%	60.0%	%
Raw Mix CaO from RCP	0.0%	5.0%	%
Raw Mix CaO Total	65.0%	65.0%	%
Raw Material	1,550,388	1,471,761	Tonnes / Year
Raw Mix CO2 (From CaCO3)	550,388	471,761	kg-CO2/kg-clk
Fuel CO2	0.3146	0.2849	kg-CO2/kg-clk
Total CO2	0.8650	0.7567	kg-CO2/kg-clk
Tons of CO2 per year	865,028	756,706	tonne-CO2/year
Reduction in CO2		108,321	tonne-CO2/year
Reduction in CO2		$ 8,124,093	Monetary Units per Year
Fuel Savings		322,766	GJ/year
Fuel Savings		$ 968,297	Monetary Units per Year
Total Savings		$ 9,092,391	Monetary Units per Year

Adding 5% of Lime (CaO):
Reduces heat consumption ~ 10%
Reduces CO_2 emissions ~ 12.5%
Plus CC Plant Capex & Opex Savings

Decarbonated Raw Materials Recycled Concrete Paste (RCP)

5% CaO instead of CaCO3
CO2 Reduction 110 kt / year
Fuel Savings ~10%
Plus, CCUS Opex and Capex Savings

Clinker Chemistry Design Impact on CO2 Emissions

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Supplemental Cementitious Material

CaO content of the RCP	25%	CaO in RCP
Tons per Year RCP	142,857	tonnes / year
CO2 Uptake	150	kgs-CO2/Tonne RCP
CO2 Uptake	21,429	Tonnes-CO2/Year
Substitution in Cement	20%	
Tonnes of Cement with SCM	714,286	tonnes cement per year
Clinker CO2 Produced	865	kgs-CO2/tonne Clk
Savings from Clinker Reduction	173	kgs-CO2/tonne Cem
Cement CO2 Savings	123,575	tonnes CO2 in Cement
Value of SCM CO2 Savings	$ 10,875,296	Monetary Units per Year

CO2 Reduction 21 kT-CO2/yr
CO2 Offsets 124 kT-CO2/yr
Limited CCUS Savings

Clinker Composition C3S / C2S

- C3S requires the most lime and therefore:
  - Has a higher CO_2 emission rate than C2S
  - Requires more heat for limestone calcination
  - But, provides more concrete strength
- Consider
  - Reducing the C3S content in the Clinker
  - Increase the cement fineness
- Rationale
  - The CO_2 from power is less than the CO_2 from Fuel
  - The fuel consumption savings may offset the power consumption increase

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Mix Design C3S / C2S Impact

C = CaO (Lime)

Fuel Calculation

	Current	New	
Clinker Production Rate	1,000,000	1,000,000	Tonnes / Year
Specific Heat Consumption	3,420	3,392	kJ/kg-clk
Fuel CO2	0.092	0.092	kg-CO2/GJ
Fuel Costs	$ 3.00	$ 3.00	Monetary Units/GJ
CO2 Cost / tax	$ 75.00	$ 75.00	Monetary Units/tonne-CO2
Current Mix	%	%	
C3S	65	61	%
C2S	20	21	%
C3A	9	10	%
C4AF	6	8	%
Total	100	100	%
Raw Mix CO2	0.5436	0.5378	kg-CO2/kg-clk
Fuel CO2	0.3146	0.3120	kg-CO2/kg-clk
Total CO2	0.8583	0.8498	kg-CO2/kg-clk
Tons of CO2 per year	858,270	849,771	tonne-CO2/year
Reduction in CO2		8,499	tonne-CO2/year
Reduction in CO2		$ 637,414	Monetary Units per Year
Fuel Savings		28,466	GJ/year
Fuel Savings		$ 85,397	Monetary Units per Year
Total Savings		$ 722,811	Monetary Units per Year

Power Calculation

Cement Clinker Factor	0.700	t-clk/t-cem
Cement Grinding Power	40	kWh/t-cem
Power Costs	$60	Monetary Units/MWh
Power Carbon Factor	0.070	kgCO2/kWh
Blaine Power Factor	1.3	Blaine Increase Exponent
Approximate Strength Change	6.2%	%
Blaine Increase	9.1%	%
Power Increase	12.0%	%
Power Increase	4.82	kWh/t-cem
Power Increase Cost	$ 412,928	$/year
CO2 Increase	481.7	t-CO2/yr
Increase in CO2	$ 36,131	Monetary Units/t-cem
Net Change in CO2	8,017.1	t-CO2/yr
Net Profit / Loss	$ 273,752	Monetary Units per Year

C3S Change 65 to 61
Clinker Fuel Consumption Reduction 1%
Clinker CO2 emissions reduction 1%
Power increase (to recoup mortar strength) 12%
CCUS Opex & Capex Reduction 1%

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Adding It All Up !

Clinker Carbon Reduction Summary

Internal Carbon Price ($/ton CO2)	$ 40.00		$/t-CO2
Current Cost of Clinker	$ 50.00		$/t-clk
Capex Cost of Equivalent GF Plant	$ 600.00		$/Annual Ton of Clk
Opex Cost of CC Plant	$ 200.00		$/t-clk
	Current	Future	
Clinker Production Rate	5000	5000	mtpd
Utilization Factor	90%	90%	%
Heat Consumption	800	750	kcal/kg
Main Fuel Carbon Factor	0.4	0.3	kgCO2/KCal
Alternative Fuel % (Excluding Biomass	10%	15%	%
Alternative Fuel Carbon Factor	0.35	0.3	kgCO2/KCal
Biomass Fuel %	5%	10%	%
Fuel Costs	$ 4.00	$ 4.00	$ / GJ
Raw Material LOI	35.50%	33%	%
Clinker LOI	0.00%	0.00%	%
Alternative Raw Materials %	10%	15%	%
Clinker Factor	85%	75%	%
Power Consumption	140	135	kWh/mt-cem
Power Costs	$75	$75	$ / MWh
Percent Green Energy	100%	90%	
Power Carbon Factor	0.700	0.680	kg-CO2/kWh
Diesel Consumption	1,000,000	800,000	gal/yr
Gasoline Consumption	120,000	100,000	gal/yr

	Scope 1 Stack	Savings per Year	$ 10,206,514
	Scope 1 Misc Fuel	Savings per Year	$ 89,413
Green Field	Scope 2	Savings per Year	$ 337,312
	CCUS Capex	Savings	$ 255,162,841
	CCUS Opex	Savings per Year	$ 66,209,659

	Current Production mt/yr	Future Production mt/yr	Difference
Clinker	1,642,500	1,642,500	-
Cement	1,932,353	2,190,000	257,647
	Current kg CO2 / yr	Future kg CO2 / yr	Difference
Fuel	492,750,000	332,606,250	160,143,750
Raw Material	904,011,628	808,992,537	95,019,091

	Current kg CO2 / ton	Future kg CO2 / ton	Difference
Stack	723	521	202

	Current kg CO2 / yr	Future kg CO2 / yr	Difference
Power	189,370,588	180,937,800	8,432,788
Diesel	10,160,520	8,128,416	2,032,104
Gasoline	1,219,262	1,016,052	203,210

Millions of Dollars

CCUS Plant	Current Capex	Future Capex	Difference
CCUS Plant	1,397	1,142	255

CCUS Plant	Future Opex	Future Opex	Difference
CCUS Plant	195	154	40

Summary & Conclusions

- Small investments in plant improvements and recipe changes can:
  - Reduce clinker specific heat consumption
  - Reduce clinker specific CO2 emissions
- These reductions not only cut plant costs & emissions today
- They reduce the future Opex & Capex cost of Carbon Capture Technologies
- Reductions as low as 1% - add up to millions of dollars saved

CCUS is the Light at the End of Tunnel !

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