COALITION FOR SUSTAINABLE CEMENT MANUFACTURING & ENVIRONMENT
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Comments of the CSCME on Proposed Revised Guidelines for AB 1613 Qualification
CEC-200-2009-016-CMF-REV1
Docket Number 08-WHCE-1

The Coalition for Sustainable Cement Manufacturing and Environment (CSCME) has previously provided comments regarding the qualification under AB 1613 of bottoming cycle combined heat and power (CHP) facilities. CSCME strongly supports the proposed revision to the bottoming cycle guideline to reduce the minimum electrical efficiency requirement to 60% from the current 62%.

The statutory requirement of 60% electrical efficiency is already greater than existing gas-fired powerplants and represents the highest efficiency requirement for bottoming cycle CHP of which we are aware. As far as the cement industry is concerned, reducing the electrical efficiency standard from 62% to 60% will result in increased electrical output and fewer purchases from utilities or other load-serving entities. At the same time, based on calculations of the application of bottoming cycle CHP with limited supplemental firing in the cement industry, the GHG emissions at a 60% electrical efficiency will be substantially below those of even the most efficient combined cycle generating plant. Calpine has touted its Russell City Energy Center has having GHG emissions 25% below the EPS. This amounts to 825 lb/MWh. The attached calculations for bottoming cycle CHP with supplemental firing for a cement plant show GHG emissions at 666 lb/MWh at 60% electrical efficiency. Thus, at 60% electrical efficiency, the GHG emissions are significantly lower than for a "state of the art" gas-fired combined cycle plant. Increased output with better GHG emissions justified the proposed revision in the standard to 60% electrical efficiency for bottoming cycle CHP with supplemental firing. We urge the Commission to make the proposed revision.

	Moderate Efficiency System				High Efficiency System			
FERC Efficiency	Maximum Supplementary Firing Ratio	Net Electricity Output (MW)	Emission Factor (lb CO_2/MW-hr)		Maximum Supplementary Firing Ratio	Net Electricity Output (MW)	Emission Factor (lb CO_2/MW-hr)	Comments
60%	0.30	9.9	663		0.52	16.9	666	Optimistic Case
60%	0.30	9.8	666		0.51	16.5	666	Less Optimistic Case
62%	0.29	9.7	643		0.49	16.4	644	Optimistic Case
62%	0.29	9.6	645		0.48	16.1	643	Less Optimistic Case

Emission Factor for Natural Gas Combustion 117 lb CO_2/MMBTU

FERC Efficiency Achieved by Kiln CHP Unit

60 Percent Optimistic Case

Moderate Efficiency Unit

Supplementary Firing Ratio	0.30	
Net Electrcity Output	10	MW
Supplementary Firing	56	MMBTU/hr
Emission Factor	663	lb CO_2/MW-hr

High Efficiency Unit

Supplementary Firing Ratio	0.52	
Net Electrcity Output	17	MW
Supplementary Firing	96	MMBTU/hr
Emission Factor	666	lb CO_2/MW-hr

60 Percent Less Optimistic Case

Moderate Efficiency Unit

Supplementary Firing Ratio	0.30	
Net Electrcity Output	10	MW
Supplementary Firing	56	MMBTU/hr
Emission Factor	666	lb CO_2/MW-hr

High Efficiency Unit

Supplementary Firing Ratio	0.51	
Net Electrcity Output	17	MW
Supplementary Firing	94	MMBTU/hr
Emission Factor	666	lb CO_2/MW-hr

62 Percent Optimistic Case

Moderate Efficiency Unit

Supplementary Firing Ratio	0.29	
Net Electrcity Output	10	MW
Supplementary Firing	54	MMBTU/hr
Emission Factor	643	lb CO_2/MW-hr

High Efficiency Unit

Supplementary Firing Ratio	0.49	
Net Electrcity Output	16	MW
Supplementary Firing	91	MMBTU/hr
Emission Factor	644	lb CO_2/MW-hr

62 Percent Less Optimistic Case

Moderate Efficiency Unit

Supplementary Firing Ratio	0.29	
Net Electrcity Output	10	MW
Supplementary Firing	53	MMBTU/hr
Emission Factor	645	lb CO_2/MW-hr

High Efficiency Unit

Supplementary Firing Ratio	0.48	
Net Electrcity Output	16	MW
Supplementary Firing	89	MMBTU/hr
Emission Factor	643	lb CO_2/MW-hr

Tangible Example - Bottoming-Cycle Cogeneration on a 5,000 ton clinker/day Kiln
Case 4p: 62% FERC Efficiency, High Efficiency System

Hot Exhaust Stream

Clinker Capacity	5,000	ton/d
Carbon Dioxide Molar Flow	61,776	mol/min
Fuel CO_2 Molar Flow	24,249	mol/min
Nitrogen Molar Flow	131,444	mol/min
Oxygen Molar Flow	7,000	mol/min
Water Vapor Molar Flow	34,314	mol/min
Volumetric Flow Rate	169,797	SCFM (dry)
Stream Temperature	800	F
Stream Temperature	427	C
Stream Temperature	700	K
Enthalpy Flow	3,241	MJ/min
Enthalpy Flow	184	MMBTU/hr

Heat Capacities

Stream	Nitrogen Spc Heat Content J/mol	Carbon Dioxide Spc Heat Content J/mol	Water Vapor Spc Heat Content J/mol	Oxygen Spc Heat Content J/mol
Hot Exhaust	11991	17679	14163	12403
Inlet to HRSG	16491	24781	19679	17119
Exhaust from HRSG	4763	6657	5538	4876
	Constants	Constants	Constants	Constants
	28.6	44.2	30.5	30.0
	0.00377	0.00879	0.01029	0.00418
	-50208	-861904	0	-167360

Supplemental Firing Input

Enthalpy Flow	88.5	MMBTU/hr
Supplementary Firing Ratio	0.48	
Enthalpy Flow	1,555	MJ/min
Enthalpy of Combustion for Methane	891	kJ/mol
Methane Required	1,745	mol/min
Carbon Dioxide Released	1,745	mol/min
Water Vapor Released	3,491	mol/min
Oxygen:Methane Ratio	2	mol O_2/mol methane
Stochiometric Oxygen Required	3,491	mol/min
Fraction Required Oxygen from Hot Exh	10%	
Oxygen from Supplemental Air	3,142	mol/min
Nitrogen Molar Flow @Stoichometry	11,891	mol/min

Hot Gas Into the Heat Recovery Steam Generator

Carbon Dioxide Molar Flow	63,521	mol/min	
Nitrogen Molar Flow	143,335	mol/min	
Oxygen Molar Flow	6,651	mol/min	
Water Vapor Molar Flow	37,805	mol/min	
Enthalpy Flow	4,796	MJ/min	4796 Comparator
Stream Temperature	843.2	K	
Stream Temperature	570	C	
Stream Temperature	1,058	F	

Gas Stream Leaving the Heat Recovery Steam Generator

Stream Temperature	375	F
Stream Temperature	191	C
Stream Temperature	464	K
Enthalpy Flow	1347	MJ/min
Enthalpy Lost from the Hot Gas Stream	3,449	MJ/min
Enthalpy Lost to the Environment	5%	
Enthalpy Lost to the Environment	172	MJ/min

Heat Recovery Steam Generator

Steam Enthalpy	3,277	MJ/min
Steam Enthalpy	186	MMBTU/hr
HRSG Efficiency	68%	
Assume HRSG output is superheated steam at 2000 psia & 850F		
Steam Enthalpy Content	1,371	BTU/lb
Steam Output	135,985	lb/hr
Steam Entropy Content	1.49	BTU/lb-R

Mechanical Work Production

Isentropic Expansion to 1 psia (100F)		
Entropy of Saturated Water @1 psia	0.13	BTU/lb-R
Entropy of Saturated Steam @1psia	1.98	BTU/lb-R
Steam Quality	0.73	
Enthalpy of Saturated Water @ 1 psia	69.7	BTU/lb
Enthalpy of Saturated Steam @1 psia	1,105	BTU/lb
Steam Enthalpy Content Post-Expansion	829	BTU/lb
Expansion Efficiency	90%	
Steam Enthalpy Content Post-Expansion	883	BTU/lb
Work Extracted	488	BTU/lb
Efficiency of Steam to Work	36%	
Work Output	66	MMBTU/hr
Efficiency of Work to Electricity	0.90	
Efficiency of Steam to Electricity	0.32	
Electricity Output	60	MMBTU/hr
Ancillary Loads	8%	
Net Electricity Output	55	MMBTU/hr
Net Electricity Output	16	MW-hr/hr
Overall Enthalpy to Net Electricity Efficier	20.1%	

Performance Metric Calculation

FERC Efficiency	62.08%	

volume conversion	0.0283	m^3/ft^3
Standard Molar Volume (1 atm, 20C)	0.024	m^3/mol
Cooling Water Temperature	86	F
Cooling Water Temperature	30	C
Cooling Water Temperature	303	K
energy conversion	1,054.4	J/BTU
energy conversion	60	J/W-hr
mass conversion	0.453	kg/lb
Molecular Weight Carbon Dioxide	0.04401	kg/mol
Oxygen Content of Air	20.9%	
Nitrogen Content of Air	79.1%	
energy conversion	3.413	BTU/W-hr

Tangible Example - Bottoming-Cycle Cogeneration on a 5,000 ton clinker/day Kiln
Case 4o: 62% FERC Efficiency, High Efficiency System

Hot Exhaust Stream

Clinker Capacity	5,000	ton/d
Carbon Dioxide Molar Flow	61,776	mol/min
Fuel CO_2 Molar Flow	24,249	mol/min
Nitrogen Molar Flow	131,444	mol/min
Oxygen Molar Flow	7,000	mol/min
Water Vapor Molar Flow	34,314	mol/min
Volumetric Flow Rate	169,797	SCFM (dry)
Stream Temperature	800	F
Stream Temperature	427	C
Stream Temperature	700	K
Enthalpy Flow	3,241	MJ/min
Enthalpy Flow	184	MMBTU/hr

Heat Capacities

Stream	Nitrogen Spc Heat Content J/mol	Carbon Dioxide Spc Heat Content J/mol	Water Vapor Spc Heat Content J/mol	Oxygen Spc Heat Content J/mol
Hot Exhaust	11991	17679	14163	12403
Inlet to HRSG	16586	24932	19797	17218
Exhaust from HRSG	4763	6657	5538	4876
	Constants	Constants	Constants	Constants
	28.6	44.2	30.5	30.0
	0.00377	0.00879	0.01029	0.00418
	-50208	-861904	0	-167360

Supplemental Firing Input

Enthalpy Flow	90.5	MMBTU/hr
Supplementary Firing Ratio	0.49	
Enthalpy Flow	1,590	MJ/min
Enthalpy of Combustion for Methane	891	kJ/mol
Methane Required	1,785	mol/min
Carbon Dioxide Released	1,785	mol/min
Water Vapor Released	3,570	mol/min
Oxygen:Methane Ratio	2	mol O_2/mol methane
Stochiometric Oxygen Required	3,570	mol/min
Fraction Required Oxygen from Hot Exh	10%	
Oxygen from Supplemental Air	3,213	mol/min
Nitrogen Molar Flow @Stoichometry	12,160	mol/min

Hot Gas Into the Heat Recovery Steam Generator

Carbon Dioxide Molar Flow	63,561	mol/min	
Nitrogen Molar Flow	143,603	mol/min	
Oxygen Molar Flow	6,643	mol/min	
Water Vapor Molar Flow	37,884	mol/min	
Enthalpy Flow	4,831	MJ/min	4831 Comparator
Stream Temperature	846.2	K	
Stream Temperature	573	C	
Stream Temperature	1,063	F	

Gas Stream Leaving the Heat Recovery Steam Generator

Stream Temperature	375	F
Stream Temperature	191	C
Stream Temperature	464	K
Enthalpy Flow	1349	MJ/min
Enthalpy Lost from the Hot Gas Stream	3,482	MJ/min
Enthalpy Lost to the Environment	5%	
Enthalpy Lost to the Environment	174	MJ/min

Heat Recovery Steam Generator

Steam Enthalpy	3,308	MJ/min
Steam Enthalpy	188	MMBTU/hr
HRSG Efficiency	68%	
Assume HRSG output is superheated steam at 2000 psia & 900F		
Steam Enthalpy Content	1,407	BTU/lb
Steam Output	133,772	lb/hr
Steam Entropy Content	1.51	BTU/lb-R

Mechanical Work Production

Isentropic Expansion to 1 psia (100F)		
Entropy of Saturated Water @1 psia	0.13	BTU/lb-R
Entropy of Saturated Steam @1psia	1.98	BTU/lb-R
Steam Quality	0.75	
Enthalpy of Saturated Water @ 1 psia	69.7	BTU/lb
Enthalpy of Saturated Steam @1 psia	1,105	BTU/lb
Steam Enthalpy Content Post-Expansion	844	BTU/lb
Expansion Efficiency	90%	
Steam Enthalpy Content Post-Expansion	900	BTU/lb
Work Extracted	507	BTU/lb
Efficiency of Steam to Work	36%	
Work Output	68	MMBTU/hr
Efficiency of Work to Electricity	0.90	
Efficiency of Steam to Electricity	0.32	
Electricity Output	61	MMBTU/hr
Ancillary Loads	8%	
Net Electricity Output	56	MMBTU/hr
Net Electricity Output	16	MW-hr/hr
Overall Enthalpy to Net Electricity Efficier	20.4%	

Performance Metric Calculation

FERC Efficiency	62.02%	

volume conversion	0.0283	m^3/ft^3
Standard Molar Volume (1 atm, 20C)	0.024	m^3/mol
Cooling Water Temperature	86	F
Cooling Water Temperature	30	C
Cooling Water Temperature	303	K
energy conversion	1,054.4	J/BTU
energy conversion	60	J/W-hr
mass conversion	0.453	kg/lb
Molecular Weight Carbon Dioxide	0.04401	kg/mol
Oxygen Content of Air	20.9%	
Nitrogen Content of Air	79.1%	
energy conversion	3.413	BTU/W-hr

Tangible Example - Bottoming-Cycle Cogeneration on a 5,000 ton clinker/day Kiln
Case 3p: 62% FERC Efficiency, Moderate Efficiency System

Hot Exhaust Stream

Clinker Capacity	5,000	ton/d
Carbon Dioxide Molar Flow	61,776	mol/min
Fuel CO_2 Molar Flow	24,249	mol/min
Nitrogen Molar Flow	131,444	mol/min
Oxygen Molar Flow	7,000	mol/min
Water Vapor Molar Flow	34,314	mol/min
Volumetric Flow Rate	169,797	SCFM (dry)
Stream Temperature	800	F
Stream Temperature	427	C
Stream Temperature	700	K
Enthalpy Flow	3,241	MJ/min
Enthalpy Flow	184	MMBTU/hr

Heat Capacities

Stream	Nitrogen Spc Heat Content J/mol	Carbon Dioxide Spc Heat Content J/mol	Water Vapor Spc Heat Content J/mol	Oxygen Spc Heat Content J/mol
Hot Exhaust	11991	17679	14163	12403
Inlet to HRSG	14761	22035	17545	15304
Exhaust from HRSG	5181	7275	6029	5309
	Constants	Constants	Constants	Constants
	28.6	44.2	30.5	30.0
	0.00377	0.00879	0.01029	0.00418
	-50208	-861904	0	-167360

Supplemental Firing Input

Enthalpy Flow	53	MMBTU/hr
Supplementary Firing Ratio	0.29	
Enthalpy Flow	931	MJ/min
Enthalpy of Combustion for Methane	891	kJ/mol
Methane Required	1,045	mol/min
Carbon Dioxide Released	1,045	mol/min
Water Vapor Released	2,091	mol/min
Oxygen:Methane Ratio	2	mol O_2/mol methane
Stochiometric Oxygen Required	2,091	mol/min
Fraction Required Oxygen from Hot Exh	10%	
Oxygen from Supplemental Air	1,882	mol/min
Nitrogen Molar Flow @Stoichometry	7,121	mol/min

Hot Gas Into the Heat Recovery Steam Generator

Carbon Dioxide Molar Flow	62,821	mol/min
Nitrogen Molar Flow	138,565	mol/min
Oxygen Molar Flow	6,791	mol/min
Water Vapor Molar Flow	36,405	mol/min
Enthalpy Flow	4,172	MJ/min
Stream Temperature	788.4	K
Stream Temperature	515	C
Stream Temperature	959	F

4172 Comparator

Gas Stream Leaving the Heat Recovery Steam Generator

Stream Temperature	400	F
Stream Temperature	204	C
Stream Temperature	478	K
Enthalpy Flow	1430	MJ/min
Enthalpy Lost from the Hot Gas Stream	2,742	MJ/min
Enthalpy Lost to the Environment	5%	
Enthalpy Lost to the Environment	137	MJ/min

Heat Recovery Steam Generator

Steam Enthalpy	2,605	MJ/min
Steam Enthalpy	148	MMBTU/hr
HRSG Efficiency	62%	
Assume HRSG output is superheated steam at 1200 psia & 660F		
Steam Enthalpy Content	1,279	BTU/lb
Steam Output	115,877	lb/hr
Steam Entropy Content	1.46	BTU/lb-R

Mechanical Work Production

Isentropic Expansion to 1 psia (100F)		
Entropy of Saturated Water @1 psia	0.13	BTU/lb-R
Entropy of Saturated Steam @1psia	1.98	BTU/lb-R
Steam Quality	0.72	
Enthalpy of Saturated Water @ 1 psia	69.7	BTU/lb
Enthalpy of Saturated Steam @1 psia	1,105	BTU/lb
Steam Enthalpy Content Post-Expansion	813	BTU/lb
Expansion Efficiency	75%	
Steam Enthalpy Content Post-Expansion	929	BTU/lb
Work Extracted	350	BTU/lb
Efficiency of Steam to Work	27%	
Work Output	41	MMBTU/hr
Efficiency of Work to Electricity	0.90	
Efficiency of Steam to Electricity	0.25	
Electricity Output	36	MMBTU/hr
Ancillary Loads	10%	
Net Electricity Output	33	MMBTU/hr
Net Electricity Output	10	MW-hr/hr
Overall Enthalpy to Net Electricity Efficier	13.8%	

Performance Metric Calculation

FERC Efficiency	61.93%	

volume conversion	0.0283	m^3/ft^3
Standard Molar Volume (1 atm, 20C)	0.024	m^3/mol
Cooling Water Temperature	86	F
Cooling Water Temperature	30	C
Cooling Water Temperature	303	K
energy conversion	1,054.4	J/BTU
energy conversion	60	J/W-hr
mass conversion	0.453	kg/lb
Molecular Weight Carbon Dioxide	0.04401	kg/mol
Oxygen Content of Air	20.9%	
Nitrogen Content of Air	79.1%	
energy conversion	3.413	BTU/W-hr

Tangible Example - Bottoming-Cycle Cogeneration on a 5,000 ton clinker/day Kiln
Case 3o: 62% FERC Efficiency, Moderate Efficiency System

Hot Exhaust Stream

Clinker Capacity	5,000	ton/d
Carbon Dioxide Molar Flow	61,776	mol/min
Fuel CO_2 Molar Flow	24,249	mol/min
Nitrogen Molar Flow	131,444	mol/min
Oxygen Molar Flow	7,000	mol/min
Water Vapor Molar Flow	34,314	mol/min
Volumetric Flow Rate	169,797	SCFM (dry)
Stream Temperature	800	F
Stream Temperature	427	C
Stream Temperature	700	K
Enthalpy Flow	3,241	MJ/min
Enthalpy Flow	184	MMBTU/hr

Heat Capacities

Stream	Nitrogen Spc Heat Content J/mol	Carbon Dioxide Spc Heat Content J/mol	Water Vapor Spc Heat Content J/mol	Oxygen Spc Heat Content J/mol
Hot Exhaust	11991	17679	14163	12403
Inlet to HRSG	14786	22075	17576	15330
Exhaust from HRSG	5181	7275	6029	5309
	Constants	Constants	Constants	Constants
	28.6	44.2	30.5	30.0
	0.00377	0.00879	0.01029	0.00418
	-50208	-861904	0	-167360

Supplemental Firing Input

Enthalpy Flow	53.5	MMBTU/hr
Supplementary Firing Ratio	0.29	
Enthalpy Flow	940	MJ/min
Enthalpy of Combustion for Methane	891	kJ/mol
Methane Required	1,055	mol/min
Carbon Dioxide Released	1,055	mol/min
Water Vapor Released	2,110	mol/min
Oxygen:Methane Ratio	2	mol O_2/mol methane
Stochiometric Oxygen Required	2,110	mol/min
Fraction Required Oxygen from Hot Exh	10%	
Oxygen from Supplemental Air	1,899	mol/min
Nitrogen Molar Flow @Stoichometry	7,188	mol/min

Hot Gas Into the Heat Recovery Steam Generator

Carbon Dioxide Molar Flow	62,831	mol/min	
Nitrogen Molar Flow	138,632	mol/min	
Oxygen Molar Flow	6,789	mol/min	
Water Vapor Molar Flow	36,424	mol/min	
Enthalpy Flow	4,181	MJ/min	4181 Comparator
Stream Temperature	789.2	K	
Stream Temperature	516	C	
Stream Temperature	961	F	

Gas Stream Leaving the Heat Recovery Steam Generator

Stream Temperature	400	F
Stream Temperature	204	C
Stream Temperature	478	K
Enthalpy Flow	1431	MJ/min
Enthalpy Lost from the Hot Gas Stream	2,750	MJ/min
Enthalpy Lost to the Environment	5%	
Enthalpy Lost to the Environment	138	MJ/min

Heat Recovery Steam Generator

Steam Enthalpy	2,613	MJ/min
Steam Enthalpy	149	MMBTU/hr
HRSG Efficiency	62%	
Assume HRSG output is superheated steam at 1200 psia & 700F		
Steam Enthalpy Content	1,310	BTU/lb
Steam Output	113,467	lb/hr
Steam Entropy Content	1.48	BTU/lb-R

Mechanical Work Production

Isentropic Expansion to 1 psia (100F)		
Entropy of Saturated Water @1 psia	0.13	BTU/lb-R
Entropy of Saturated Steam @1psia	1.98	BTU/lb-R
Steam Quality	0.73	
Enthalpy of Saturated Water @ 1 psia	69.7	BTU/lb
Enthalpy of Saturated Steam @1 psia	1,105	BTU/lb
Steam Enthalpy Content Post-Expansion	828	BTU/lb
Expansion Efficiency	75%	
Steam Enthalpy Content Post-Expansion	949	BTU/lb
Work Extracted	362	BTU/lb
Efficiency of Steam to Work	28%	
Work Output	41	MMBTU/hr
Efficiency of Work to Electricity	0.90	
Efficiency of Steam to Electricity	0.25	
Electricity Output	37	MMBTU/hr
Ancillary Loads	10%	
Net Electricity Output	33	MMBTU/hr
Net Electricity Output	10	MW-hr/hr
Overall Enthalpy to Net Electricity Efficier	14.0%	

Performance Metric Calculation

FERC Efficiency	62.11%	

volume conversion	0.0283	m^3/ft^3
Standard Molar Volume (1 atm, 20C)	0.024	m^3/mol
Cooling Water Temperature	86	F
Cooling Water Temperature	30	C
Cooling Water Temperature	303	K
energy conversion	1,054.4	J/BTU
energy conversion	60	J/W-hr
mass conversion	0.453	kg/lb
Molecular Weight Carbon Dioxide	0.04401	kg/mol
Oxygen Content of Air	20.9%	
Nitrogen Content of Air	79.1%	
energy conversion	3.413	BTU/W-hr

Tangible Example - Bottoming-Cycle Cogeneration on a 5,000 ton clinker/day Kiln
Case 2p: 60% FERC Efficiency, High Efficiency System, Less Optimistic

Hot Exhaust Stream

Clinker Capacity	5,000	ton/d
Carbon Dioxide Molar Flow	61,776	mol/min
Fuel CO_2 Molar Flow	24,249	mol/min
Nitrogen Molar Flow	131,444	mol/min
Oxygen Molar Flow	7,000	mol/min
Water Vapor Molar Flow	34,314	mol/min
Volumetric Flow Rate	169,797	SCFM (dry)
Stream Temperature	800	F
Stream Temperature	427	C
Stream Temperature	700	K
Enthalpy Flow	3,241	MJ/min
Enthalpy Flow	184	MMBTU/hr

Heat Capacities

Stream	Nitrogen Spc Heat Content J/mol	Carbon Dioxide Spc Heat Content J/mol	Water Vapor Spc Heat Content J/mol	Oxygen Spc Heat Content J/mol
Hot Exhaust	11991	17679	14163	12403
Inlet to HRSG	16846	25346	20119	17491
Exhaust from HRSG	4763	6657	5538	4876
	Constants	Constants	Constants	Constants
	28.6	44.2	30.5	30.0
	0.00377	0.00879	0.01029	0.00418
	-50208	-861904	0	-167360

Supplemental Firing Input

Enthalpy Flow	94	MMBTU/hr
Supplementary Firing Ratio	0.51	
Enthalpy Flow	1,652	MJ/min
Enthalpy of Combustion for Methane	891	kJ/mol
Methane Required	1,854	mol/min
Carbon Dioxide Released	1,854	mol/min
Water Vapor Released	3,708	mol/min
Oxygen:Methane Ratio	2	mol O_2/mol methane
Stochiometric Oxygen Required	3,708	mol/min
Fraction Required Oxygen from Hot Exh	10%	
Oxygen from Supplemental Air	3,337	mol/min
Nitrogen Molar Flow @Stoichometry	12,630	mol/min

Hot Gas Into the Heat Recovery Steam Generator

Carbon Dioxide Molar Flow	63,630	mol/min	
Nitrogen Molar Flow	144,074	mol/min	
Oxygen Molar Flow	6,629	mol/min	
Water Vapor Molar Flow	38,022	mol/min	
Enthalpy Flow	4,893	MJ/min	4921 Comparator
Stream Temperature	854.4	K	
Stream Temperature	581	C	
Stream Temperature	1,078	F	

Gas Stream Leaving the Heat Recovery Steam Generator

Stream Temperature	375	F
Stream Temperature	191	C
Stream Temperature	464	K
Enthalpy Flow	1353	MJ/min
Enthalpy Lost from the Hot Gas Stream	3,540	MJ/min
Enthalpy Lost to the Environment	5%	
Enthalpy Lost to the Environment	177	MJ/min

Heat Recovery Steam Generator

Steam Enthalpy	3,363	MJ/min
Steam Enthalpy	191	MMBTU/hr
HRSG Efficiency	69%	
Assume HRSG output is superheated steam at 2000 psia & 850F		
Steam Enthalpy Content	1,371	BTU/lb
Steam Output	139,586	lb/hr
Steam Entropy Content	1.49	BTU/lb-R

Mechanical Work Production

Isentropic Expansion to 1 psia (100F)		
Entropy of Saturated Water @1 psia	0.13	BTU/lb-R
Entropy of Saturated Steam @1psia	1.98	BTU/lb-R
Steam Quality	0.73	
Enthalpy of Saturated Water @ 1 psia	69.7	BTU/lb
Enthalpy of Saturated Steam @1 psia	1,105	BTU/lb
Steam Enthalpy Content Post-Expansion	829	BTU/lb
Expansion Efficiency	90%	
Steam Enthalpy Content Post-Expansion	883	BTU/lb
Work Extracted	488	BTU/lb
Efficiency of Steam to Work	36%	
Work Output	68	MMBTU/hr
Efficiency of Work to Electricity	0.90	
Efficiency of Steam to Electricity	0.32	
Gross Electricity Output	61	MMBTU/hr
Ancillary Loads	8%	
Net Electricity Output	56	MMBTU/hr
Net Electricity Output	17	MW-hr/hr

Performance Metric Calculation

FERC Efficiency	59.99%	

volume conversion	0.0283	m^3/ft^3
Standard Molar Volume (1 atm, 20C)	0.024	m^3/mol
Cooling Water Temperature	86	F
Cooling Water Temperature	30	C
Cooling Water Temperature	303	K
energy conversion	1,054.4	J/BTU
energy conversion	60	J/W-hr
mass conversion	0.453	kg/lb
Molecular Weight Carbon Dioxide	0.04401	kg/mol
Oxygen Content of Air	20.9%	
Nitrogen Content of Air	79.1%	
energy conversion	3.413	BTU/W-hr

Tangible Example - Bottoming-Cycle Cogeneration on a 5,000 ton clinker/day Kiln
Case 2o: 60% FERC Efficiency, High Efficiency System

Hot Exhaust Stream

Clinker Capacity	5,000	ton/d
Carbon Dioxide Molar Flow	61,776	mol/min
Fuel CO_2 Molar Flow	24,249	mol/min
Nitrogen Molar Flow	131,444	mol/min
Oxygen Molar Flow	7,000	mol/min
Water Vapor Molar Flow	34,314	mol/min
Volumetric Flow Rate	169,797	SCFM (dry)
Stream Temperature	800	F
Stream Temperature	427	C
Stream Temperature	700	K
Enthalpy Flow	3,241	MJ/min
Enthalpy Flow	184	MMBTU/hr

Heat Capacities

Stream	Nitrogen Spc Heat Content J/mol	Carbon Dioxide Spc Heat Content J/mol	Water Vapor Spc Heat Content J/mol	Oxygen Spc Heat Content J/mol
Hot Exhaust	11991	17679	14163	12403
Inlet to HRSG	16846	25346	20119	17491
Exhaust from HRSG	4763	6657	5538	4876
	Constants	Constants	Constants	Constants
	28.6	44.2	30.5	30.0
	0.00377	0.00879	0.01029	0.00418
	-50208	-861904	0	-167360

Supplemental Firing Input

Enthalpy Flow	96	MMBTU/hr
Supplementary Firing Ratio	0.52	
Enthalpy Flow	1,687	MJ/min
Enthalpy of Combustion for Methane	891	kJ/mol
Methane Required	1,893	mol/min
Carbon Dioxide Released	1,893	mol/min
Water Vapor Released	3,787	mol/min
Oxygen:Methane Ratio	2	mol O_2/mol methane
Stochiometric Oxygen Required	3,787	mol/min
Fraction Required Oxygen from Hot Exh	10%	
Oxygen from Supplemental Air	3,408	mol/min
Nitrogen Molar Flow @Stoichometry	12,899	mol/min

Hot Gas Into the Heat Recovery Steam Generator

Carbon Dioxide Molar Flow	63,669	mol/min	
Nitrogen Molar Flow	144,342	mol/min	
Oxygen Molar Flow	6,622	mol/min	
Water Vapor Molar Flow	38,101	mol/min	
Enthalpy Flow	4,928	MJ/min	4928 Comparator
Stream Temperature	854.4	K	
Stream Temperature	581	C	
Stream Temperature	1,078	F	

Gas Stream Leaving the Heat Recovery Steam Generator

Stream Temperature	375	F
Stream Temperature	191	C
Stream Temperature	464	K
Enthalpy Flow	1355	MJ/min
Enthalpy Lost from the Hot Gas Stream	3,574	MJ/min
Enthalpy Lost to the Environment	5%	
Enthalpy Lost to the Environment	179	MJ/min

Heat Recovery Steam Generator

Steam Enthalpy	3,395	MJ/min
Steam Enthalpy	193	MMBTU/hr
HRSG Efficiency	69%	
Assume HRSG output is superheated steam at 2000 psia & 900F		
Steam Enthalpy Content	1,407	BTU/lb
Steam Output	137,280	lb/hr
Steam Entropy Content	1.51	BTU/lb-R

Mechanical Work Production

Isentropic Expansion to 1 psia (100F)		
Entropy of Saturated Water @1 psia	0.13	BTU/lb-R
Entropy of Saturated Steam @1psia	1.98	BTU/lb-R
Steam Quality	0.75	
Enthalpy of Saturated Water @ 1 psia	69.7	BTU/lb
Enthalpy of Saturated Steam @1 psia	1,105	BTU/lb
Steam Enthalpy Content Post-Expansion	844	BTU/lb
Expansion Efficiency	90%	
Steam Enthalpy Content Post-Expansion	900	BTU/lb
Work Extracted	507	BTU/lb
Efficiency of Steam to Work	36%	
Work Output	70	MMBTU/hr
Efficiency of Work to Electricity	0.90	
Efficiency of Steam to Electricity	0.32	
Gross Electricity Output	63	MMBTU/hr
Ancillary Loads	8%	
Net Electricity Output	58	MMBTU/hr
Net Electricity Output	17	MW-hr/hr

Performance Metric Calculation

FERC Efficiency	60.00%	

volume conversion	0.0283	m^3/ft^3
Standard Molar Volume (1 atm, 20C)	0.024	m^3/mol
Cooling Water Temperature	86	F
Cooling Water Temperature	30	C
Cooling Water Temperature	303	K
energy conversion	1,054.4	J/BTU
energy conversion	60	J/W-hr
mass conversion	0.453	kg/lb
Molecular Weight Carbon Dioxide	0.04401	kg/mol
Oxygen Content of Air	20.9%	
Nitrogen Content of Air	79.1%	
energy conversion	3.413	BTU/W-hr

Tangible Example - Bottoming-Cycle Cogeneration on a 5,000 ton clinker/day Kiln
Case 1p: 60% FERC Efficiency, Moderate Efficiency System. Less Optimistic

Hot Exhaust Stream

Clinker Capacity	5,000	ton/d
Carbon Dioxide Molar Flow	61,776	mol/min
Fuel CO_2 Molar Flow	24,249	mol/min
Nitrogen Molar Flow	131,444	mol/min
Oxygen Molar Flow	7,000	mol/min
Water Vapor Molar Flow	34,314	mol/min
Volumetric Flow Rate	169,797	SCFM (dry)
Stream Temperature	800	F
Stream Temperature	427	C
Stream Temperature	700	K
Enthalpy Flow	3,241	MJ/min
Enthalpy Flow	184	MMBTU/hr

Heat Capacities

Stream	Nitrogen Spc Heat Content J/mol	Carbon Dioxide Spc Heat Content J/mol	Water Vapor Spc Heat Content J/mol	Oxygen Spc Heat Content J/mol
Hot Exhaust	11991	17679	14163	12403
Inlet to HRSG	14912	22274	17731	15462
Exhaust from HRSG	5181	7275	6029	5309
	Constants	Constants	Constants	Constants
	28.6	44.2	30.5	30.0
	0.00377	0.00879	0.01029	0.00418
	-50208	-861904	0	-167360

Supplemental Firing Input

Enthalpy Flow	56	MMBTU/hr
Supplementary Firing Ratio	0.30	
Enthalpy Flow	984	MJ/min
Enthalpy of Combustion for Methane	891	kJ/mol
Methane Required	1,104	mol/min
Carbon Dioxide Released	1,104	mol/min
Water Vapor Released	2,209	mol/min
Oxygen:Methane Ratio	2	mol O_2/mol methane
Stochiometric Oxygen Required	2,209	mol/min
Fraction Required Oxygen from Hot Exh	10%	
Oxygen from Supplemental Air	1,988	mol/min
Nitrogen Molar Flow @Stoichometry	7,524	mol/min

Hot Gas Into the Heat Recovery Steam Generator

Carbon Dioxide Molar Flow	62,880	mol/min	
Nitrogen Molar Flow	138,968	mol/min	
Oxygen Molar Flow	6,779	mol/min	
Water Vapor Molar Flow	36,523	mol/min	
Enthalpy Flow	4,225	MJ/min	4225 Comparator
Stream Temperature	793.2	K	
Stream Temperature	520	C	
Stream Temperature	968	F	

Gas Stream Leaving the Heat Recovery Steam Generator

Stream Temperature	400	F
Stream Temperature	204	C
Stream Temperature	478	K
Enthalpy Flow	1434	MJ/min
Enthalpy Lost from the Hot Gas Stream	2,792	MJ/min
Enthalpy Lost to the Environment	5%	
Enthalpy Lost to the Environment	140	MJ/min

Heat Recovery Steam Generator

Steam Enthalpy	2,652	MJ/min
Steam Enthalpy	151	MMBTU/hr
HRSG Efficiency	63%	
Assume HRSG output is superheated steam at 1200 psia & 680F		
Steam Enthalpy Content	1,295	BTU/lb
Steam Output	116,504	lb/hr
Steam Entropy Content	1.47	BTU/lb-R

Mechanical Work Production

Isentropic Expansion to 1 psia (100F)		
Entropy of Saturated Water @1 psia	0.13	BTU/lb-R
Entropy of Saturated Steam @1psia	1.98	BTU/lb-R
Steam Quality	0.73	
Enthalpy of Saturated Water @ 1 psia	69.7	BTU/lb
Enthalpy of Saturated Steam @1 psia	1,105	BTU/lb
Steam Enthalpy Content Post-Expansion	821	BTU/lb
Expansion Efficiency	75%	
Steam Enthalpy Content Post-Expansion	939	BTU/lb
Work Extracted	356	BTU/lb
Efficiency of Steam to Work	27%	
Work Output	41	MMBTU/hr
Efficiency of Work to Electricity	0.90	
Efficiency of Steam to Electricity	0.25	
Electricity Output	37	MMBTU/hr
Ancillary Loads	10%	
Net Electricity Output	34	MMBTU/hr
Net Electricity Output	10	MW-hr/hr

Performance Metric Calculation

FERC Efficiency	59.96%	

volume conversion	0.0283	m^3/ft^3
Standard Molar Volume (1 atm, 20C)	0.024	m^3/mol
Cooling Water Temperature	86	F
Cooling Water Temperature	30	C
Cooling Water Temperature	303	K
energy conversion	1,054.4	J/BTU
energy conversion	60	J/W-hr
mass conversion	0.453	kg/lb
Molecular Weight Carbon Dioxide	0.04401	kg/mol
Oxygen Content of Air	20.9%	
Nitrogen Content of Air	79.1%	
energy conversion	3.413	BTU/W-hr

Tangible Example - Bottoming-Cycle Cogeneration on a 5,000 ton clinker/day Kiln
Case 1o: 60% FERC Efficiency, Moderate Efficiency System

Hot Exhaust Stream

Clinker Capacity	5,000	ton/d
Carbon Dioxide Molar Flow	61,776	mol/min
Fuel CO_2 Molar Flow	24,249	mol/min
Nitrogen Molar Flow	131,444	mol/min
Oxygen Molar Flow	7,000	mol/min
Water Vapor Molar Flow	34,314	mol/min
Volumetric Flow Rate	169,797	SCFM (dry)
Stream Temperature	800	F
Stream Temperature	427	C
Stream Temperature	700	K
Enthalpy Flow	3,241	MJ/min
Enthalpy Flow	184	MMBTU/hr

Heat Capacities

Stream	Nitrogen Spc Heat Content J/mol	Carbon Dioxide Spc Heat Content J/mol	Water Vapor Spc Heat Content J/mol	Oxygen Spc Heat Content J/mol
Hot Exhaust	11991	17679	14163	12403
Inlet to HRSG	14912	22274	17731	15462
Exhaust from HRSG	5181	7275	6029	5309
	Constants	Constants	Constants	Constants
	28.6	44.2	30.5	30.0
	0.00377	0.00879	0.01029	0.00418
	-50208	-861904	0	-167360

Supplemental Firing Input

Enthalpy Flow	56	MMBTU/hr
Supplementary Firing Ratio	0.30	
Enthalpy Flow	984	MJ/min
Enthalpy of Combustion for Methane	891	kJ/mol
Methane Required	1,104	mol/min
Carbon Dioxide Released	1,104	mol/min
Water Vapor Released	2,209	mol/min
Oxygen:Methane Ratio	2	mol O_2/mol methane
Stochiometric Oxygen Required	2,209	mol/min
Fraction Required Oxygen from Hot Exh	10%	
Oxygen from Supplemental Air	1,988	mol/min
Nitrogen Molar Flow @Stoichometry	7,524	mol/min

Hot Gas Into the Heat Recovery Steam Generator

Carbon Dioxide Molar Flow	62,880	mol/min
Nitrogen Molar Flow	138,968	mol/min
Oxygen Molar Flow	6,779	mol/min
Water Vapor Molar Flow	36,523	mol/min
Enthalpy Flow	4,225	MJ/min
Stream Temperature	793.2	K
Stream Temperature	520	C
Stream Temperature	968	F

4225 Comparator

Gas Stream Leaving the Heat Recovery Steam Generator

Stream Temperature	400	F
Stream Temperature	204	C
Stream Temperature	478	K
Enthalpy Flow	1434	MJ/min
Enthalpy Lost from the Hot Gas Stream	2,792	MJ/min
Enthalpy Lost to the Environment	5%	
Enthalpy Lost to the Environment	140	MJ/min

Heat Recovery Steam Generator

Steam Enthalpy	2,652	MJ/min
Steam Enthalpy	151	MMBTU/hr
HRSG Efficiency	63%	
Assume HRSG output is superheated steam at 1200 psia & 700F		
Steam Enthalpy Content	1,310	BTU/lb
Steam Output	115,171	lb/hr
Steam Entropy Content	1.48	BTU/lb-R

Mechanical Work Production

Isentropic Expansion to 1 psia (100F)		
Entropy of Saturated Water @1 psia	0.13	BTU/lb-R
Entropy of Saturated Steam @1psia	1.98	BTU/lb-R
Steam Quality	0.73	
Enthalpy of Saturated Water @ 1 psia	69.7	BTU/lb
Enthalpy of Saturated Steam @1 psia	1,105	BTU/lb
Steam Enthalpy Content Post-Expansion	828	BTU/lb
Expansion Efficiency	75%	
Steam Enthalpy Content Post-Expansion	949	BTU/lb
Work Extracted	362	BTU/lb
Efficiency of Steam to Work	28%	
Work Output	42	MMBTU/hr
Efficiency of Work to Electricity	0.90	
Efficiency of Steam to Electricity	0.25	
Electricity Output	37	MMBTU/hr
Ancillary Loads	10%	
Net Electricity Output	34	MMBTU/hr
Net Electricity Output	10	MW-hr/hr

Performance Metric Calculation

FERC Efficiency	60.23%	

volume conversion	0.0283	m^3/ft^3
Standard Molar Volume (1 atm, 20C)	0.024	m^3/mol
Cooling Water Temperature	86	F
Cooling Water Temperature	30	C
Cooling Water Temperature	303	K
energy conversion	1,054.4	J/BTU
energy conversion	60	J/W-hr
mass conversion	0.453	kg/lb
Molecular Weight Carbon Dioxide	0.04401	kg/mol
Oxygen Content of Air	20.9%	
Nitrogen Content of Air	79.1%	
energy conversion	3.413	BTU/W-hr

10% Oxygen Case @ 3.25 MMBTU/Ton (short ton)

Unit Clinker Carbon Dioxide Mass Rate Calcinin	1,050	lb/ton
Unit Clinker Carbon Dioxide Mole Rate Calcining	10,808	mol/ton
Unit Clinker Carbon Dioxide Mass Rate Fuel	678	lb/ton
Unit Clinker Carbon Dioxide Mole Rate Fuel	6,984	mol/ton
Unit Clinker Carbon Dioxide Mole Rate Total	17,791	mol/ton
Diluted Exhaust Carbon Dioxide Content	19.3%	(dry)
Diluted Exhaust Oxygen Content	10%	(dry)
Unit Clinker Oxygen Mole Rate	9,207	mol/ton
Diluted Exhaust Nitrogen Content (balance)	71%	(dry)
Unit Clinker Nitrogen Mole Rate	65,071	mol/ton
Water Vapor Content	10%	
Unit Clinker Water Vapor Mole Rate	10,230	mol/ton
Unit Clinker Total Diluted Exhaust Mole Rate	102,299	mol/ton
Diluted Exhaust Temperature	525	F
Diluted Exhaust Temperature	274	C
Diluted Exhaust Temperature	547	K
Dilution Air Temperature	100	F
Dilution Air Temperature	38	C
Dilution Air Temperature	311	K
Dilution Air Nitrogen Content	79%	(dry)
Dilution Air Oxygen Content	21%	(dry)
Dilution Air Water Vapor Content	1%	
Dilution Air Nitrogen Mole Fraction	0.783	
Dilution Air Oxygen Mole Fraction	0.207	
Dilution Air Water Vapor Mole Fraction	0.010	
Hot Exhaust Temperature	800	F
Hot Exhaust Temperature	427	C
Hot Exhaust Temperature	700	K
Unit Clinker Moles of Dilution Air	34,750	mol/ton
Unit Clinker Moles of Dilution Nitrogen	27,215	mol/ton
Unit Clinker Moles of Dilution Oxygen	7,191	mol/ton
Unit Clinker Moles of Dilution Water Vapor	348	mol/ton
Enthalpy Gain by Dilution Air	247	MJ/ton
Unit Clinker Moles Hot Exhaust Nitrogen	37,856	mol/ton
Unit Clinker Moles Hot Exhaust Carbon Dioxide	17,791	mol/ton
Unit Clinker Moles Hot Exhaust Oxygen	2,016	mol/ton
Unit Clinker Moles Hot Exhaust Water Vapor	9,882	mol/ton
Unit Clinker Moles Hot Exhaust Total	67,546	mol/ton
Enthalpy Loss from Hot Exhaust	-373	MJ/ton
Enthalpy Loss to the Environment	34%	
Enthalpy Loss to the Environment	-126	MJ/ton
Enthalpy Loss to Dilution Air	-247	MJ/ton
Enthalpy Balance	0	MJ/ton
Hot Exhaust Mole Fraction Nitrogen	0.560	
Hot Exhaust Mole Fraction Carbon Dioxide	0.263	
Hot Exhaust Mole Fraction Oxygen	0.030	
Hot Exhaust Mole Fraction Water Vapor	0.146	
Hot Exhaust Oxygen Content	3.50%	(dry)

Mass Conversion Factor	0.453	kg/lb
Molecular Weight Carbon Dioxide	0.04401	kg/mol
Cooling Water Temperature	86	F
Cooling Water Temperature	30	C
Cooling Water Temperature	303	K

Heat Capacities

	Stream	Nitrogen Spc Heat Content	Carbon Dioxide Spc Heat Content	Water Vapor Spc Heat Content	Oxygen Spc Heat Content
		J/mol	J/mol	J/mol	J/mol
	Diluted Exhaust	7286	10430	8516	7494
	Dilution Air	227	-	262	229
	Hot Exhaust	11991	17679	14163	12403
		Constants	Constants	Constants	Constants
		28.6	44.2	30.5	30.0
4022.037961		0.00377	0.00879	0.01029	0.00418
		-50208	-861904	0	-167360

CO_2 CONCENTRATION AT 3.25 MMBTU/TON CLINKER

Parameter	0% O_2	8% O_2	9% O_2	10% O_2	11% O_2	12% O_2	13% O_2	14% O_2
CO_2 from calcination (lb/ton clinker)	1,050	1,050	1,050	1,050	1,050	1,050	1,050	1,050
CO_2 from calcination (scf/ton clinker)	9,056	9,056	9,056	9,056	9,056	9,056	9,056	9,056
CO_2 from fuel (lb/ton clinker)	678	678	678	678	678	678	678	678
CO_2 from fuel (scf/ton clinker)	5,852	5,852	5,852	5,852	5,852	5,852	5,852	5,852
Total CO_2 (scf/ton clinker)	14,907	14,907	14,907	14,907	14,907	14,907	14,907	14,907
N_2 for stoichiometric air (lb/ton clinker)	1,870	1,870	1,870	1,870	1,870	1,870	1,870	1,870
N_2 for stoichiometric air (scf/ton clinker)	25,326	25,326	25,326	25,326	25,326	25,326	25,326	25,326
Total exhaust (scf/ton clinker)	40,234	65,185	70,662	77,145	84,937	94,481	106,441	121,867
% CO_2	37.1	22.9	21.1	19.3	17.6	15.8	14.0	12.2
% CO_2 at 3.0 MMBtu/ton clinker	38.2	23.6	21.8	19.9	18.1	16.3	14.4	12.6

MMBtu/ton clinker	3.25
Btu/lb fuel	11,000
lb air/10,000 Btu	7.5
lb N_2/lb air	0.767
lb CO_2/mol	44
ft^3/mol. gas @ 60 ºF	379.48
lb_{N2}/mol_{N2}	28.01
kg CO_2/ton fuel	2082.89