September 30, 2020

Conceptual Design of a State-of-the-Art PC Plant for Flexible Operation

Marc Turner – Leidos
Matt Adams – NETL
Aaron Kilstofte – Black & Veatch

Transformative Power Generation

NATIONAL ENERGY TECHNOLOGY LABORATORY

INTERNAL USE ONLY – NOT APPROVED FOR PUBLIC RELEASE

U.S. DEPARTMENT OF ENERGY

Disclaimer and Acknowledgment

DISCLAIMER

"This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."

ACKNOWLEDGMENT

Team KeyLogic's contributions to this work were funded by the National Energy Technology Laboratory under the Mission Execution and Strategic Analysis contract (DE-FE0025912) for support services. The authors would like to thank Robert (R.J.) James, (NETL), Travis Shultz (NETL), Bob Slettehaugh (Kiewit), and Mark Woods (KeyLogic) for their support and assistance in performing this work.

Overview

- **Presents cost and performance estimates of near-term commercially available small(er), flexible coal-fired power plants**
  - Applies the NETL techno-economic methodology to evaluate the cost and performance of a subcritical, 150 MW-gross, greenfield plant designed for a range of operational flexibility.
  - Uses only technology and design options that are commercially available today (does not include CO_2 capture).
  - Identifies a set of design configurations that provide varied degrees of operational flexibility.
  - Intended to "define" the cost and performance of current state-of-the-art options; will be used as the basis of comparison for improvements in cost and performance.

Flexibility Metrics

- Part load heat rate
- Startup time
- Ramp rate
- Minimum load
- Design life
- Availability/reliability
- Planned outages
- Number of starts
- Engineering, procurement, and construction (EPC) capital cost
- Operation and maintenance costs

Study Design Basis

- **NETL QGESS for "standard" assumptions**
  - Properties for fuel and consumables
    - —Detailed Coal Specifications
    - —Specification for Selected Feedstocks
  - Plant location, ambient conditions, and generic equipment specifications
    - —Process Modeling Design Parameters
  - Cost estimation methodology and cost of fuel and consumables
    - —Cost Estimation Methodology for NETL Assessments of Power Plant Performance
    - —Fuel Prices for Selected Feedstocks in NETL Studies

Study Design Basis (Cont'd)

- **Additional assumptions:**
  - Limited use of natural gas (start-up/shutdown, flame stabilization at low load)
  - Vendors willing to provide "commercially acceptable" performance guarantees for application (cycling, more frequent start-ups and shutdowns)

Plant Characteristics Summary

Case	Baseload Plant Case 0	Flexible Plants (Cases 1 and 2)	Flexible Plants (Cases 3 and 4)
Nameplate Gross Plant Output, MW	150		
Steam Cycle	Subcritical		
Condenser	Air-Cooled		
Boiler Type	Wall-Fired		
NOx Control	Selective Catalytic Reduction		
SO_2 Control	Wet Flue Gas Desulfurization (Wet FGD)		
Particulate Matter (PM) Control	Fabric Filter		
Hg Control	Powdered Activated Carbon		
SO_3 Control	Dry Sorbent Injection		
Steam Turbine	Constant-Pressure Main Steam	Sliding-Pressure Main Steam	
Feedwater Pump	Steam Drive	Static Frequency, Electric Drive	Variable Frequency Drive (VFD)
Fan Drive	Static Frequency, Electric Drive		VFD
Minimum Load, %	40	20	

Cost Estimation Methodology

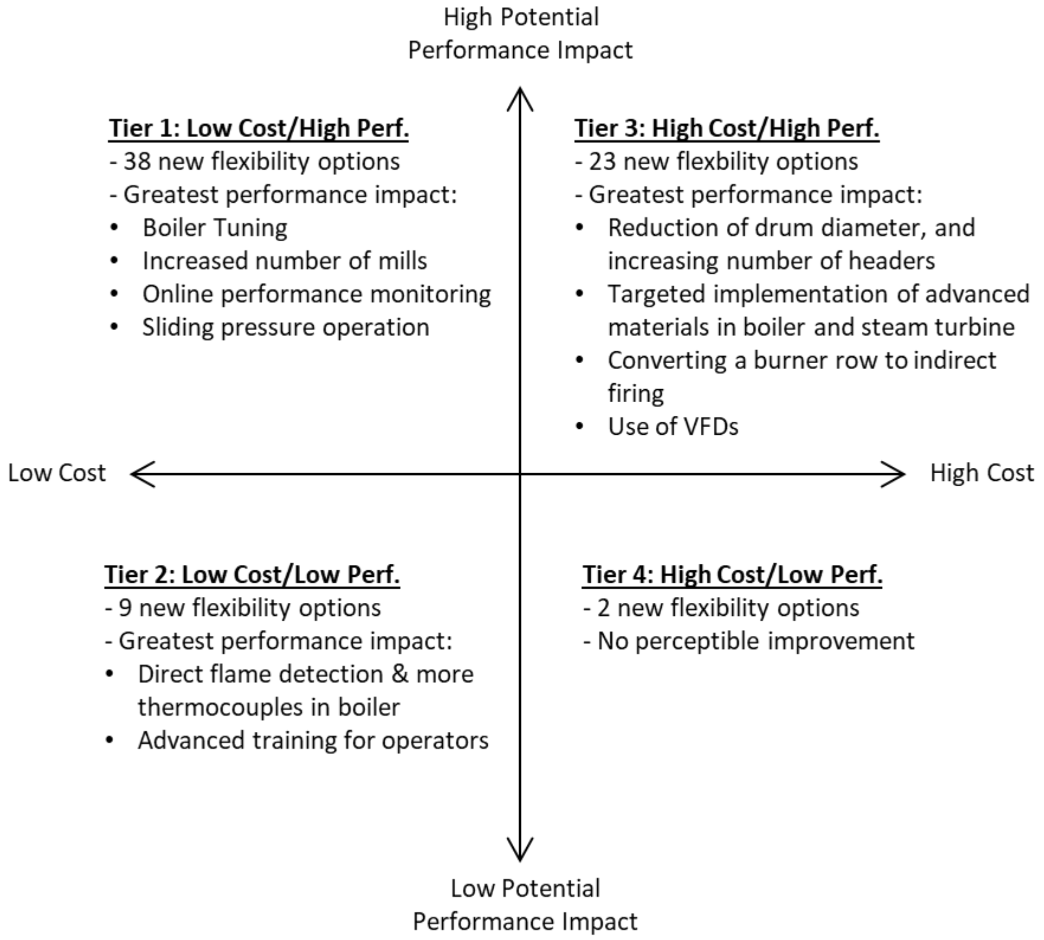
NATIONAL ENERGY TECHNOLOGY LABORATORY

- **Capital Cost Methodology**
  - New-build/Nth-of-a-kind estimate bases
    - The cost estimates for plant designs that include technologies that are not yet fully mature use the same cost estimating methodology as for mature plant designs. Thus, it is anticipated that initial deployments may incur costs higher than those reflected within this report.
  - Project contingencies range from 15 to 20 percent
  - No process contingencies were applied
  - American Association of Cost Engineers (AACE) Class 4 estimate with an uncertainty range of -20/+40 percent
- **O&M Cost Methodology**
  - Consumable consumption rates were estimated via Aspen Plus models
  - The maintenance material and labor costs were increased to 2.3 percent of total plant cost (TPC) for the flexible plant cases, from 1.6 percent used in the baseload plant case

Designs for Increased Operational Flexibility

- **Flexible design options prioritized into four "tiers" based on cost and performance impact**
- **Evaluated five separate cases to enable comparison (all 150 MW-gross at full design load)**
  - Basis for comparison
    - Case 0: Design for baseload operation
  - Design for operational flexibility
    - Case 1: Tier 1 Options
    - Case 2: Tier 1 & 2 Options
    - Case 3: Tier 1, 2, and 3 Options
    - Case 4: Tier 1, 2, 3, and 4 Options

Cost and Performance Quads



Baseload Flexibility Options

Metric	Option	Cost Impact	Performance Impact	Description
Design Life	44	Low	High	Implement best practices for layup procedures, depending on the duration of the offline period
Heat Rate	54	Low	High	Online performance monitoring
Heat Rate	57	Low	High	Limiting excess air and air heater air in-leakage to lowest practical levels
Heat Rate	58	Low	High	Maintaining tight air heater outlet temperature target through use of upstream alkali (e.g., hydrated lime) injection
Availability/Reliability	64	Low	High	Full leveraging/utilization of the supplier’s long-term service agreement
Availability/Reliability	66	Low	Low	Advanced training of operators to reduce errors and improve situational awareness
Availability/Reliability	67	Low	Low	Automated prioritization of plant alarm signals to allow for simplified triage of plant information received in the control room
EPC Capital Cost	74	Low	High	Contracting structure (e.g., open-book EPC, turn-key EPC) of overall project

Tier 1 Plant Design Options

Low Cost – High Performance Impact

Metric	Option	Description
Startup Time	4	Steam sparging
Startup Time	5	Furnace heating utilizing small dedicated coal feeder/pulverizer/burner level
Startup Time	7	Economizer and/or feedwater heater bypass
Startup Time	9	Equipping the EGU with black start capability (e.g., reciprocating engine units)
Startup Time	11	Draft system isolation/modifications to retain boiler heat as long as possible during shutdown periods
Startup Time	16	Main steam warmup line to accelerate pipe wall temperature rise during startup
Startup Time	18	Additional thermocouples to measure the steam-metal temperature differentials
Startup Time	19	Electric-resistance heating blankets for the steam turbine casing sections to pre-heat the casing (also works to retain heat)
Ramp Rate and Cycling	23	Enhanced water chemistry monitoring and system response to cycling
Ramp Rate and Cycling	25	Avoid use of forced cooling during boiler shutdowns to mitigate boiler tube failures
Ramp Rate and Cycling	26	Replace all steam turbine driven pumps (e.g., BFP) with an electric motor drives
Availability/Reliability	64	Full leveraging/utilization of the supplier's LTSA
Availability/Reliability	65	Full implementation of NERC GADS program for outage, trip, and malfunction tracking
Availability/Reliability	68	Modify start-up, shut-down, turndown, and ramping protocols to lower component fatigue stresses
Availability/Reliability	69	Reducing/eliminating dissimilar metal welds to the greatest extent practical

Tier 1 Plant Design Options

Low Cost – High Performance Impact (cont'd)

Metric	Option	Description
Minimum Stable Load	30	Economizer gas-side/water-side bypass
Minimum Stable Load	31	Air heater gas-side/air-side bypass
Minimum Stable Load	32	SCR gas bypass
Minimum Stable Load	36	Determination of the optimal boiler operating philosophy for each set load point
Minimum Stable Load	37	Designing the boiler with a larger number of smaller sized mills
Minimum Stable Load	43	Application of 'continuous coupled' last stage blades to reduce flutter and dynamic stresses during low load operation
Design Life	44	Implement best practices for layup procedures, depending on the duration of the offline period
Design Life	45	Use of film forming amines/products to protect equipment from corrosion during layup and operation
Heat Rate	54	Online performance monitoring
Heat Rate	56	Enhanced operator interface to monitor and diagnose plant heat rate issues
Heat Rate	57	Limiting excess air and air heater air in-leakage to lowest practical levels
Heat Rate	58	Maintaining tight air heater outlet temperature target through use of upstream alkali (e.g., hydrated lime) injection
Heat Rate	59	Self-cleaning condenser design with stable backpressure target
Heat Rate	61	Steam turbine sliding pressure operation
Heat Rate	63	Application of advanced air heater sealing systems that maintain low air in-leakage during startup and low load operation

Tier 1 Plant Design Options

Low Cost – High Performance Impact (cont'd)

Metric	Option	Description
EPC Capital Cost	73	Reliability-based operations and maintenance program; reduces reactive (unplanned maintenance) and maintenance equipment premiums when needed for forced outage situations
EPC Capital Cost	74	Contracting structure (e.g., open-book EPC, turn-key EPC) of overall project
EPC Capital Cost	75	Reducing plant layout (plan) area and optimizing proximity of plant to major shipping/transportation modes
Operations & Maintenance	76	Fully integrated online performance and conditional health assessment for major equipment categories
Operations & Maintenance	77	Advanced training for operators (e.g., professional certifications, onsite power plant simulator)
Operations & Maintenance	78	Additional plant automation/performance monitoring can lead to reduced plant staff requirements
Operations & Maintenance	80	Implement additional steam cycle instruments to improve cycle isolation during low load conditions
Number of Starts	84	Investment in redundant/higher accuracy steam turbine casing metal temperature instruments; closer monitoring of these temperatures allows for more accurate tracking of design life/maintenance overhaul projections

Tier 2 Plant Design Options

Low Cost – Low Performance Impact

Metric	Option	Description
Startup Time	10	Installation of condensate drains, and instrumentation for condensate detection, in all boiler headers and piping systems
Minimum Stable Load	28	Low-load coal burner flame stabilization with dedicated flame stabilization burner with lower heat input than igniter
Minimum Stable Load	35	Installation of direct flame detection sensors and more thermocouples to monitor temperatures within the boiler
Heat Rate	51	Auxiliary load optimization
Heat Rate	52	Auxiliary load dispatch at low loads
Heat Rate	53	Automated boiler blowdown and drains (full monitoring and operator control from control room)
Heat Rate	55	Enhanced operator training and heat rate awareness
Availability/Reliability	66	Advanced training of operators to reduce errors and improve situational awareness
Availability/Reliability	67	Automated prioritization of plant alarm signals to allow for simplified triage of plant information received in the control room

Tier 3 Plant Design Options

High Cost – High Performance Impact

Metric	Option	Description
Startup Time	1	Use of advanced materials to reduce tube and pressure wall thickness requirements to improve rate of warm-up
Startup Time	2	Decrease drum holding time to reduce drum diameter and drum wall thickness
Startup Time	3	Increase the number of headers to decrease header size and warm-up time
Startup Time	12	Use of condensate polishing system to maintain cycle chemistry parameters during shutdown/layup periods and reduce startup times
Startup Time	13	Use of advanced materials to reduce turbine casing thickness and reduce STG warm-up times
Startup Time	14	Turbine blade coatings for improved resistance to water impingement
Startup Time	15	Steam turbine bypass to dump condenser
Startup Time	20	Use of a steam-cooled turbine outer casing to reduce casing thickness
Ramp Rate and Cycling	21	Use of advanced creep strength enhanced materials
Ramp Rate and Cycling	22	Enhanced inspection and failure prediction
Minimum Stable Load	33	Converting a burner row to indirect firing
Minimum Stable Load	34	Intelligent soot blowing for managing heat transfer within the boiler
Design Life	46	Any measure (either equipment or operational) that reduces the number of start/stop thermal cycles of the EGU

Tier 3 Plant Design Options

High Cost – High Performance Impact (cont'd)

Metric	Option	Description
Heat Rate	47	Neural networks and online combustion optimizer
Heat Rate	49	Fuel additives for slagging/fouling mitigation
Heat Rate	42	Application of variable frequency drives on large electric motors
Availability/Reliability	70	Formal high-energy piping (HEP)/flow-accelerated corrosion (FAC) monitoring programs as a part of an overall plant reliability, availability and maintainability (a so-called RAM program) with data tracking and observation logging for benchmarking
Availability/Reliability	71	Participation in steam turbine 'rotor exchange programs' through the STG supplier
EPC Capital Cost	72	Targeted/limited deployment of advanced creep strength enhanced materials (i.e., controlling cost of advanced materials)
Operations & Maintenance	81	Reducing the number and/or total cumulative cost of each start-up
Operations & Maintenance	82	Utilization of electrode boiler for fast saturated steam production for supporting plant systems (evaluated on case by case basis)

Tier 4 Plant Design Options

High Cost – Low Performance Impact

Metric	Option	Description
Startup Time	17	Use of improved turbine seals to ensure correct clearances during start-ups
Heat Rate	48	Use of water cannons to improve range of load

Most Impactful Design Options by Tier

NATIONAL ENERGY TECHNOLOGY LABORATORY

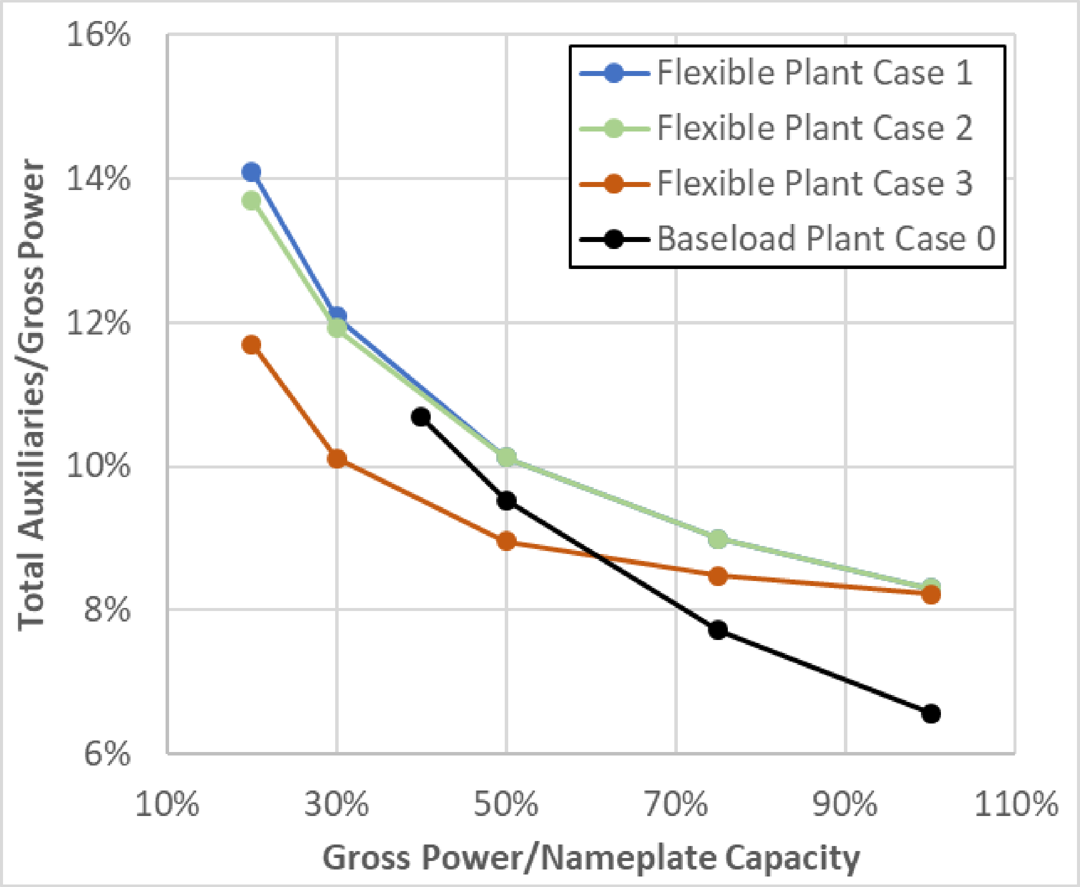
Tier	Metric	Option	Description
1	Minimum Stable Load	36	Determination of the optimal boiler operating philosophy for each set load point
		37	Designing the boiler with a larger number of smaller sized mills
	Heat Rate	54	Online performance monitoring
		61	Steam turbine sliding pressure operation
2	Availability/Reliability	66	Advanced training of operators to reduce errors and improve situational awareness
	Minimum Stable Load	35	Installation of direct flame detection sensors and more thermocouples to monitor temperatures within the boiler
3	Startup Time	2	Decrease drum holding time to reduce drum diameter and drum wall thickness
		3	Increase the number of headers to decrease header size and warm-up time
	Minimum Stable Load	33	Converting a burner row to indirect firing
	Heat Rate	42	Application of variable frequency drives on large electric motors
	EPC Capital Cost	72	Targeted/limited deployment of advanced creep strength enhanced materials (i.e., controlling cost of advanced materials)

Excluded Plant Design Options

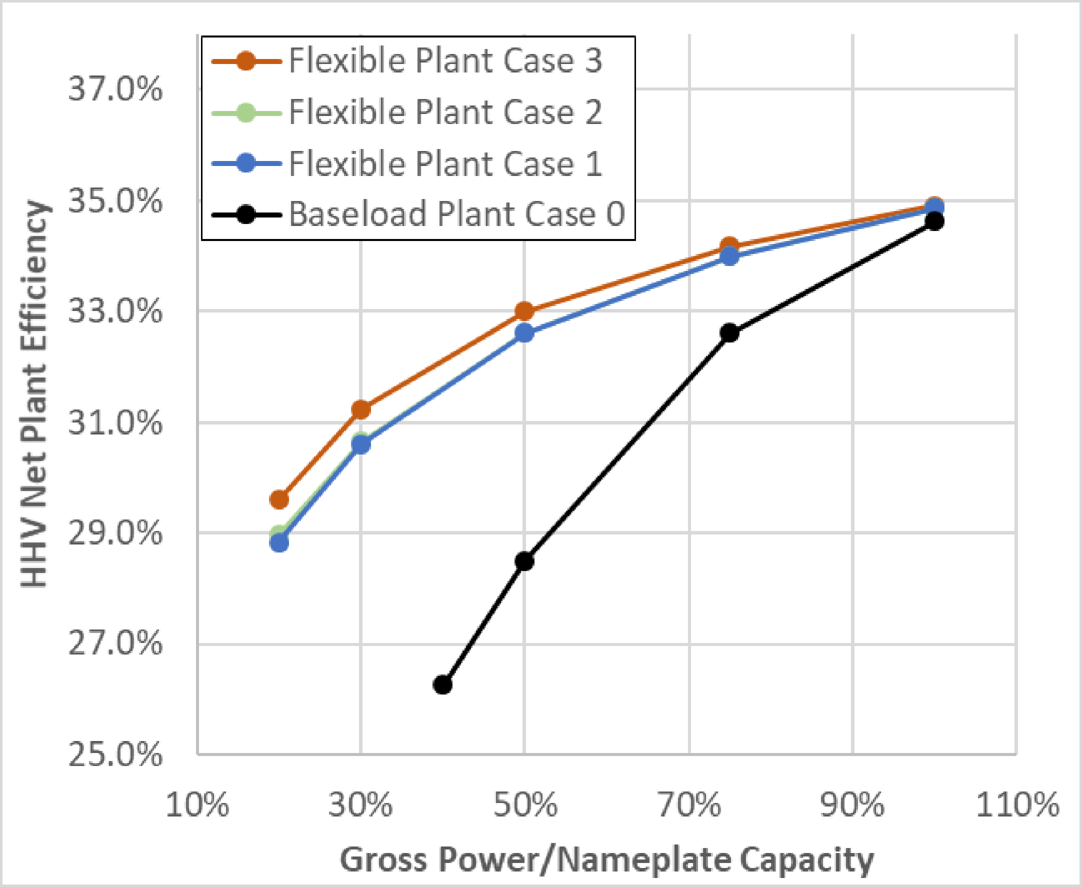
Option	Description	Reason for Omission
6	Improve cold and warm start through furnace heating utilizing small dedicated igniter fuel or alternative fuels	To minimize auxiliary fuel use
24	Implementation of a smaller, fast-response generation resource to allow for additional power export while allowing boiler to ramp according to prescribed time-based intervals	
27	Low-load coal burner flame stabilization with igniters	
8	Application of a once-through Benson-type boiler	Mutually exclusive with Option 2 - Decrease drum holding time to reduce drum diameter and drum wall thickness
29	Dedicated coal feeder, pulverizer, and burner level sized for lower-load operation	Mutually exclusion with option 28 - Low-load coal burner flame stabilization with dedicated flame stabilization burner with lower heat input than igniter
39	Cogeneration steam to neighboring facility	Regionally agnostic design intent
40	Multi-train steam turbine generator	Technology complexity, anticipated high cost, and other steam-turbine-specific flexibility options being incorporated
41	Dedicated low-load steam turbine	
60	Steam turbine partial-arc admission	
50	Coal drying system	Incompatible with the coal type used in this study
79	Increasing plant staffing and/or reducing "hours per shift" to avoid operator fatigue and errors from cyclical operation	It was desired to maximize the cost-competitiveness of the plant by reducing O&M costs to the greatest practical degree.
83	Installation of a package boiler for sparging steam supply	Mutually exclusive with Option 82 - Utilization of electrode boiler for fast saturated steam production for supporting plant systems

Performance Results Comparison

Normalized Auxiliaries vs Capacity



Net Plant Efficiency vs Capacity



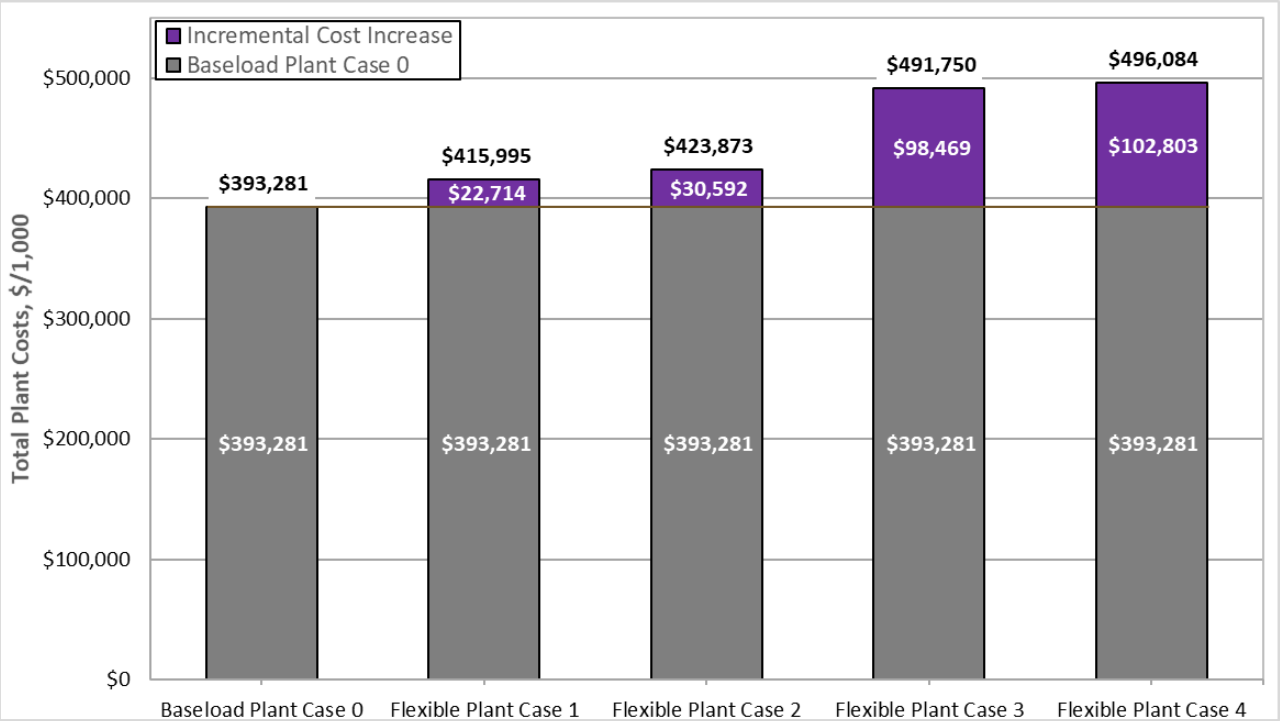
Flexibility Metric Performance

NATIONAL ENERGY TECHNOLOGY LABORATORY

	Case 0	Case 1	Case 2	Case 3
Start-up Time to Full Load				
Cold Start to Full Load, hr	7 – 15	5 – 6	5 – 6	4 – 5
Warm Start to Full Load, hr	3 – 6	1 - 2	1 – 2	1 – 2
Hot Start to Full Load, hr	1 – 3	0.5 – 1.0	0.5 – 1.0	0.5 – 1.0
Ramp Rate, % /min	3 – 5	5 – 7	7 – 8	8 – 9
Minimum Stable Load, %	40	20	20	20
Minimum Achievable Load, %	30	15	15	12.5
Design Life, Years	30	30+	30+	30+
Availability/Reliability (New Construction)				
Equivalent Availability Factor, %	88 – 90	90 – 92	92 – 94	92 – 94
Equivalent Forced Outage Rate, %	5 – 8	4 – 6	4 – 5	4 – 5
Planned Plant Maintenance Outage (Spring/Fall)				
Frequency, #/yr	1 – 2	2 – 4	2 – 4	2 – 4
Duration, days	1 – 7	1 – 4	1 – 4	1 – 4
Number of Starts Tolerable, #/yr	10 – 20	30 – 60	30 – 60	30 – 60

Note: Based on literature review sources, industry experience/precedence, and Black & Veatch in-house data.

Capital Cost Incremental Results



High Potential Performance Impact

Low Cost ⟷ High Cost

Low Potential Performance Impact

Tier 1: Low Cost/High Perf.
- TPC increase of $23 MM
- 38 new flexibility options
- Greatest performance impact:
  - Boiler Tuning
  - Increased number of mills
  - Online performance monitoring
  - Sliding pressure operation

Tier 3: High Cost/High Perf.
- TPC increase of $68 MM
- 23 new flexbility options
- Greatest performance impact:
  - Reduction of drum diameter, and increasing number of headers
  - Targeted implementation of advanced materials in boiler and steam turbine
  - Converting a burner row to indirect firing
  - Use of VFDs

Tier 2: Low Cost/Low Perf.
- TPC increase of $8 MM
- 9 new flexibility options
- Greatest performance impact:
  - Direct flame detection & more thermocouples in boiler
  - Advanced training for operators

Tier 4: High Cost/Low Perf.
- TPC increase of $4 MM
- 2 new flexibility options
- No perceptible improvement

Summary of Key Findings

- **Most critical metrics for PC units competing with other flexible generation assets in current power markets are (listed in order of importance):**
    - Minimum load
    - Ramp rate
    - Startup time (cold to full load)
- **Numerous low cost, high performance impact flexibility options are available with existing technology**
    - Boiler tuning at each load point
    - Increased number of smaller sized mills
    - Online performance monitoring
    - Sliding pressure operation
- **The TPC increase, relative to a baseload plant, for including low cost, high performance flexibility options is less than 6 percent. Implementation of these design options results in:**
    - Minimum load: 20% (Baseload: 40%)
    - Ramp rate: 5 – 7%/min (Baseload: 3 – 5%/min)
    - Cold startup time: 5 – 6 hours (Baseload 7-15 hours)

On-Going and Future Work

- The Flexible Plant Baseline is currently being expanded to include an analogous analysis of supercritical PC plants at 300 MW-gross
- The flexibility, limitations, and design options of CO_2 capture systems are being assessed with support from technology suppliers
- A supplemental study is currently being developed to characterize the flexible capabilities of competing technologies, including:

Option	Technology	Cycle Type	Number of Combustion Turbine Generator (CTG)/RICE	Representative Unit	Approximate ISO Gross Output, MW	Notes
1	RICE	SC	12	Wärtsilä 20V34SG	112	Efficiency Mode
2	RICE	SC	12	Wärtsilä 20V34SG	112	Spinning Mode
3	RICE	SC	6	Wärtsilä 18V50SG	112	Efficiency Mode
4	RICE	SC	6	Wärtsilä 18V50SG	112	Spinning Mode
5	CTG	SC	2	GE LM6000 PF+	106	Fast Start
6	CTG	SC	1	GE LMS100	117	Fast Start
7	CTG	CC	1	GE 7F.05	382	Fast Start
8	CTG	CC	1	GE 7HA.02	580	Fast Start
9	CTG	CC	2	GE 7F.05	767	Fast Start
10	CTG	CC	2	GE 7F.05	767	Conventional Start
11	CTG	CC	2	GE 7HA.02	1,162	Fast Start

Questions?