Generation Plant Cost of Operations and Cycling Optimization

Award No. DE-FE0031751

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Outline

- Project Overview
- Timeline and Progress
- Technical Progress Update
- Challenges and Future Plan
- Summary

Overview

Motivation

Near- to long-term technology options for **flexible, reliable, and cost competitive** coal-based power generation at both new and existing plants, allowing them to **cycle safely** to accommodate **increased penetration of renewable resources**

Objective

Develop a tool to estimate the **costs of cycling boilers** in large coal plants so that coal generators can be fairly considered and **efficiently operated as part of a generation and dispatch strategy**

Approach

Semi-empirical physics-based model → Calibration / Training → Deployed and refined at Coal Creek Station

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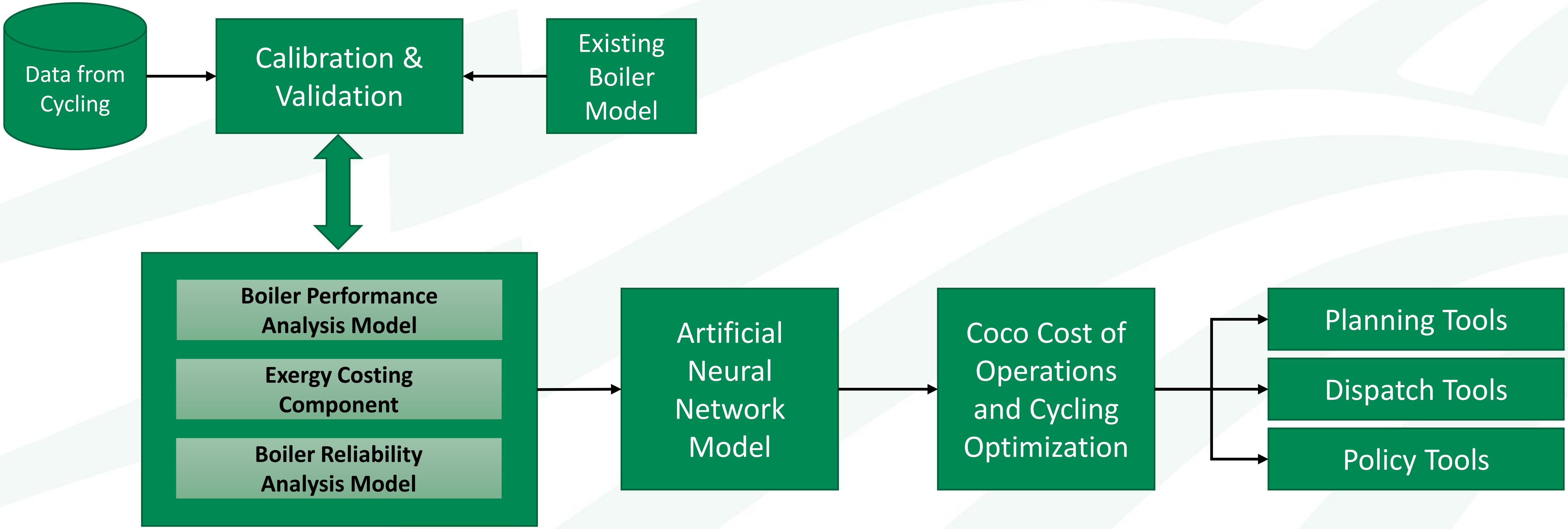
Team

Project Management and Planning Model integration and release	Data and domain expertise Deployment and testing
Hybrid models implementation Testing and validation	System level physics-based model Reliability analysis

Concept



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Timeline & Progress

Milestone	Task	Event	Schedule	Status
1	1	End of Phase 1	Month 14	In Progress
2	1	End of Project	Month 28	Planned
3	2.1	Boiler performance model	Month 6	Complete
4	2.2	Exergy cost analysis	Month 10	Complete
5	2.3	Reliability analysis	Month 14	In Progress
6	3	Artificial Neural Net	Month 14	In Progress
7	4	Model integration	Month 16	Planned
8	5	Coco operational for Coal Creek Station	Month 18	Planned
9	6	Model refinements	Month 22	Planned
10	7	Coco integrated into utility applications	Month 24	Planned
11	8	Model released and publicized	Month 28	Planned

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Cost of Operations and Cycling Optimization (Coco)

Coco Overview

Background

- Coal-fired generation plants refined over many decades to be efficient and cleaner.
- Efficiency optimized at steady load near maximum capacity.
- However, steady growth in distributed energy resources (DER) has caused coal fired generation plants to cycle, adversely affecting efficiency.

Approach

- Team with experience in coal-fired plant operations (GRE), physical and data dependent boiler modeling (Purdue), model implementation (PNNL) and project management (NRECA) to accurately evaluating and optimizing the cost of cycling for generation planning.

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Coal Creek Station (CCS)

(A) - steam generator unit 1 and unit 2
(B) - alternating current (AC) to direct current (DC) converter station
(C) - cooling towers
(D) - dry finning area utilized for minimizing the moisture carried by the lignite coal
(E) - SO_2 scrubber and emissions controller
(F) - conveyer belt that supplies coal from the Mine-Mouth coal mine
(G) - coal storage reserve
(H) - ethanol plant that utilizes steam produced by CCS
(I) - coal load-out area for sending coal to the Spirit wood station
(J) - ponds that contain nonmarketable remains from the scrubber and fly ash
(K) - water supply from the Missouri River
(L) - Fly ash storage

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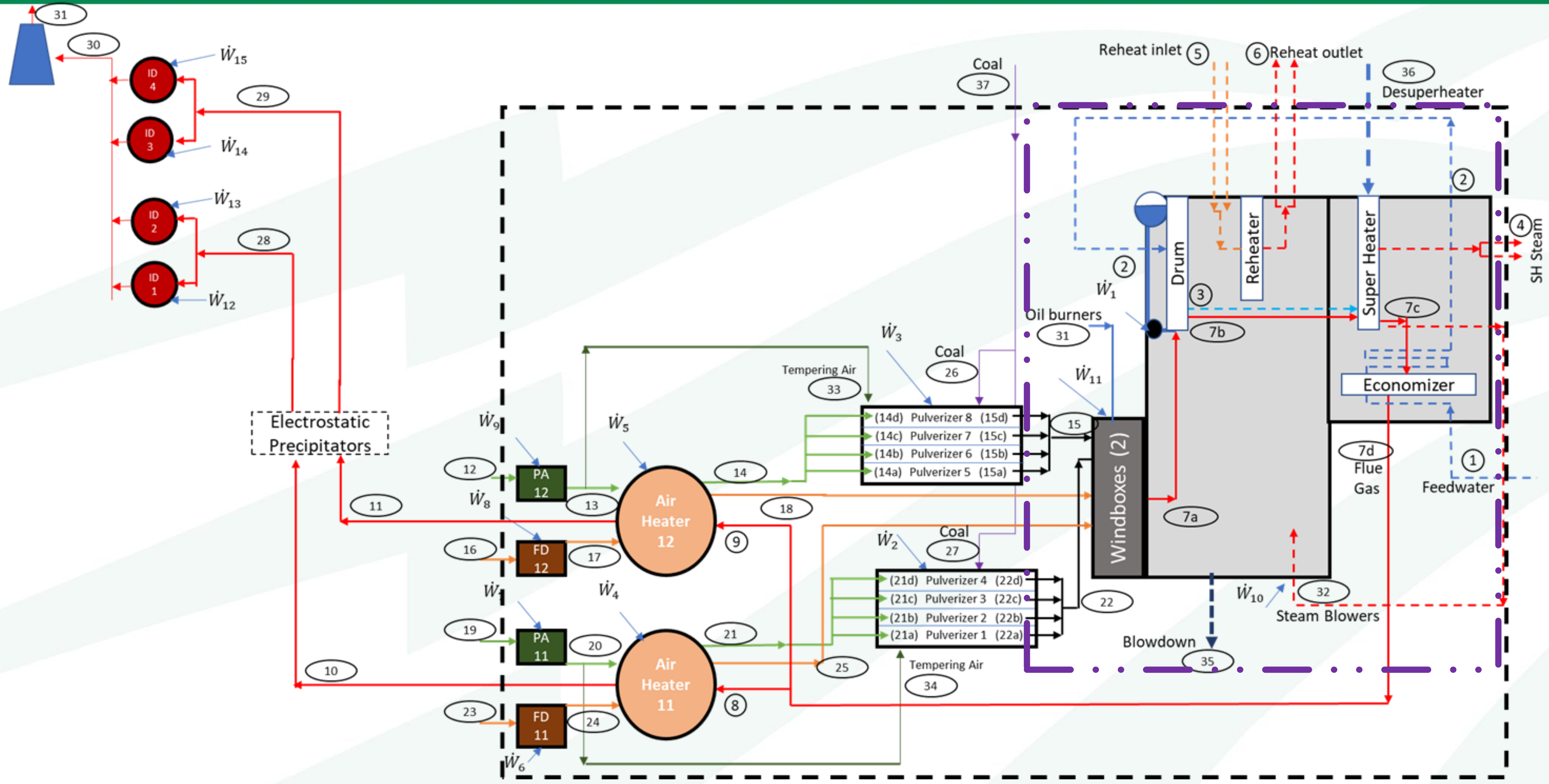
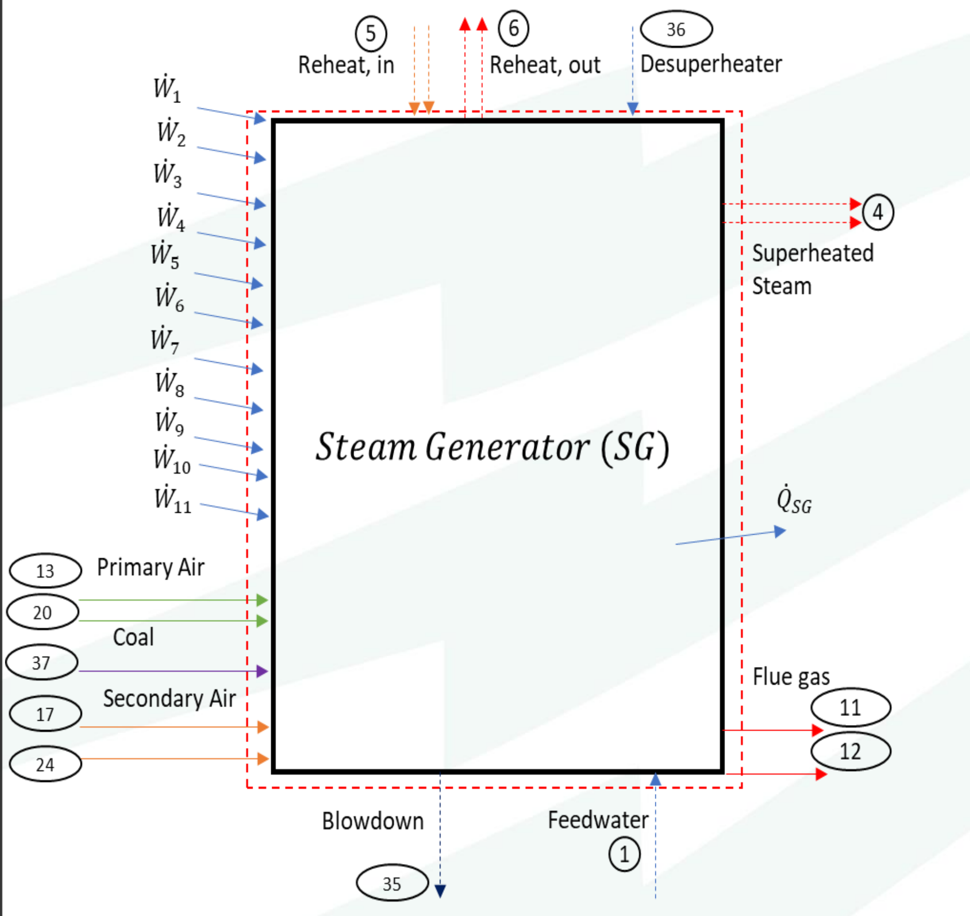
Steam Generator System Definition



Steam Generator: Control Volume



Nomenclature

Units for $\dot{W}_i$ & $\dot{Q}_{sg}$ are $\left[\frac{Btu}{hr}\right]$

$\sum_{i=1}^{11}(\dot{W}_i)$ is the total power supplied by the following components

1 = Evaporator circulating pumps
2 = Pulverizes receiving air from air heater 11
3 = Pulverizes receiving air from air heater 12
4 = Air heater 11
5 = Air heater 12
6 = Forced draft fan 11
7 = Primary air fan 11
8 = Forced draft fan 12
9 = Primary air fan 12
10 = Steam blowers
11 = Windboxes

$\dot{Q}_{SG}$ = Heat loss/time

Nomenclature

h - *Enthalpy [kJ/kg]*

s – Entropy [kJ/kg-K]

P – Pressure [kPa]

T – Temperature [C, K]

x – Specific exergy [kJ/kg]

$\dot{m}$ *– Rate of mass flow [kg/s]*

$\dot{Q}$ *– Rate of heat transfer [MW]*

$\dot{W}$ *– Rate of work [MW]*

$\dot{\sigma}$ *– Rate of entropy generation [MW/K]*

$\dot{X}$ *– Rate of change of exergy [MW]*

$\dot{C}$ *– Cost rate [$/hr.]; c – cost per unit energy [$/MW]*

Subscripts

SG – Boiler, Pulverizers, Air heaters, Primary and forced draft fans

Coal – Pulverized coal

SA – Secondary air

PA – Primary air

FW – Feedwater

DSH – Desuperheater

BD – Blowdown

FG – Flue gas

RHI – Reheat steam, in

RHO – Reheat steam, out

SH1 – East Outlet Superheated steam

SH2 – West Outlet Superheated steam

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Transient Mass, Energy Balance and Efficiency

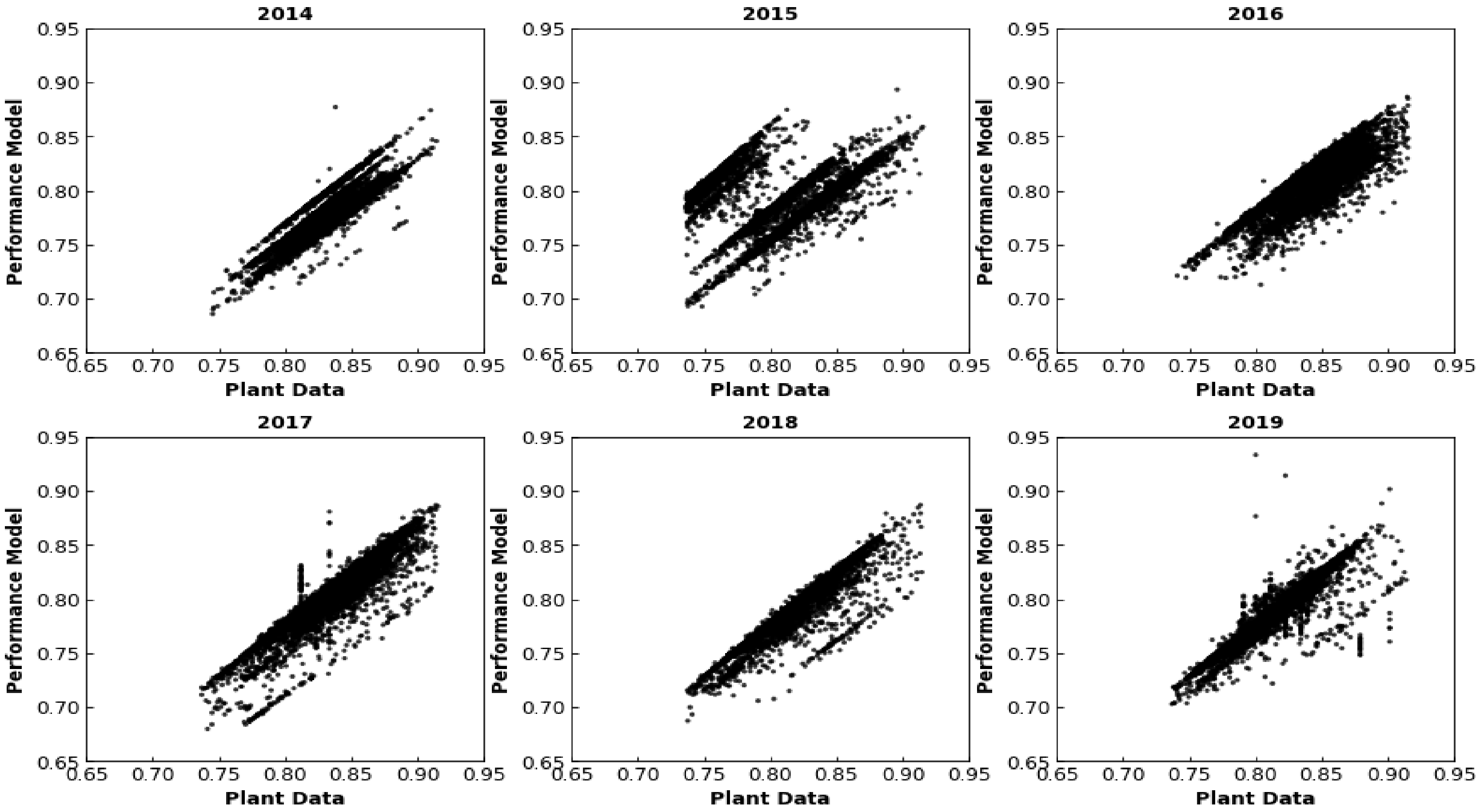
$$\frac{dM_{SG}}{dt} = \dot{M}_{SG} = \dot{m}_{coal} + \sum_{i=1}^{2}\left(\dot{m}_{PA,i} + \dot{m}_{SA,i} + \dot{m}_{RHI,i} - \dot{m}_{RHO,i} - \dot{m}_{SH,i}\right)$$
$$+\dot{m}_{FW} + \dot{m}_{DSH} - \left(\dot{m}_{BD} + \dot{m}_{FG}\right)$$

$$\frac{dE_{SG}}{dt} = \frac{d(M_{SG}h_{SG})}{dt} = \dot{E}_{coal} + \sum_{i=1}^{Air}\left(\dot{E}_i\right)_{in} + \sum_{i=1}^{water}\left[\left(\dot{E}_i\right)_{in} - \left(\dot{E}_i\right)_{out}\right] - \dot{E}_{FG} - \dot{Q}_{SG} + \sum_{i=1}^{11}\left(\dot{W}_i\right)$$

$$\eta_{SG} = \frac{\sum_{i=1}^{2}\left(\dot{m}_i h_i|_{SH}\right) - \dot{m}_{FW}h_{FW} + \sum_{i=1}^{2}\left(\dot{m}_i h_i|_{RHO} - \dot{m}_i h_i|_{RHI}\right)}{\sum_{i=1}^{11}\left(\dot{W}_i\right) + \sum_{i=1}^{2}\left(\dot{m}_i h_i|_{PA} + \dot{m}_i h_i|_{SA}\right) + HHV \cdot \dot{m}_{coal}}$$

Model Comparison to Energy Efficiency Data

- Y axis represents results of the Coco model X axis represents GRE plant data. 45º line is the best comparison.
- Results show that the modeled efficiencies are generally within -5% except in 2015 for a clearly delineated portion of the data
- We will reexamine the suspect 2015 data and calculations



Entropy $(\dot{S}_i = \dot{m}_i s_i)$ & Exergy $\dot{X}_i = \dot{m}_i(h_i - T_o s_i)$ Balance

$$\frac{dS_{SG}}{dt} = \dot{S}_{coal} + \sum_{i=1}^{Air}(\dot{S}_i)_{in} + \sum_{i=1}^{water}\left[(\dot{S}_i)_{in} - (\dot{S}_i)_{out}\right] - \left(\dot{S}_{FG} + \frac{\dot{Q}_{SG}}{T_b}\right) + \dot{\sigma}_{SG}$$

$$\frac{dX_{SG}}{dt} = \dot{X}_{coal} + \sum_{i=1}^{Air}(\dot{X}_i)_{in} + \sum_{i=1}^{water}\left[(\dot{X}_i)_{in} - (\dot{X}_i)_{out}\right] - \left(\dot{X}_{FG} + \dot{Q}_{SG} - T_o\frac{\dot{Q}_{SG}}{T_b}\right) + T_o\dot{\sigma}_{SG}$$

Exergy Efficiency:

$$\epsilon_{SG} = \frac{\dot{X}_{Out}}{\dot{X}_{In}} = 1 - \frac{(\dot{X}_D + \dot{X}_{Loss})}{\dot{X}_{In}} = 1 - \frac{\left(T_o\dot{\sigma}_{SG} + \dot{m}_{FG}x_{FG} + \dot{Q}_{SG}\left(1 - {T_o}/{T_b}\right)\right)}{\dot{X}_{In}}$$

- Theoretical exergy efficiency based on data is determined by minimizing the rate of both exergy destruction and exergy loss
- This optimum is achieved by maximizing the exergy in the products while minimizing the exergy destroyed

Optimum Exergy Efficiency:

$$\epsilon_{SG,Optimum} = 1 - \frac{(\dot{X}_D + \dot{X}_{Loss})_{min}}{\dot{X}_{In}} = 1 - \frac{\left(T_o\dot{\sigma}_{SG} + \dot{m}_{FG}x_{FG} + \dot{Q}_{SG}\left(1 - {T_o}/{T_b}\right)\right)_{min}}{\dot{X}_{In}}$$

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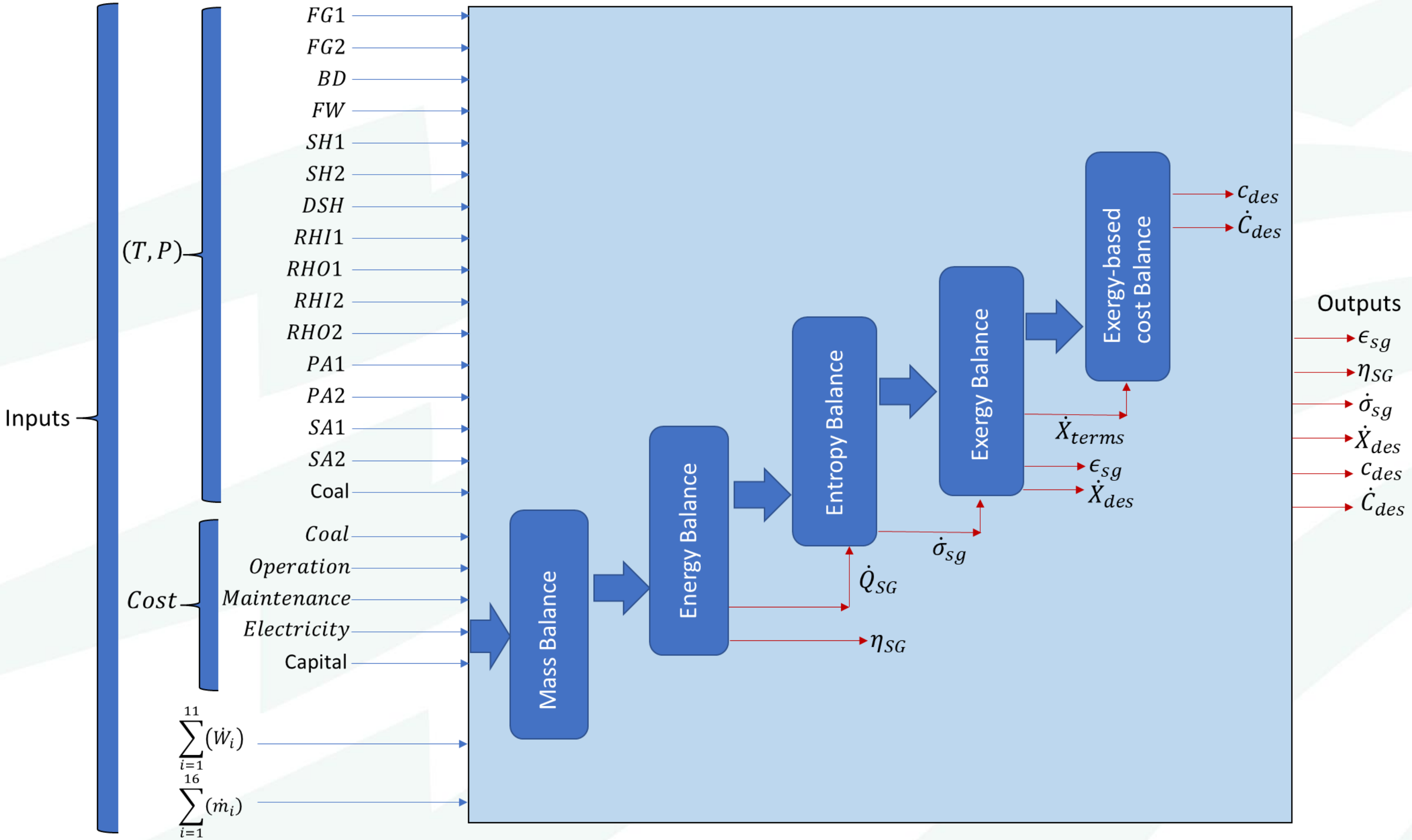
Performance Model: Modules



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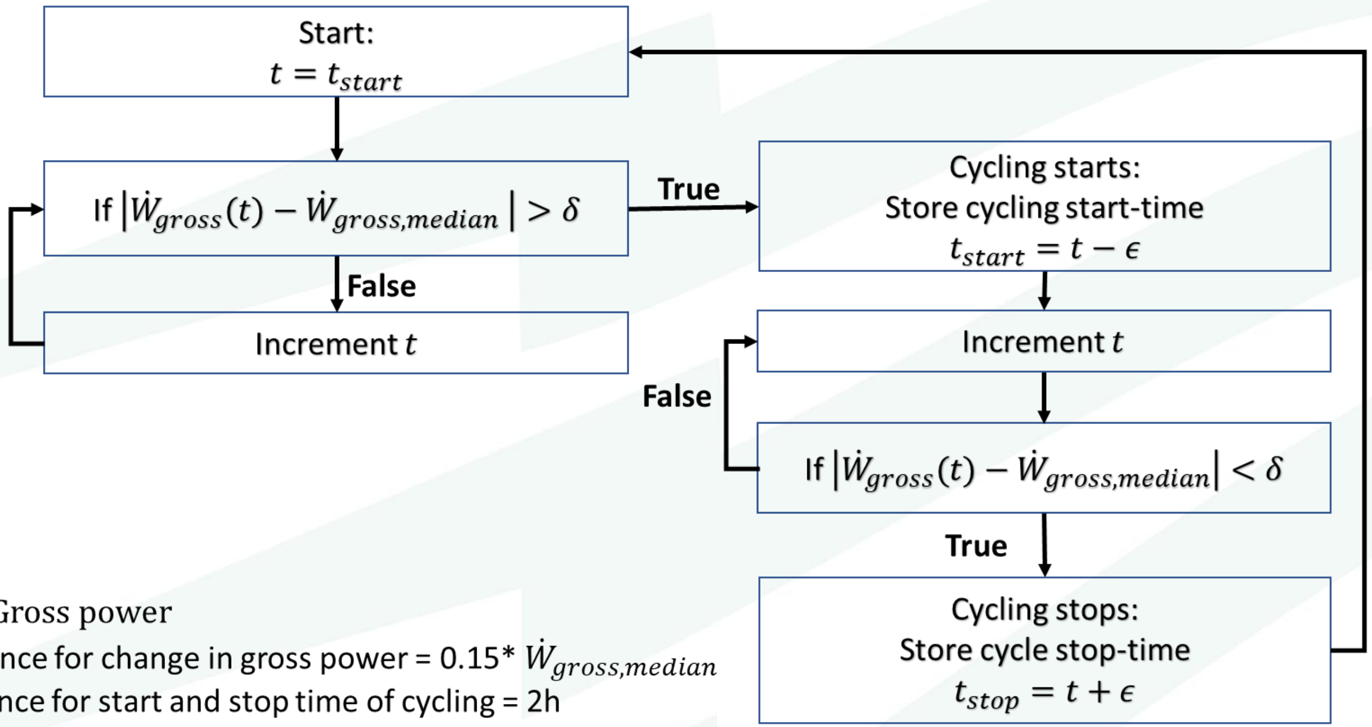
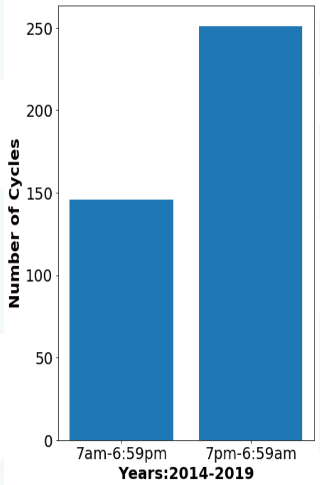
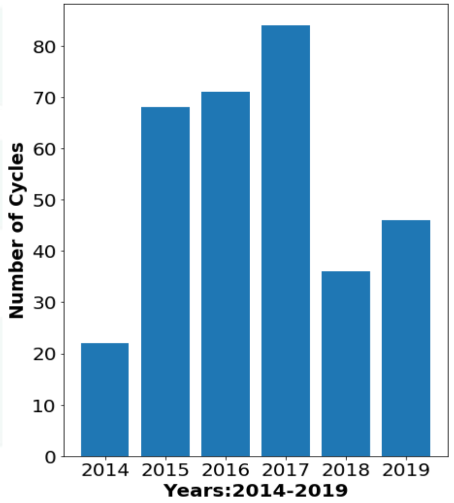
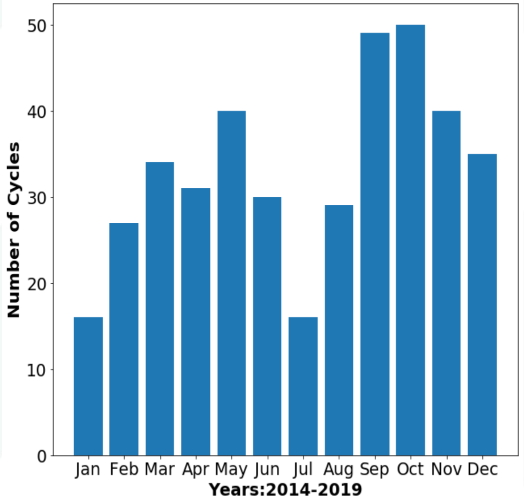
Identifying Cycling









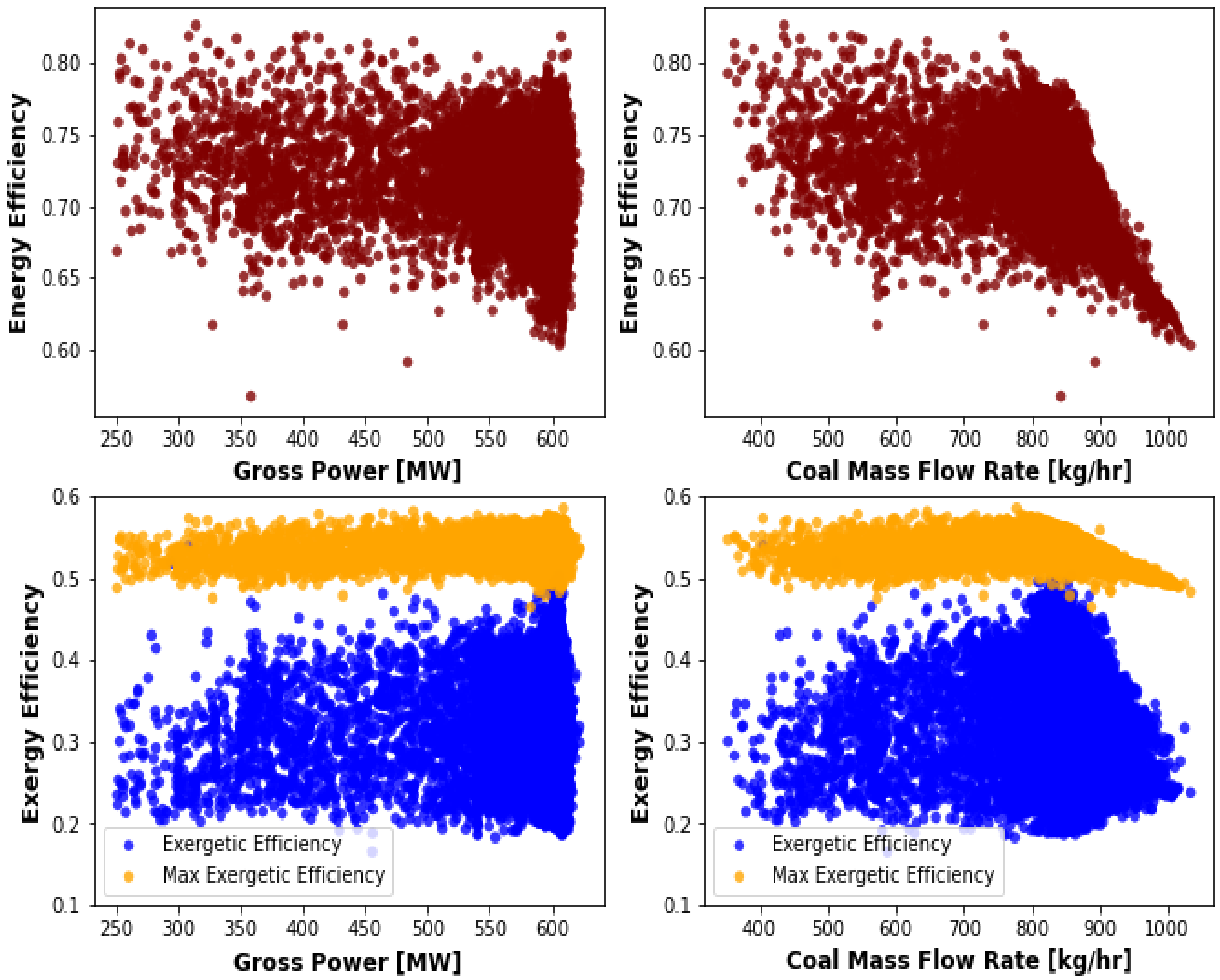
$\dot{W}_{gross}$: Gross power

δ: tolerance for change in gross power = 0.15* $\dot{W}_{gross,median}$

ϵ: tolerance for start and stop time of cycling = 2h

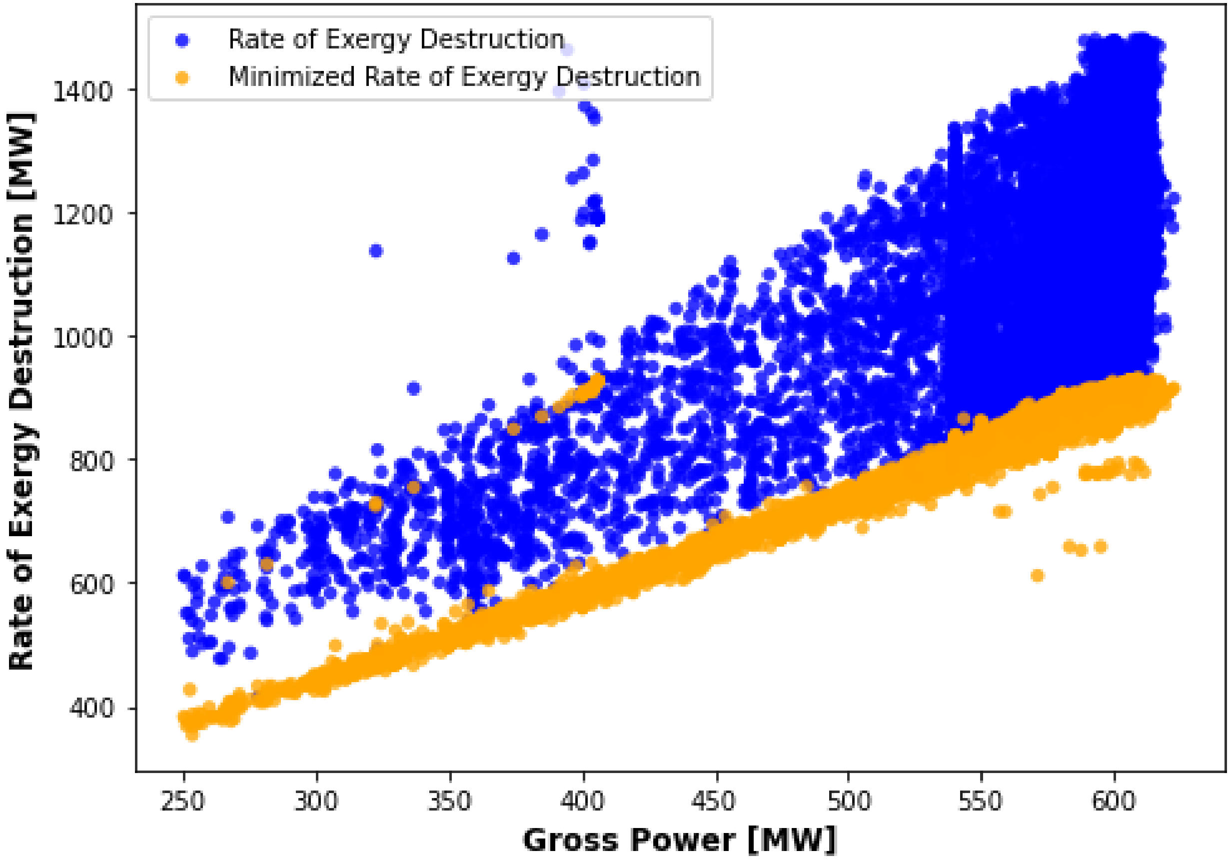
Energy vs Exergy Efficiency

- Load is represented as Gross Power (left column) and Coal Mass Flow Rate (right column). Representation as gross power is important for business but the representation by coal mass flow rate allows a focus on the steam generator
- Load as Gross Power:
  - Energy Efficiency increases at lower loads
  - Exergy Efficiency decreases at lower loads
  - Part load Exergy Efficiencies are lower
- Load as Coal Mass Flow Rate:
  - Energy Efficiency increases at lower loads
  - Exergy Efficiency decreases at lower loads
  - Peak Coal Mass Flow Rates result in lower Efficiencies
- Gold points represents Exergy Efficiency during optimum operating conditions based on historical performance



Potential for improved operations

- **Large variations in the rate of exergy destruction at high loads**
- **Lowest exergy destructions show a tight correlation of the rate of exergy destruction to gross power**
- **Significant room for performance improvements by optimization using exergy analysis**



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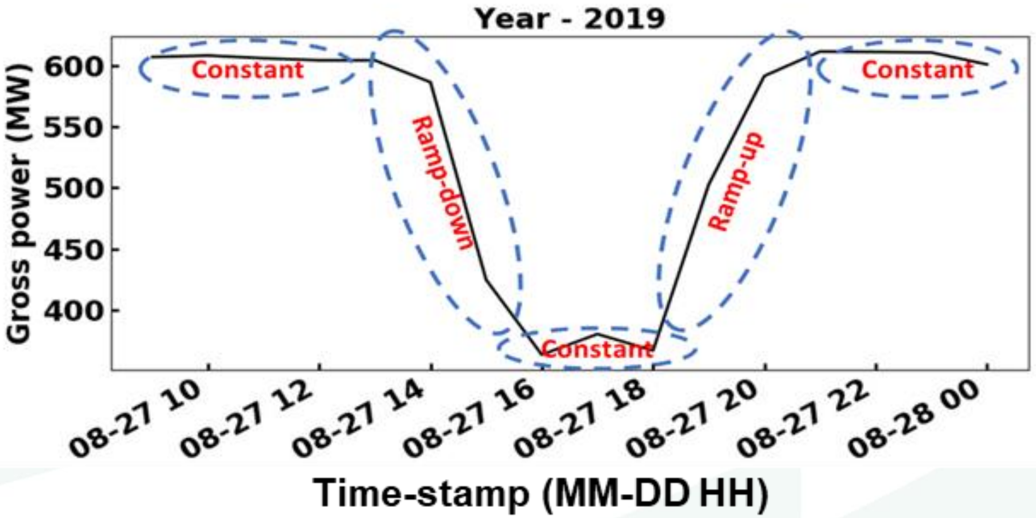
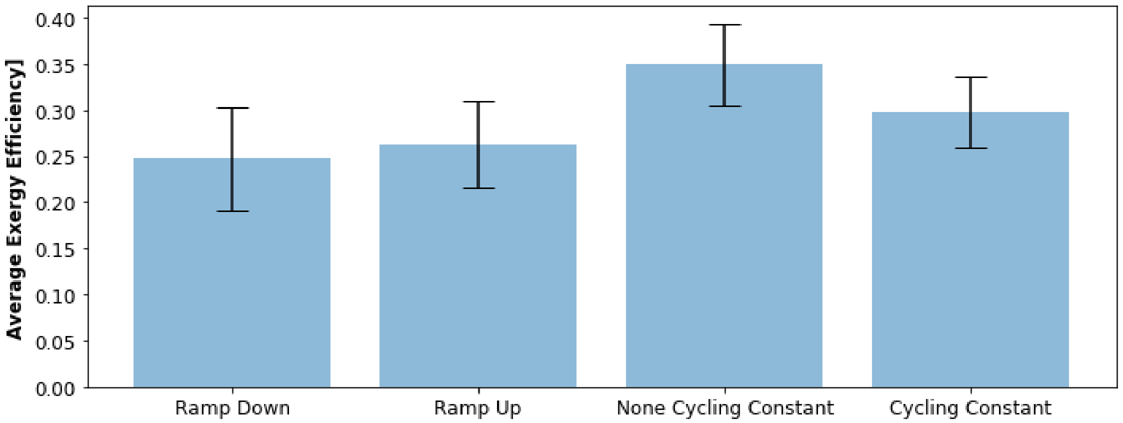
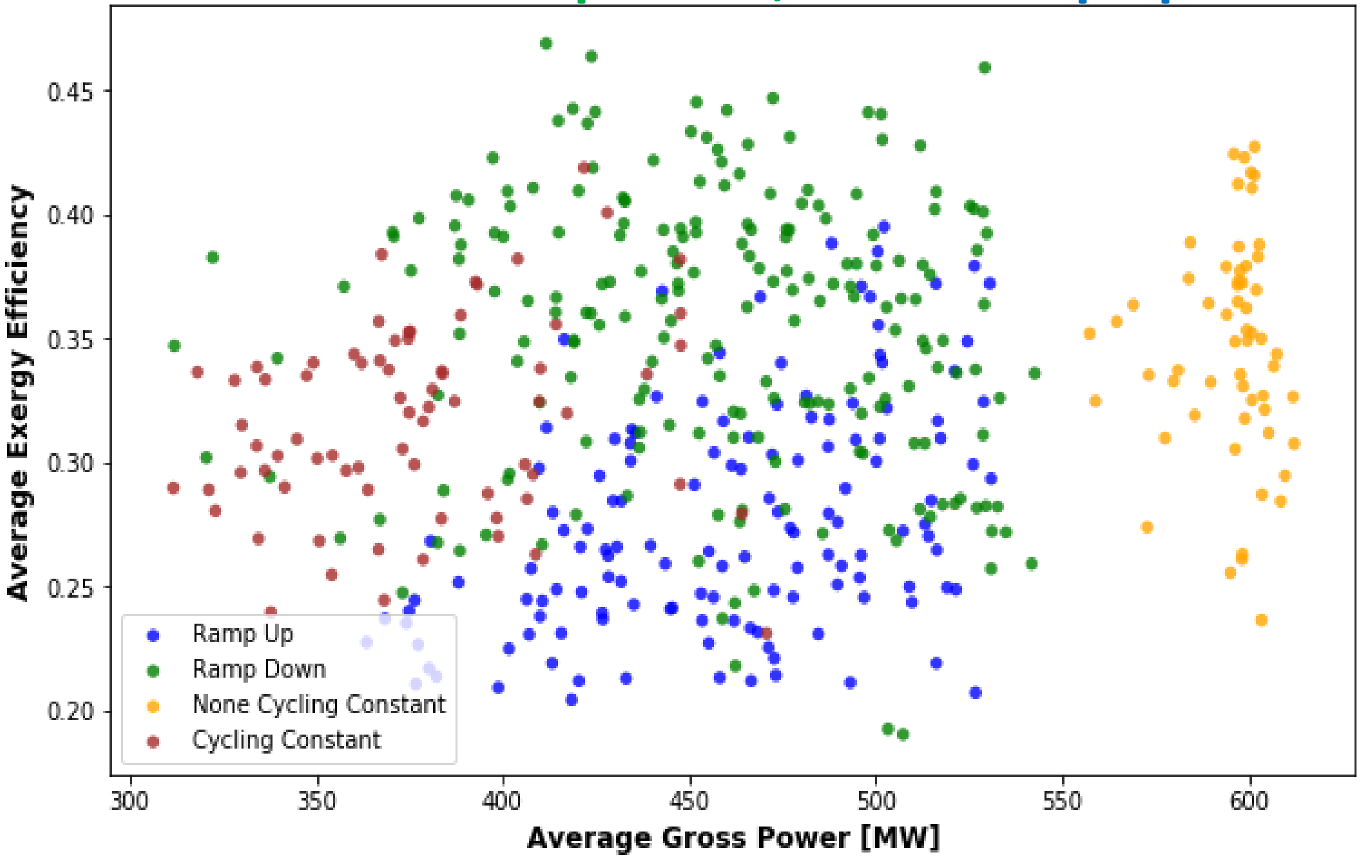
Example of Effects of Cycling





Gold: No cycling; Red: Cycling;
Green: Ramp down; Blue: Ramp up



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Cost Data

	Lignite coal [1]	Operation [2]	Maintenance [3]	Electricity [3]	Water [4]	Cost of Capital [5]
Period	**$/lbm**	**$/MWhr**	**$/MWhr**	**$/MWhr**	**$/Kgallon**	**$/MWhr**
2010	**0.022**	**4.04**	**3.99**	**111**	**3.75**	**12.8**
2011	**0.023**	**4.02**	**3.99**	**111**	**3.75**	**12.8**
2012	**0.023**	**4.38**	**4.48**	**102**	**3.75**	**12.8**
2013	**0.0225**	**4.57**	**4.41**	**105**	**3.75**	**12.8**
2014	**0.023**	**4.55**	**5.11**	**109**	**3.75**	**12.8**
2015	**0.0215**	**5.16**	**5.41**	**108**	**3.75**	**12.8**
2016	**0.02**	**5.05**	**5.53**	**102**	**3.75**	**12.8**
2017	**0.0195**	**5.01**	**5.13**	**102**	**3.75**	**12.8**
2018	**0.0195**	**5.19**	**5.27**	**102**	**3.75**	**12.8**
2019	**0.0195**	**5.19**	**5.27**	**102**	**3.75**	**12.8**
2020	**0.0195**	**5.19**	**5.27**	**102**	**3.75**	**12.8**

[1] “Coal Prices and Outlook - Energy Explained, Your Guide To Understanding Energy - Energy Information Administration.” [Online]. Available: https://www.eia.gov/energyexplained/index.php?page=coal_prices.

[2] “SAS Output.” [Online]. Available: https://www.eia.gov/electricity/annual/html/epa_08_04.html.

[3] “Lazard.com | Levelized Cost of Energy 2017.” [Online]. Available: https://www.lazard.com/perspective/levelized-cost-of-energy-2017/.

[4] “The City of Fargo - Water & Sewer Rates.” [Online]. Available: https://fargond.gov/city-government/departments/auditors/utility-billing-department/water-sewer-rates.

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Exergy-Based Cost Analysis

Total Exergy destruction $

Specific Exergy destruction $

Pumps and Fans exergy destruction $

Exergy destruction by inflows and outflows of coal, air, flue gases and ash $

$$\boldsymbol{C_D} = \boldsymbol{c_D X_D} = \sum_{i=1}^{11} \boldsymbol{c_i (W_i)} + \sum_{i=1}^{Air} \boldsymbol{(c_i X_i)_{in}} + \boldsymbol{c_{coal} X_{coal}} - \boldsymbol{c_{FG} X_{FG}} + \sum_{i=1}^{water} \boldsymbol{[(c_i X_i)_{in} - (c_i X_i)_{out}]} - \sum_{Q=1}^{Heaters} \boldsymbol{c_Q X_Q} + \boldsymbol{Z}$$

Exergy destruction by inflows and outflows of water into feedwater heaters, boiler vessel, reheaters, superheaters, and desuperheaters $

Heat loss through the insulations $

Capital Investment Operations & Maintenance costs $

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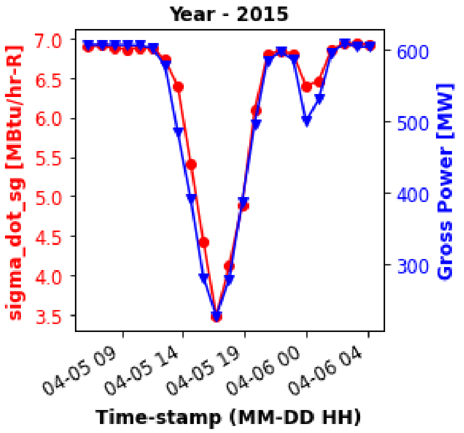
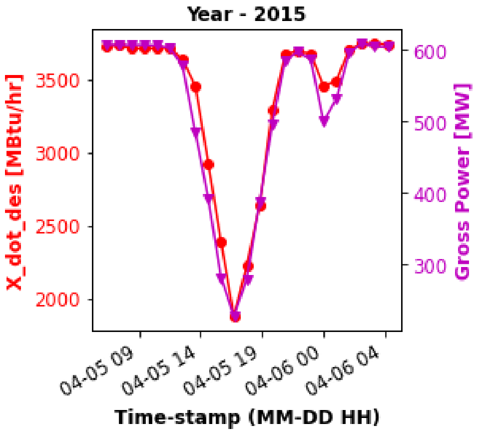
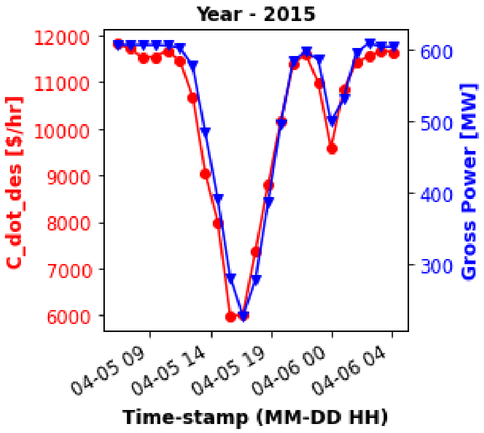
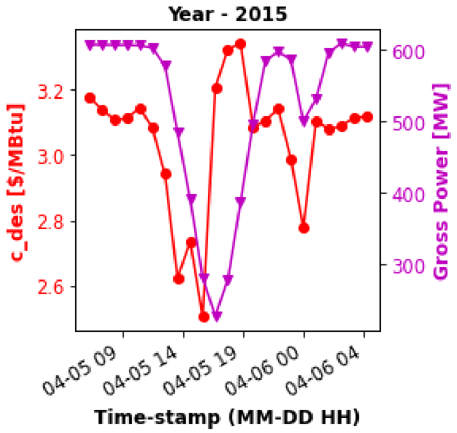
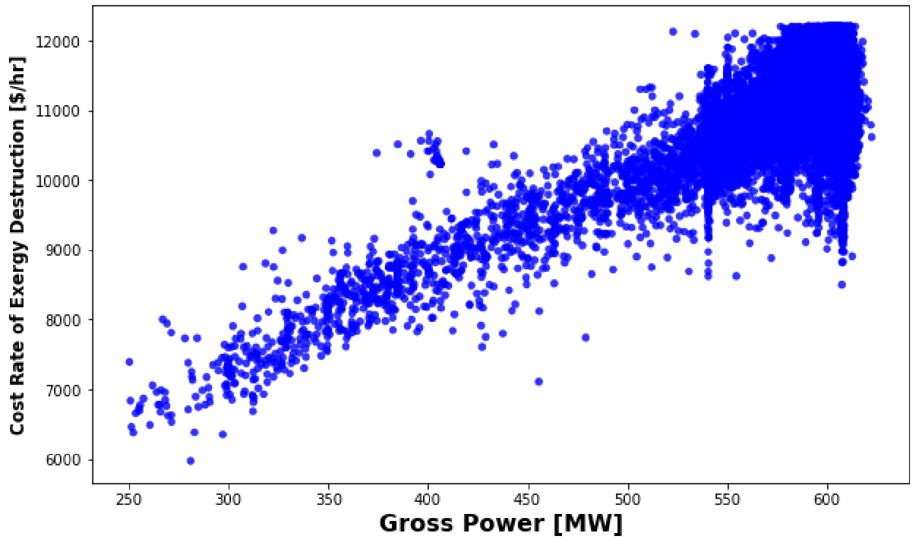
Cost Of Irreversibility

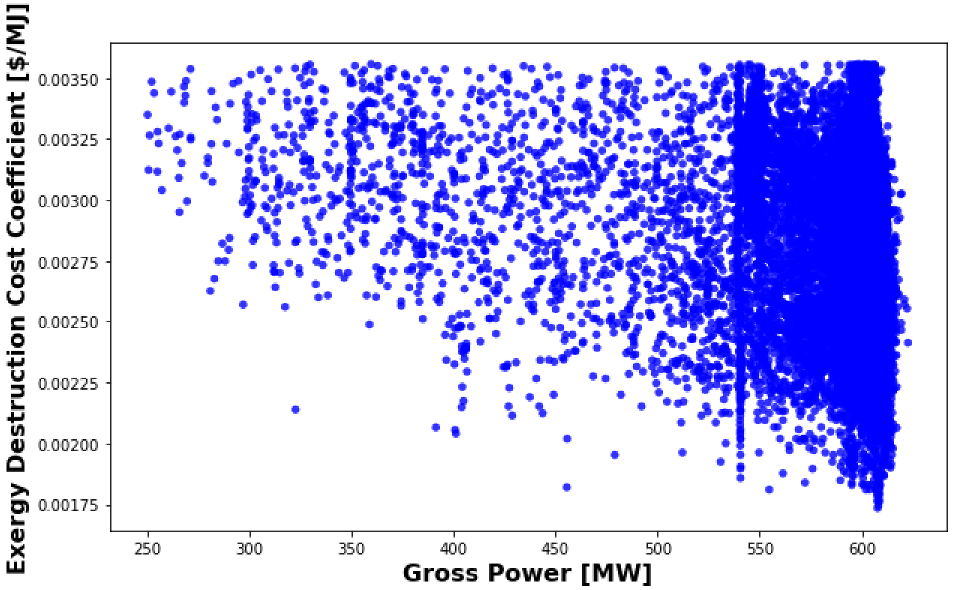












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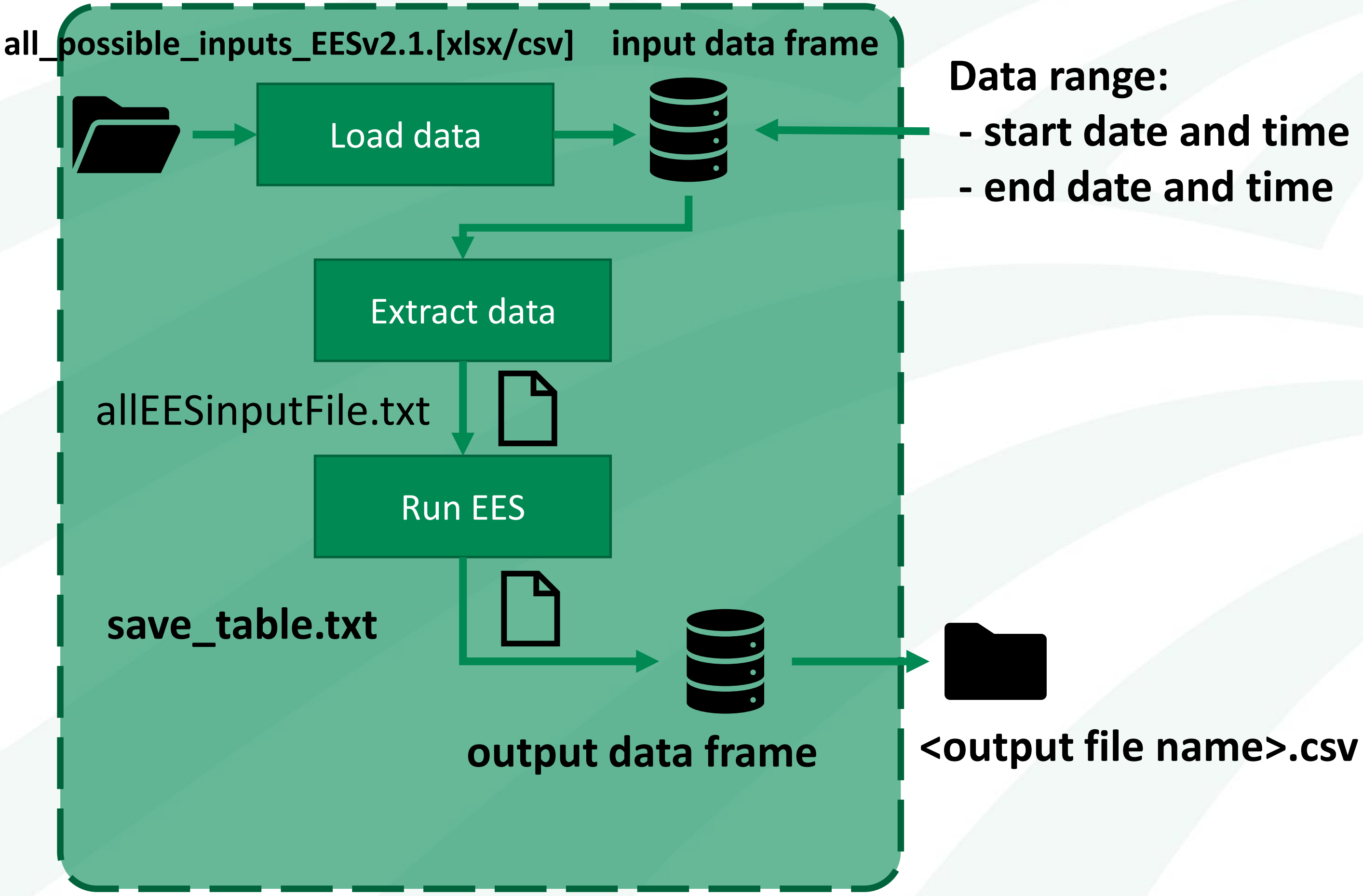
PNNL Modeling Workflow and Performance Testing

- **Updated workflow for running boiler performance and exergy cost models for enhanced automation**

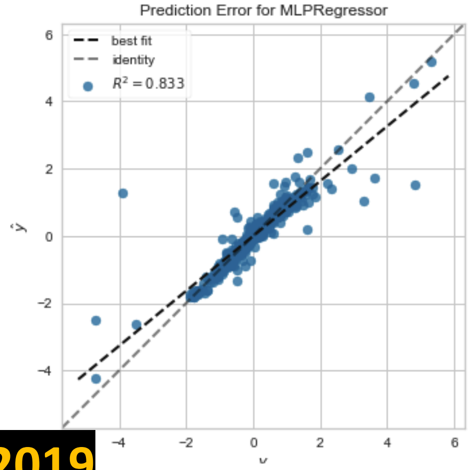
- **Models validated to run on PNNL computation platform with reproducible results**

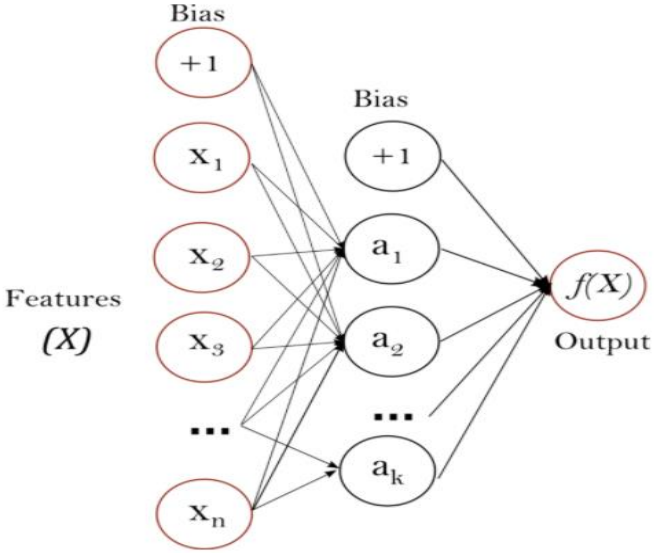


PNNL Data-driven Boiler Performance Model

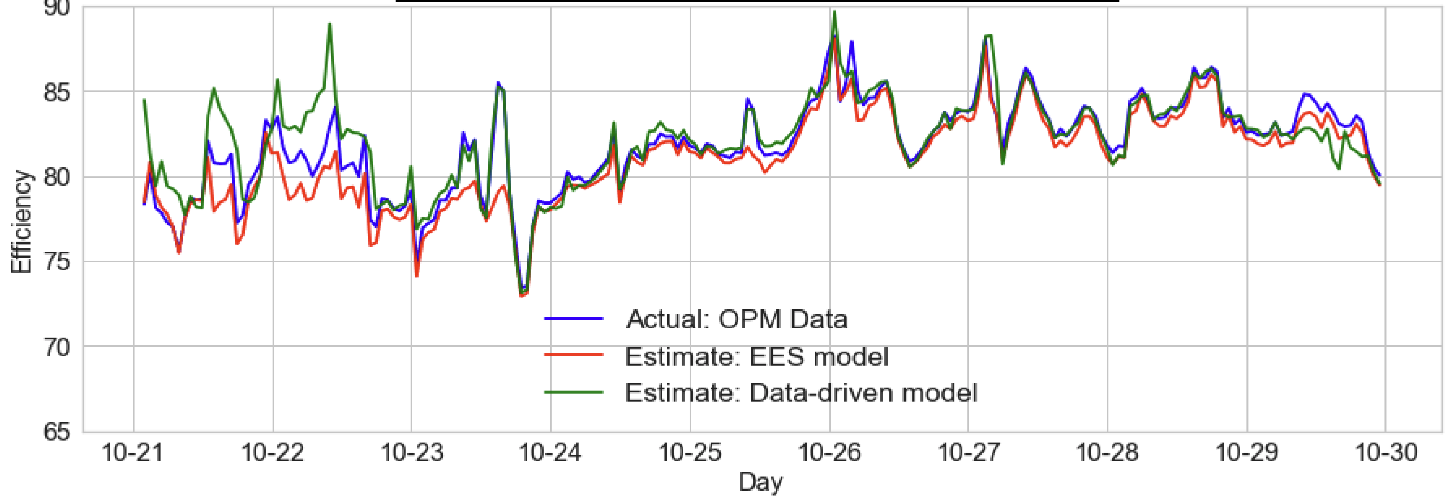
Boiler plant efficiency modeling

- ANN model captures the Coal Creek Station Online Performance Monitoring (OPM) data and Physics-Based Model with (Engineering Equation Solver - EES)
- Model output captures OPM data trends with small errors





Efficiency Model Validation 2019



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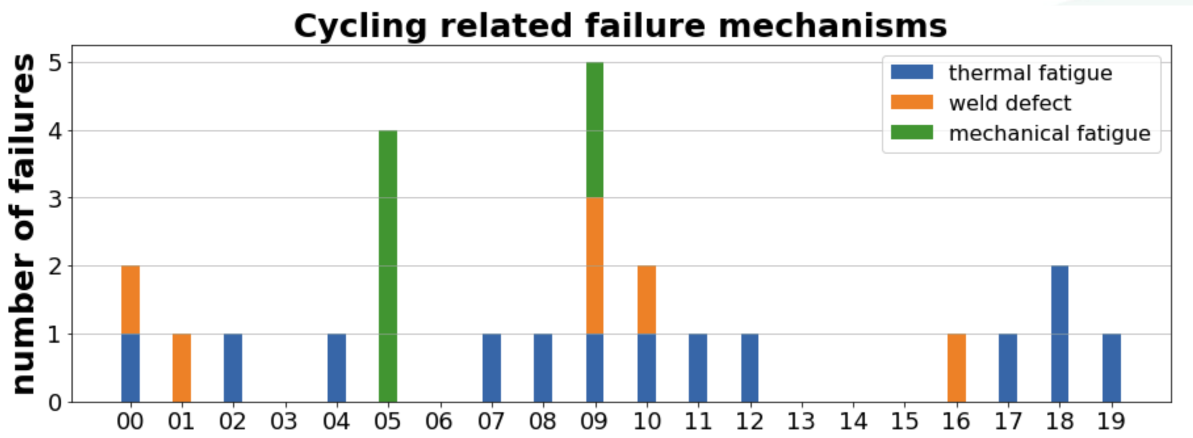
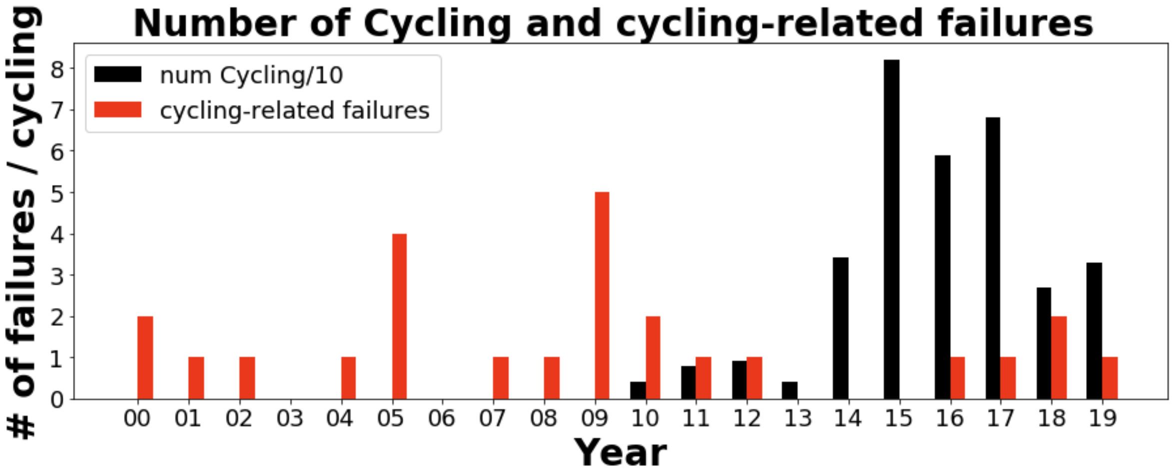
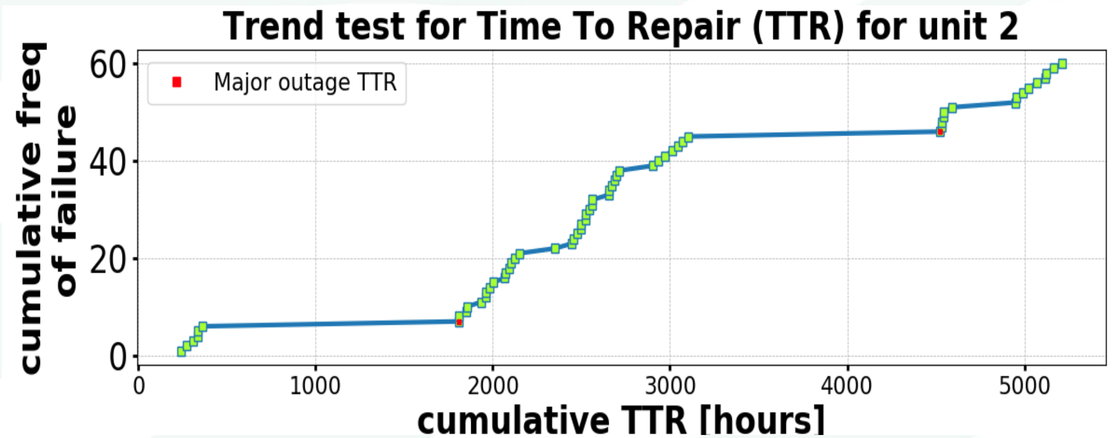
PNNL Data Analytics towards Reliability Model

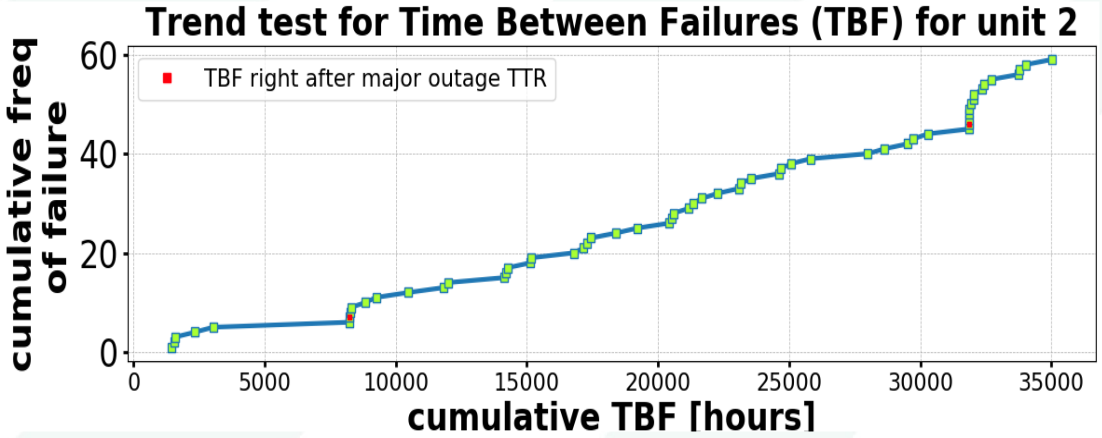
Probabilistic Methods





TTR: Time To Repair; TBF: Time Before Failure





Accomplishments

Journal Manuscripts (In preparation 2020)

- **Energy : A data-driven model to predict thermodynamic properties of a steam generator under cycling operation**
- **Applied Energy: Cyclic loading condition analysis of a steam generator in a coal-burning power plant**
- **Energy Conversion and Management: Exergy-based cost analysis of a coal-fired steam generator under cyclic loading**

Completed Milestones

- **Tasks 1.1 Physics based model**
- **Tasks 1.2 Exergy-cost based model**

Personnel: Abhishek Navarkar received MSME and is now working for MATLAB

Challenges & Future Plan

- Reliability model
  - Challenges in correlating maintenance expenses to cycling events
- Model generalization
  - Challenges in developing generalized schema for executing models
- Future work:
  - Implement model at CSS
  - Model refinements based on CSS run
  - API for generation planning and dispatch model(s)
  - Release and publicize

Summary

- Goal: Develop a tool that is easy to deploy and use, to estimate cost of cycling large coal boilers
- Plan: Develop hybrid model → Calibrate and test model → Deploy model at CSS and refine
- Progress: Completed boiler performance model and exergy cost model complete
- Challenges: Reliability analysis and model generalization
- Future Work: Implement → Refine → Release

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Questions?