Advanced Modeling and Optimization to Support the Existing Fleet

April 9, 2019

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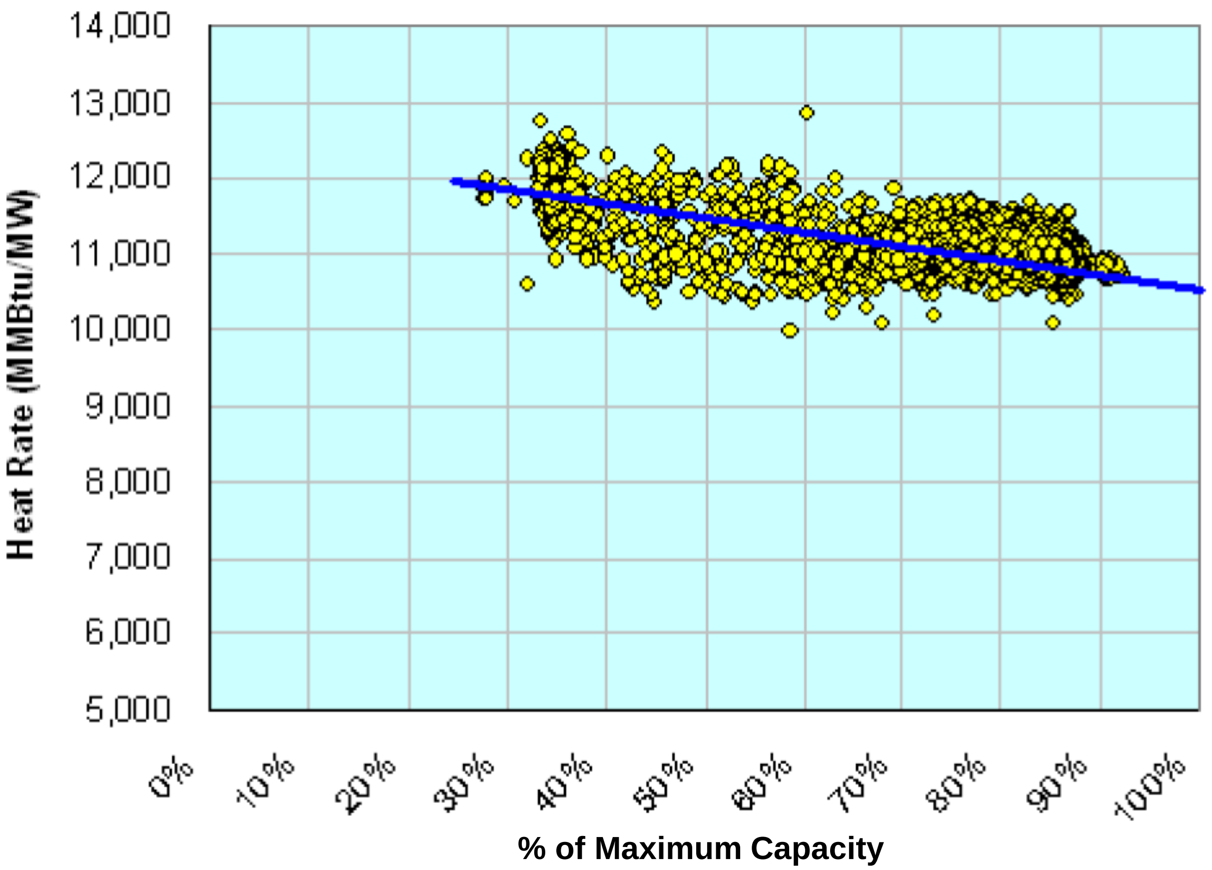
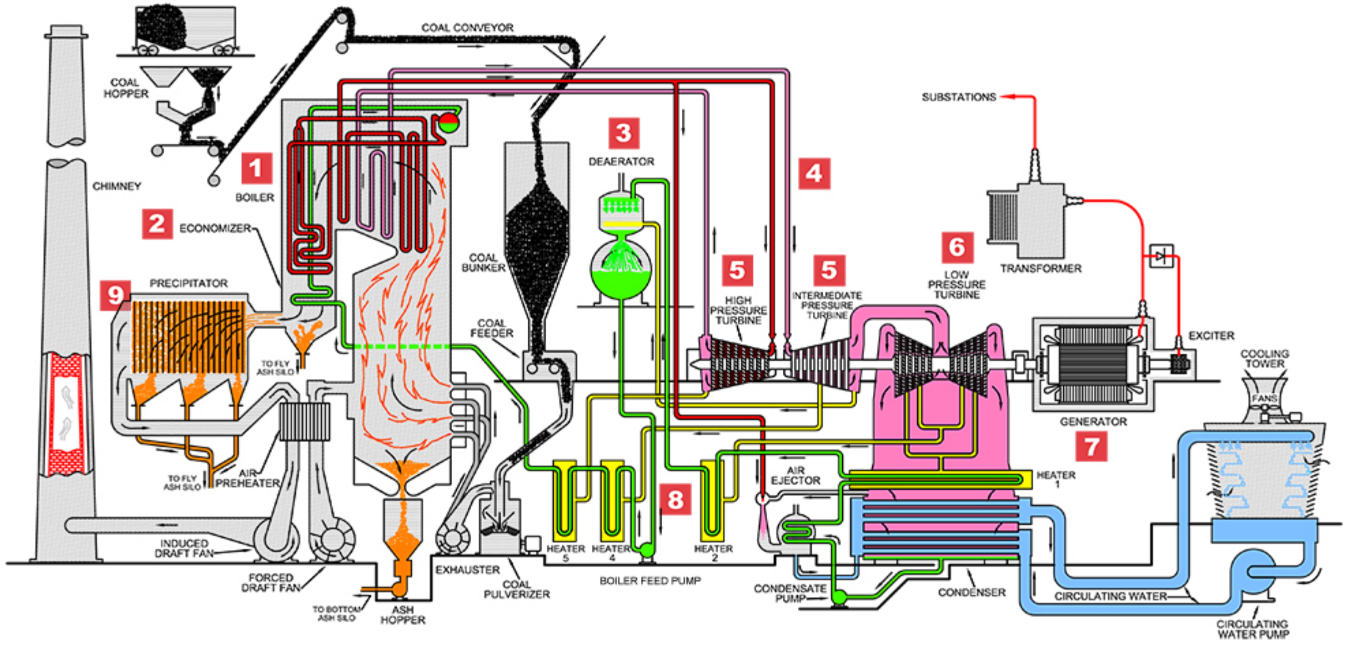
Why are we doing this work?

- **FE Strategic Goal to develop technologies, verified through modeling, that improve the average heat rate (i.e., efficiency) of a typical coal-fired power plant**
- 80% of coal power plants are 30+ yrs old.
- Plants designed for base-loaded operation are being forced to cycle their load.
- Operations at partial load are far from optimized!
- 1% heat rate reduction for a 500 MW plant → $700K/year fuel cost savings



* Figure source: Power Generation Energy Efficiency Opportunity Identification Report, ABB, 2010

Accomplishments to Date



Source: Electric Power Research Institute, "Primer on Flexible Operations - 3002000045," EPRI, Palo Alto, Ca, September 2013

- Usable PSE framework for constructing optimization-ready process models
- Steady-state power plant model
  - Boiler fire side (combustion, NO_x, SO_x formation)
  - Boiler water side (vertical tubes, convective superheaters, economizer)
  - Steam cycle (turbines, condenser, feedwater heaters, deaerator)
  - Pollution controls (SCR, FGD)
- Established partnership with Tri-State Generation & Transmission Association

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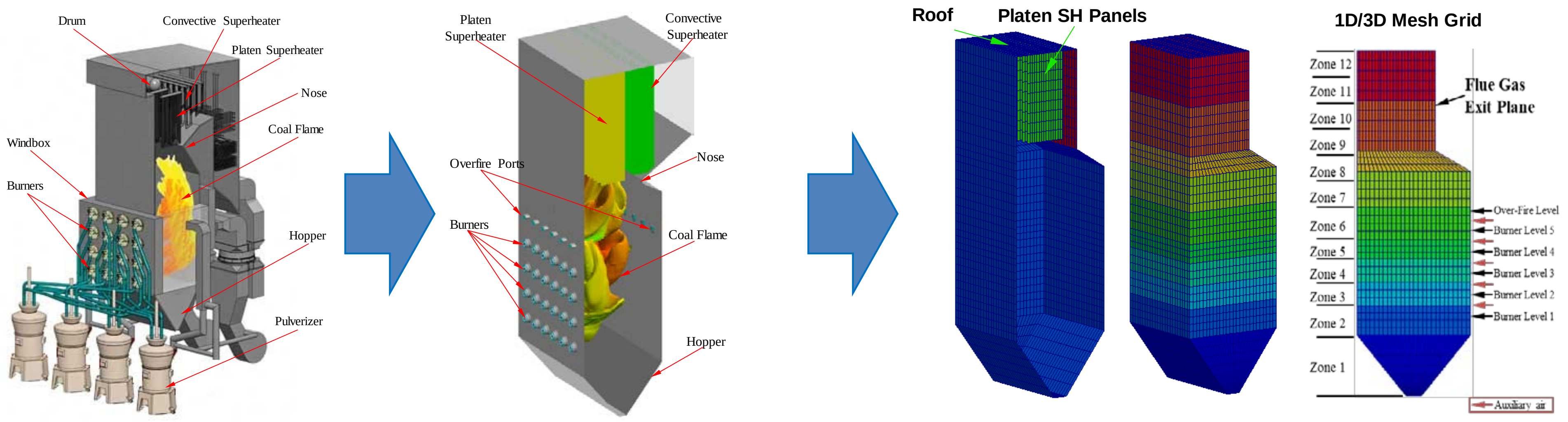
Key Features: Optimizing with High Fidelity Models



- 1-D discretization along furnace height
  - Uniform flow properties in each zone
  - Combustion & char kinetics
- 3-D discretization for radiation model
  - Radiation intensity
  - Radiative heat loss

	Unit	(1-2 minutes) Hybrid Model	(days-weeks) CFD Model	Error%
Flue Gas Temp. at Horizontal Nose	K	1679	1674	0.3%
Carbon Burnout	wt %	99.86	99.70	0.2%
Heat Loss to Enclosure Wall *	W	4.108×10^8	4.36×10^8	5.8%
Heat Loss to Platen SH Wall	W	1.018×10^8	1.02×10^8	0.2%

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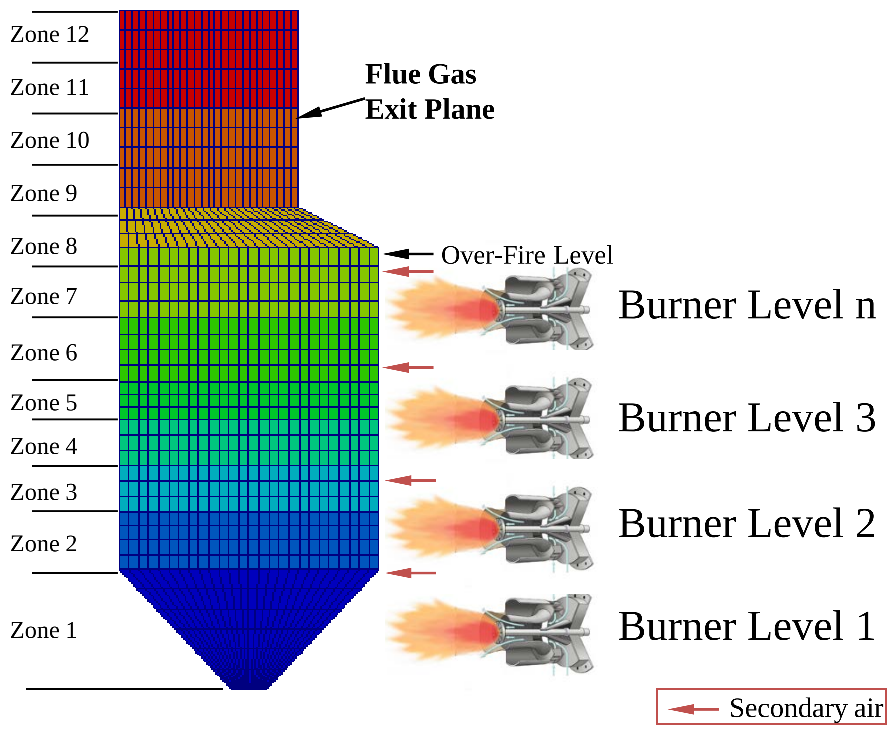
Key Features: Highly Accurate Algebraic Surrogate Models

Inputs

- Fuel flow rate
- Wall temperature (each zone)
- Stoichiometric ratio
- Secondary air temperature
- Burners operation
  - Full load (i.e. n burners)



Outputs

- Flue gas exit temperature
- Heat transfer rate
- Flue gas composition
  - x_{CO2}
  - x_{H2O}
  - x_{O2}
  - x_{NOx}
  - x_{SOx}
- Unburned carbon

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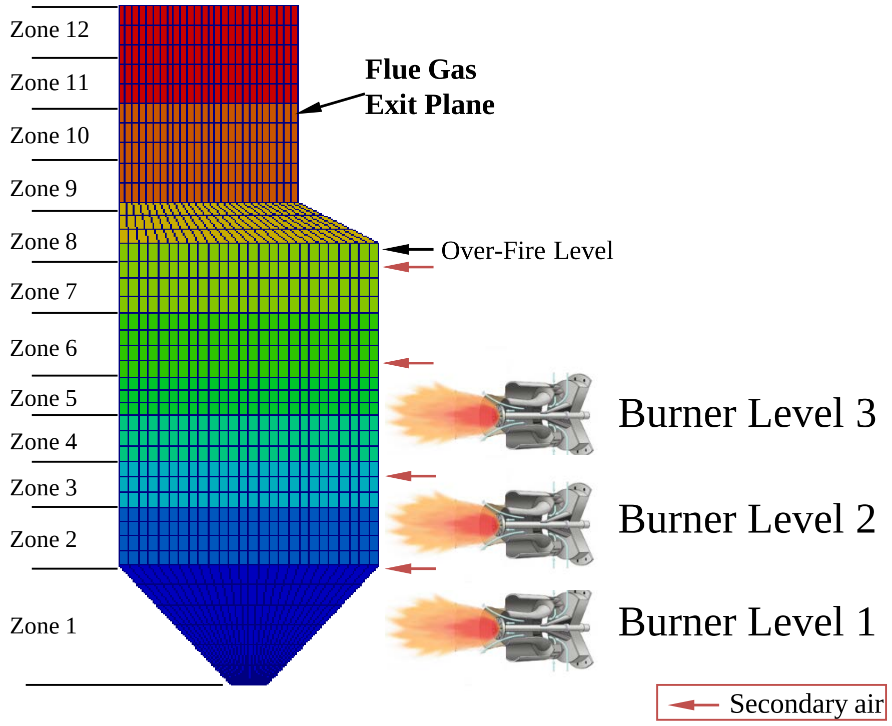

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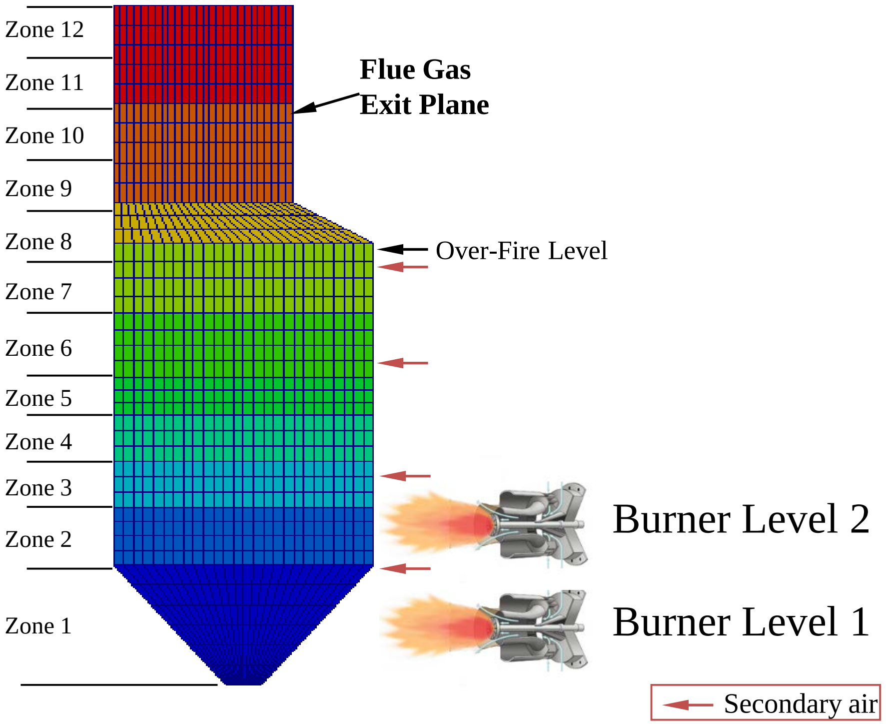

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Key Features: Highly Accurate Algebraic Surrogate Models

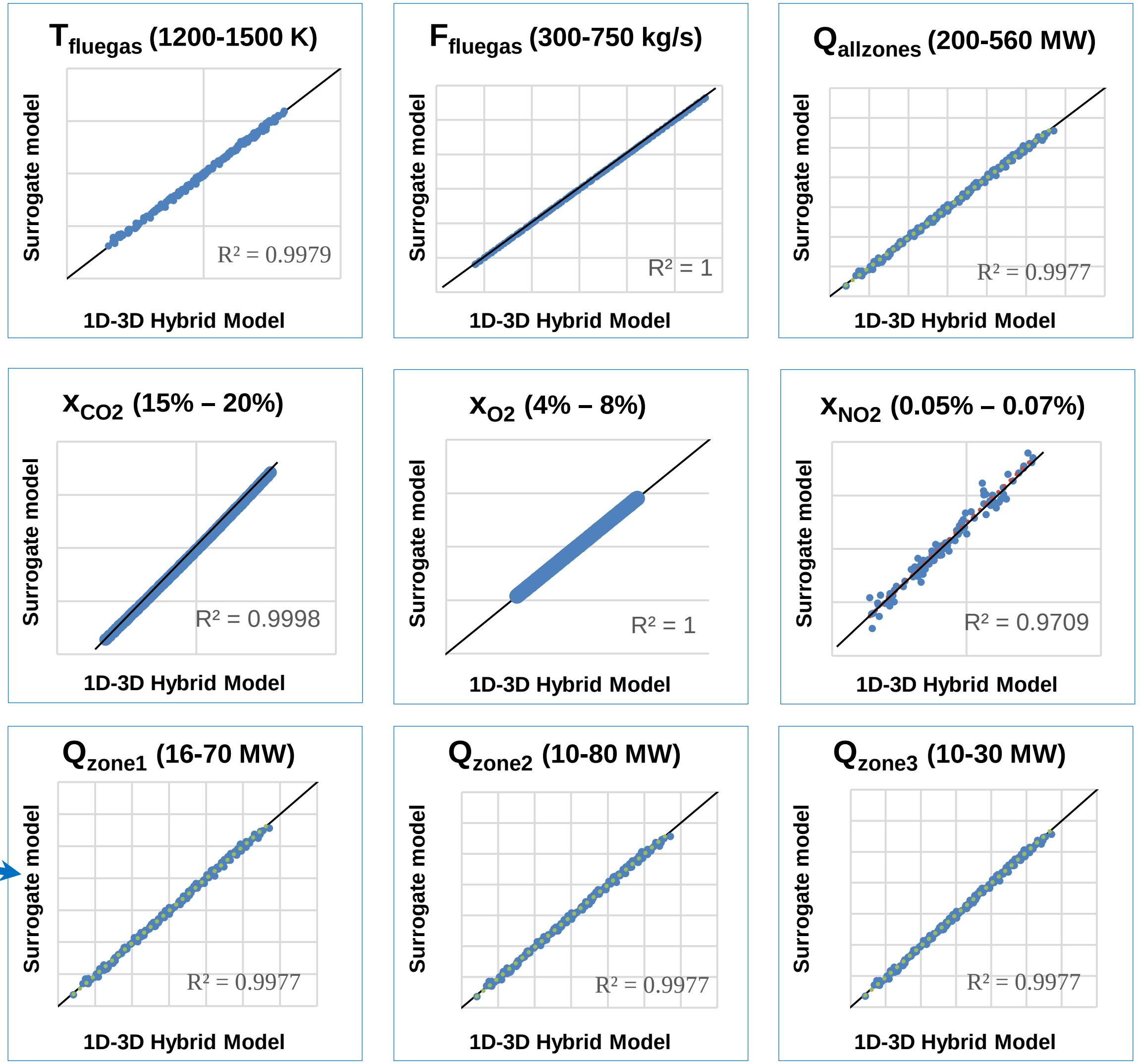
Surrogate models developed using ALAMO
(Cozad, Sahinidis, Miller, AICHE J, 2014)

Inputs, Latin hypercube sampling

- Fuel flow rate
  - 20 – 90 kg/s
- Wall temperature (each zone)
  - 400 – 1100 K
- Stoichiometric ratio
  - 1.1-1.2 actual O_2/ stoichiometric O_2
- Secondary air temperature
  - 550 – 650 K
- Burners operation
  - Full load (i.e. n burners)
  - Mid load (i.e. 3 burners)
  - Low load (i.e. 2 burners)

$$Q_1 = \alpha_1 F_F + \alpha_2 2ndAirT - \alpha_3 T_{w1} + \alpha_4 T_{w2} + \alpha_5 T_{w7} + \alpha_5 T_{w7} + \log(2ndAirT) - \log(F_F) \ \ldots$$

Outputs



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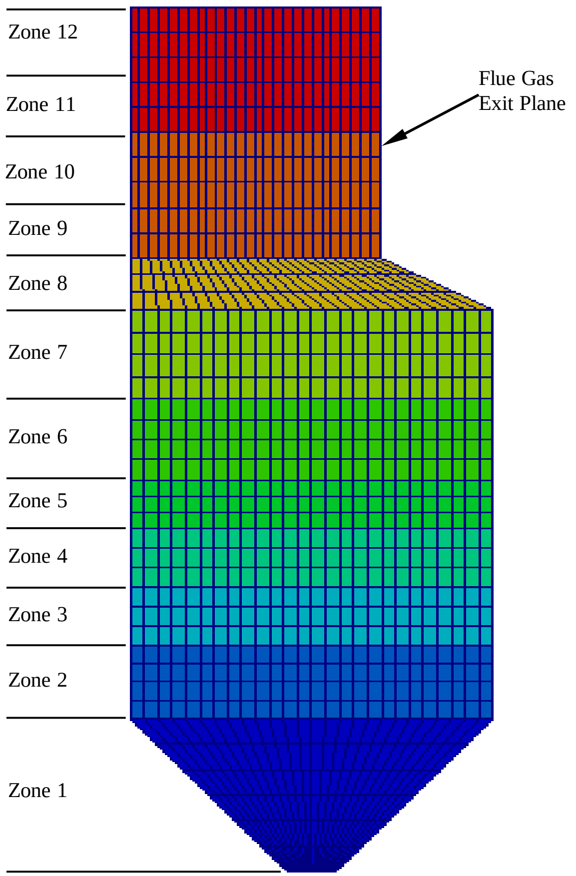
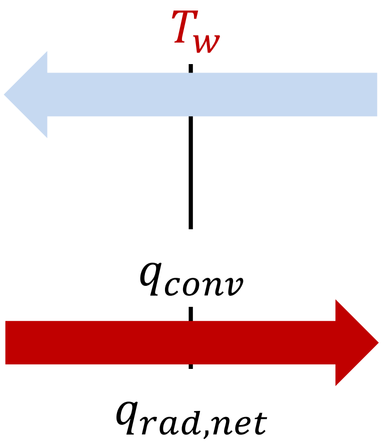
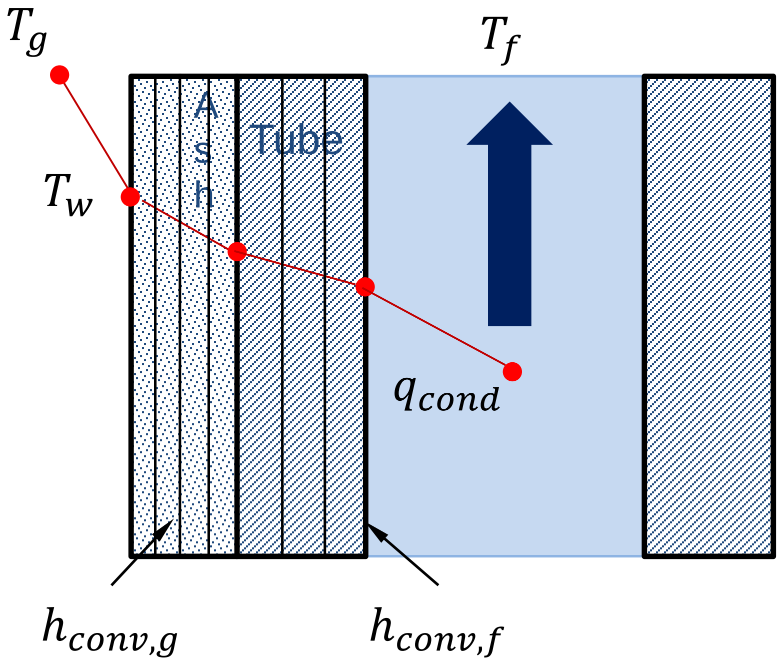
Key Features: Coupled Fire Side and Water Side Boiler Models

Fire Side

Water Side







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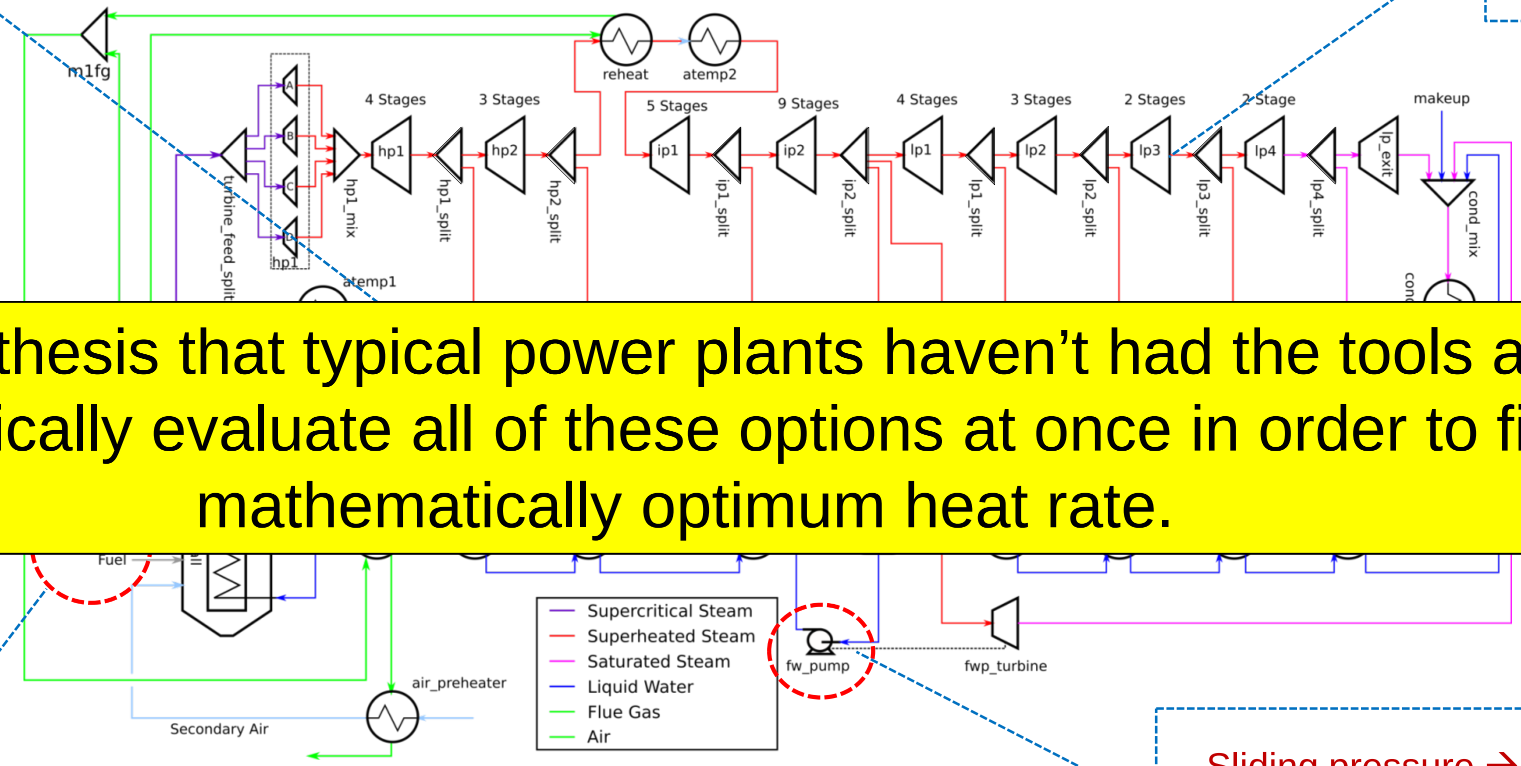
Key Features: Optimization under Design & Off-Design Conditions

Fixed pressure
→ Fix pressure of BFW in boiler but change pressure at turbine inlet

Steam extraction rates (at full and partial loads)



It is our hypothesis that typical power plants haven't had the tools available to systematically evaluate all of these options at once in order to find the mathematically optimum heat rate.

Coal firing rate

Sliding pressure → Change pressure of BFW in boiler

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Escalante Generating Station

- Wholly owned and operated by Tri-State G&T
- Built 1984 (~120 employees)
- Baseload: 245 MW
- Average Heat Rate: 10,884 BTU/KWH (net)
- Subcritical unit
- Frequent cycling
- Coal:
  - Lee Ranch Mine, 37 miles away
  - Low S, 800,000 tons/yr
- Other info:
  - Sliding pressure ramping
  - Some steam sold to paper recycle facility
  - Zero liquid discharge, evaporation ponds for wastewater

Initial focus areas:
Reducing minimum load
Improving heat rate at all loads

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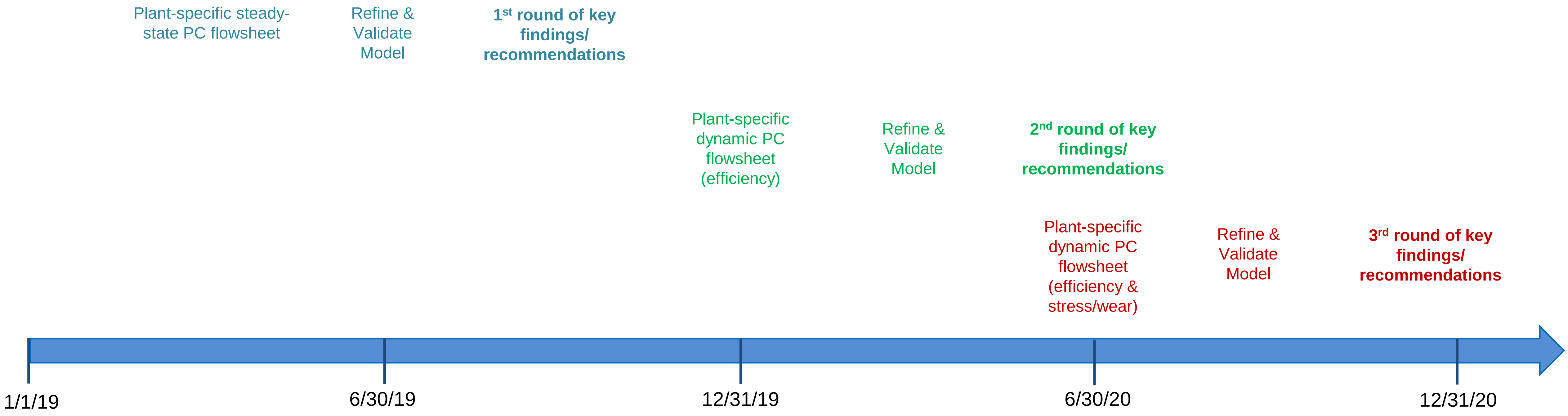
2019-2020 IDAES Power Plant Optimization Timeline



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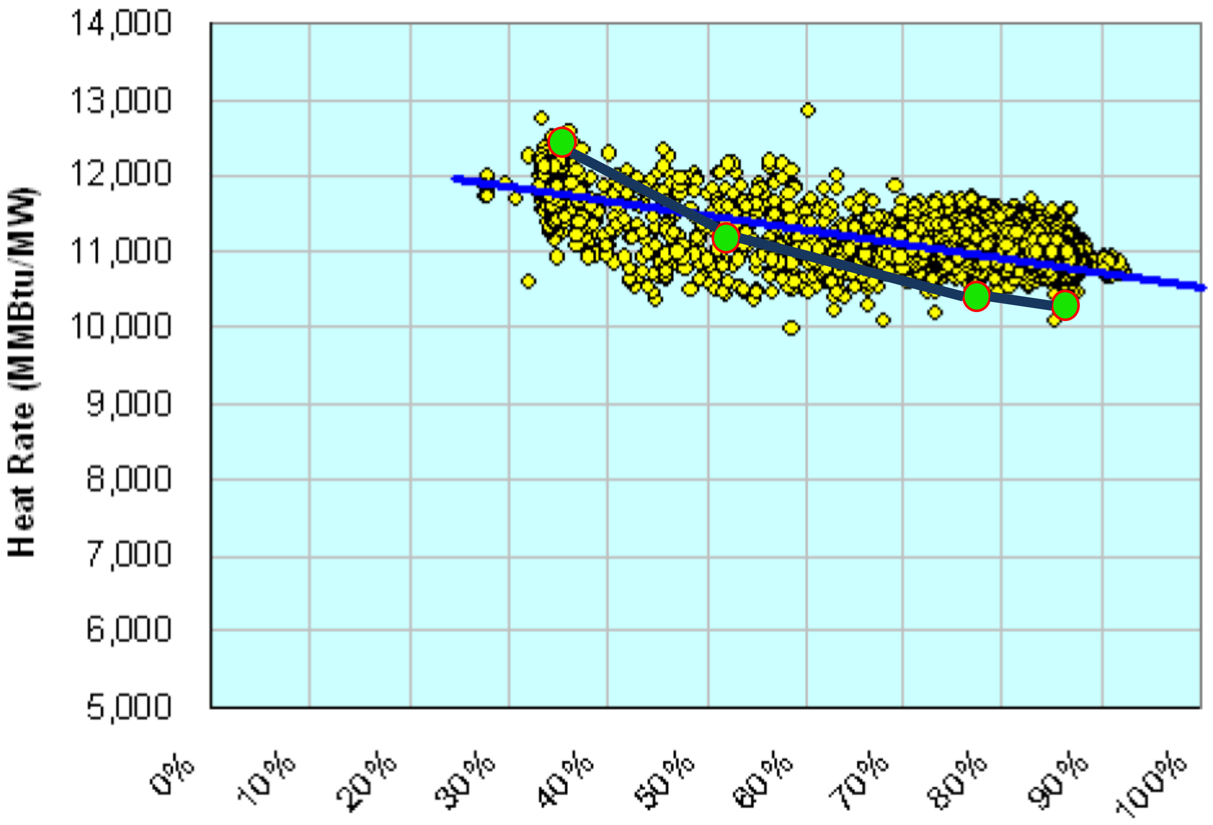
Customizing IDAES Models to Escalante Plant

- Creating process flow diagram (PFD) representing process flow connectivity of Escalante plant
  - Discussions from site visit
  - Piping & Instrumentation Diagrams
- Locating equipment geometries and specifications necessary for modeling
  - 1000’s of pages of equipment drawings, plant manuals
- Identifying measurement tags of high interest
  - 30+ screenshots from Distributed Control System (DCS)
  - Master list of 6000 data points routinely collected
- Creating and modifying IDAES flowsheet model to match Escalante topology and specifications
- Mapping operating data to our process flow diagram and then to our model variables

Working with Power Plant Data

- Significant unexplained variability exists (~ +/- 10-15%)



* Figure source: Power Generation Energy Efficiency Opportunity Identification Report, ABB, 2010

Potential reasons:
1) Variability in coal flow rate
2) Variability in heat content of coal
3) System dynamics
(takes time for changes in coal flow rate to impact power output)
4) Several others
(ambient temperature differences, equipment performance degradation, etc.)

Rigorous performance tests are the current standard but…
They occur infrequently.
They do not quantify uncertainty.

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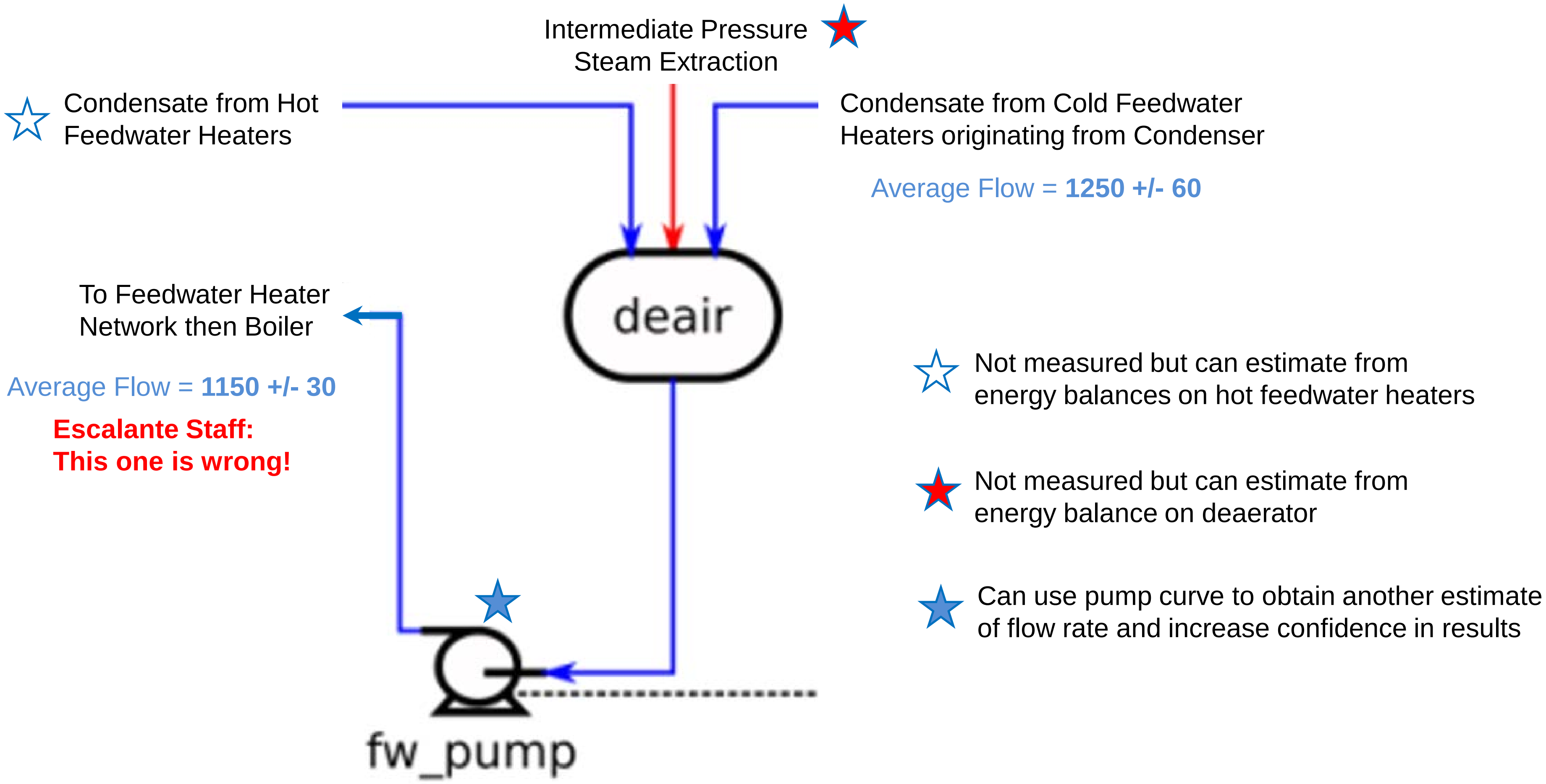
Working with Power Plant Data

- Gross errors exist
- Won't initially have all data required for useful modeling



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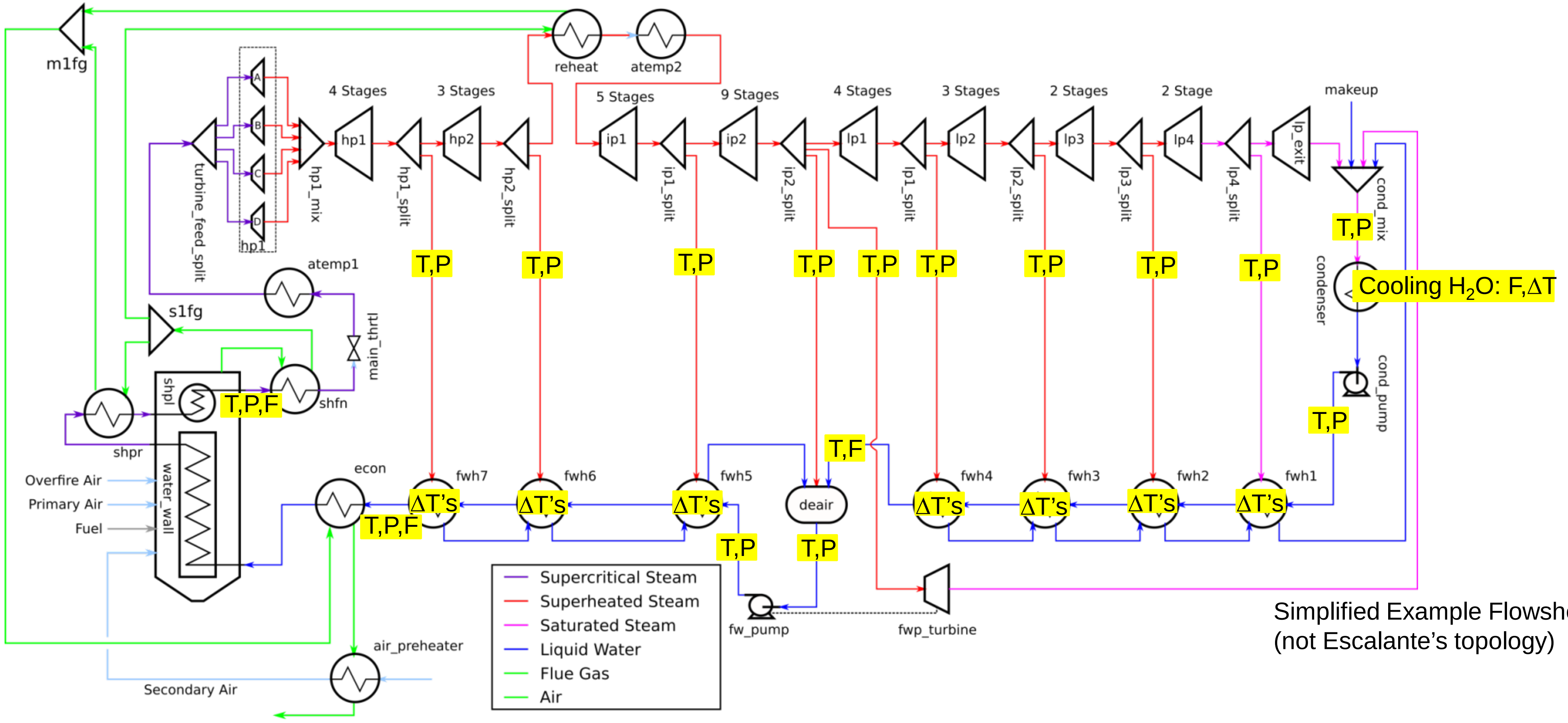
Working with Power Plant Data

- Applying a systematic way of filling in knowledge gaps and leveraging measurement redundancy



Simplified Example Flowsheet
(not Escalante's topology)

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Implementing Data Reconciliation

- Uses process information and mathematical models (e.g., mass & energy balances) to automatically correct measurements and **produce a single, consistent set of data representing most likely process operation**.

- Gross Error Detection: Identify and remove gross measurement (or model) errors

- Identifiability Analysis: Systematically evaluate where we have sufficient data and where we do not

- Uncertainty quantification:

  System-wide temperatures, pressures, compositions, and flow rates with 95% confidence limits on measured and unmeasured quantities.

Why is this step so important?

- Enables reliable comparisons of different operational conditions (low vs. high efficiency)
- Can quantify how far each operational condition is from ‘optimal’ (room for improvement?)

$$error_{meas} = \frac{\text{measurement – model prediction}}{\text{measurement uncertainty}}$$

IDAES Facilitates Complete Workflow

Data Reconciliation

"Ensure data is reliable"

$$\underset{\{temps, pressures, flows\}}{\textbf{Minimize}} \sum_{data} (error_{meas})^2$$

subject to

- Flowsheet connectivity
- Mass and energy balances
- Physical property calculations

Parameter Estimation

"Make models predictive"

$$\underset{\{parameters\}}{\textbf{Minimize}} \sum_{data} (error_{meas})^2$$

subject to

- Flowsheet connectivity
- Mass and energy balances
- Physical property calculations
- Performance equations for unit models

System-wide Optimization

"Generate insights & results"

$$\underset{\{temps, pressures, flows\}}{\textbf{Minimize}} \; Heat\ Rate$$

subject to

- Flowsheet connectivity
- Mass and energy balances
- Physical property calculations
- Performance equations for unit models
- Load = Target Load
- Operational Constraints (e.g., $T<T_{max}$)
- Emissions < Emission Limits

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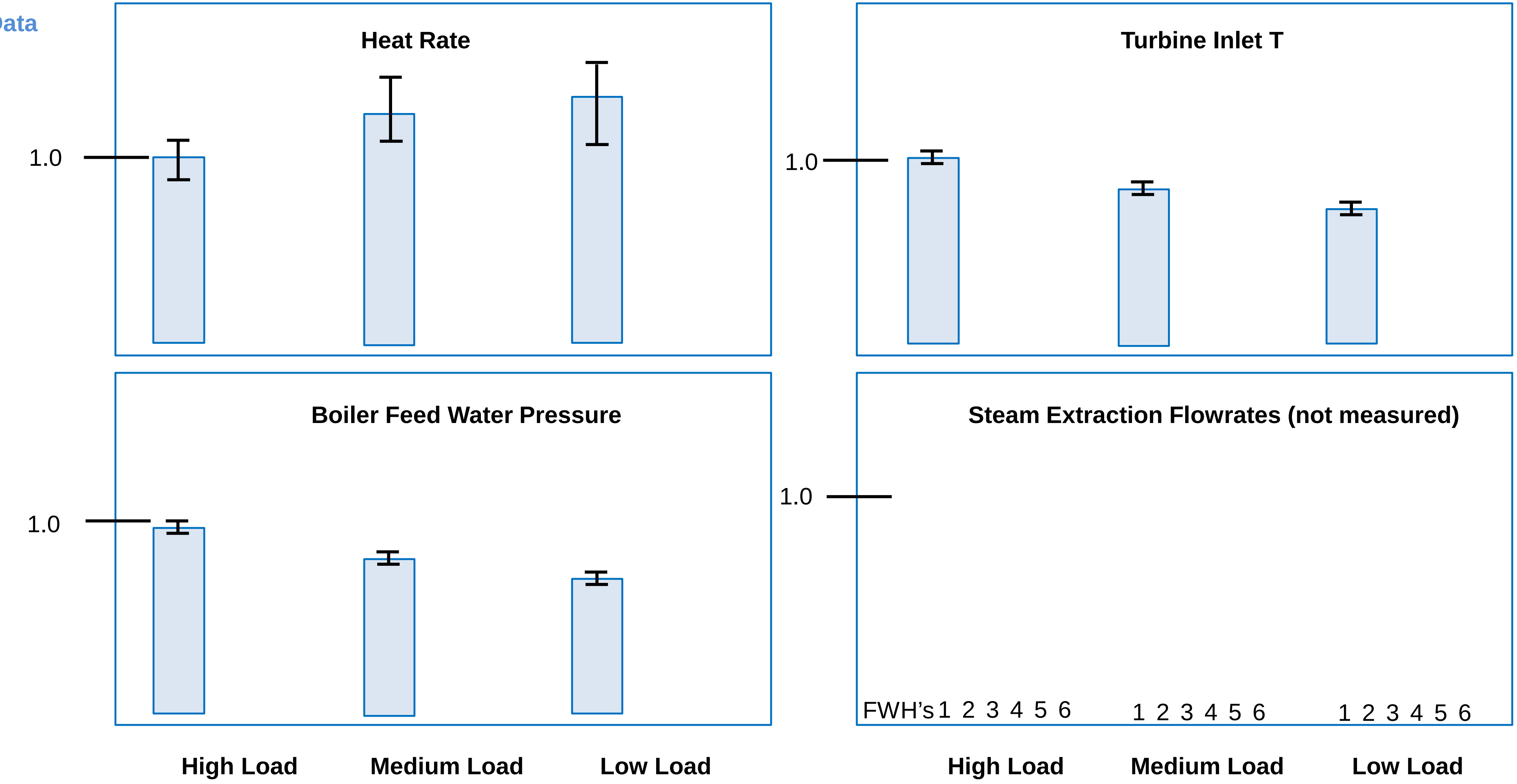
Characterizing System Uncertainty at Various Loads

Measured Data



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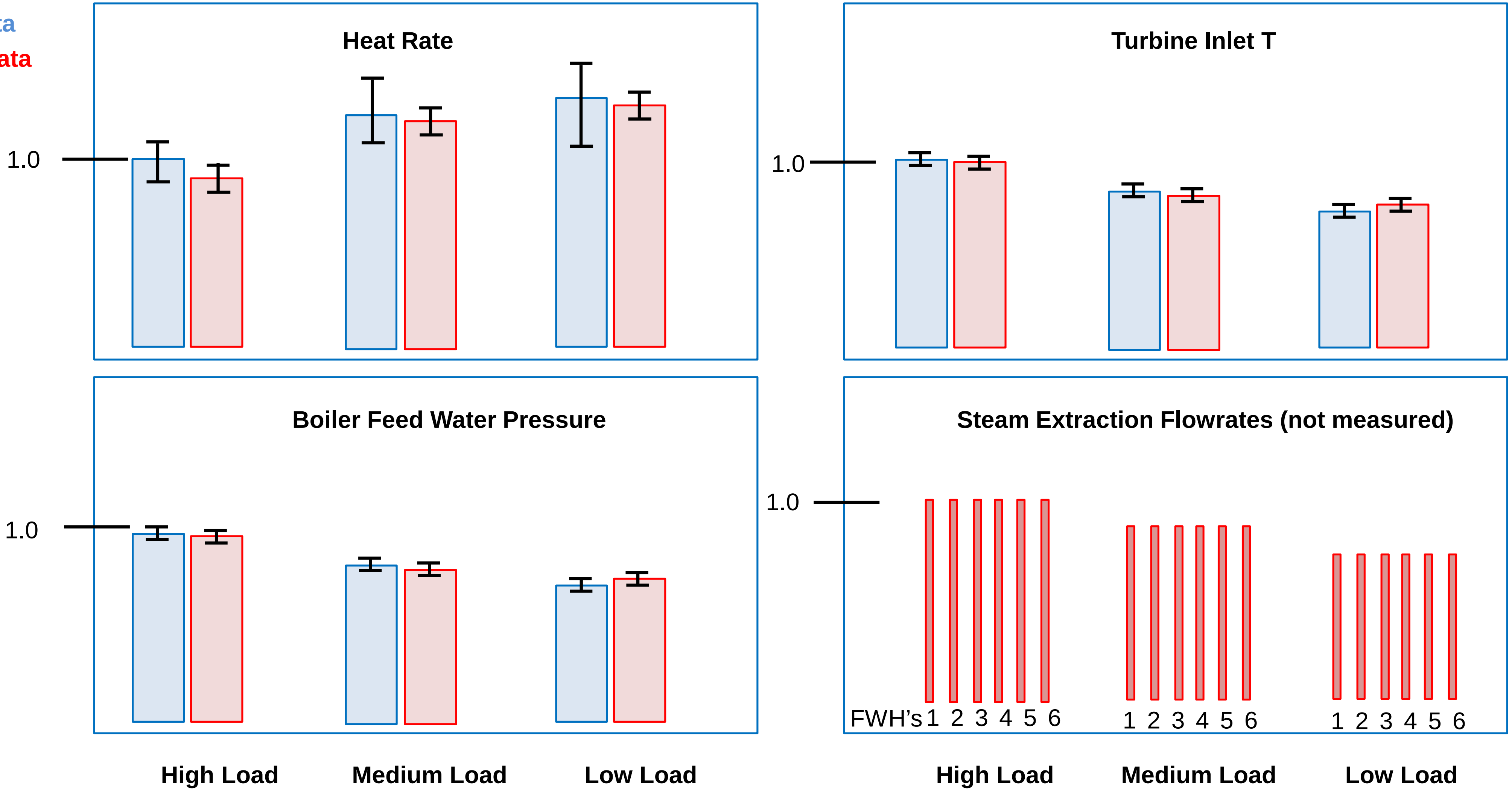
Reducing Uncertainty with Reconciled Data

Measured Data
Reconciled Data



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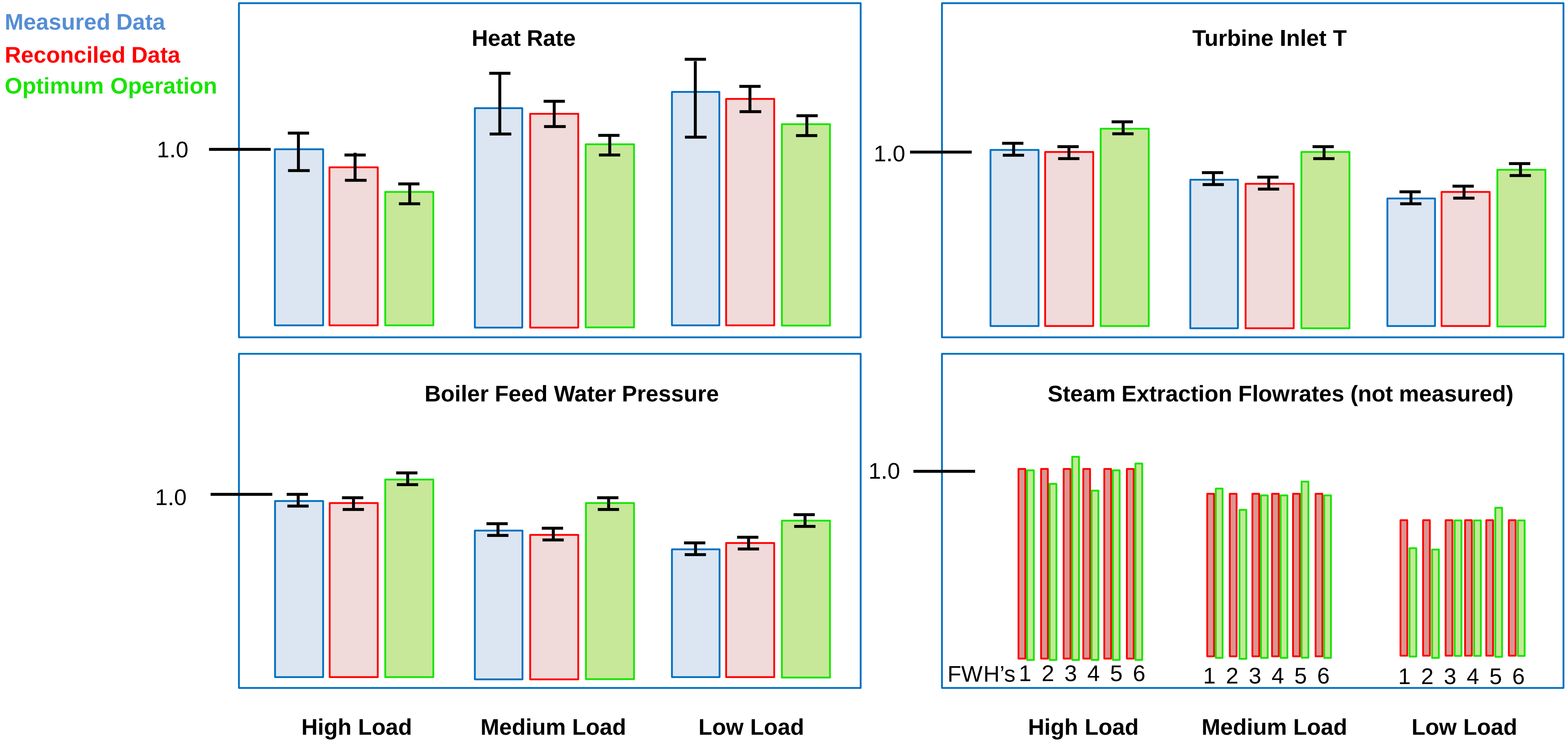
Quantifying Available Room for Improvement



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Summary

- Recent program accomplishments enabled our 1st major partnership with Tri-State Generation and Transmission Association
  - Usable framework for constructing optimization-ready process models
  - Steady-state power plant model

- IDAES/Tri-State partnership is 1/3rd of the way into our first major deliverable 9/30

- IDAES facilitates application-centered workflows by leveraging several core capabilities within a unified process systems engineering framework
  - Model construction
  - Data reconciliation
  - Parameter estimation
  - Uncertainty quantification
  - System-wide optimization

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