SAND2021-14468C

IDAES
Institute for the Design of Advanced Energy Systems

DISPATCHES
Design Integration and Synthesis Platform to Advance Tightly Coupled Hybrid Energy Systems

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

Toward Future Energy Generation Systems: Multi-Scale Optimization with Market Interactions

AIChE Annual Meeting, November 10th, 2021, Boston, MA

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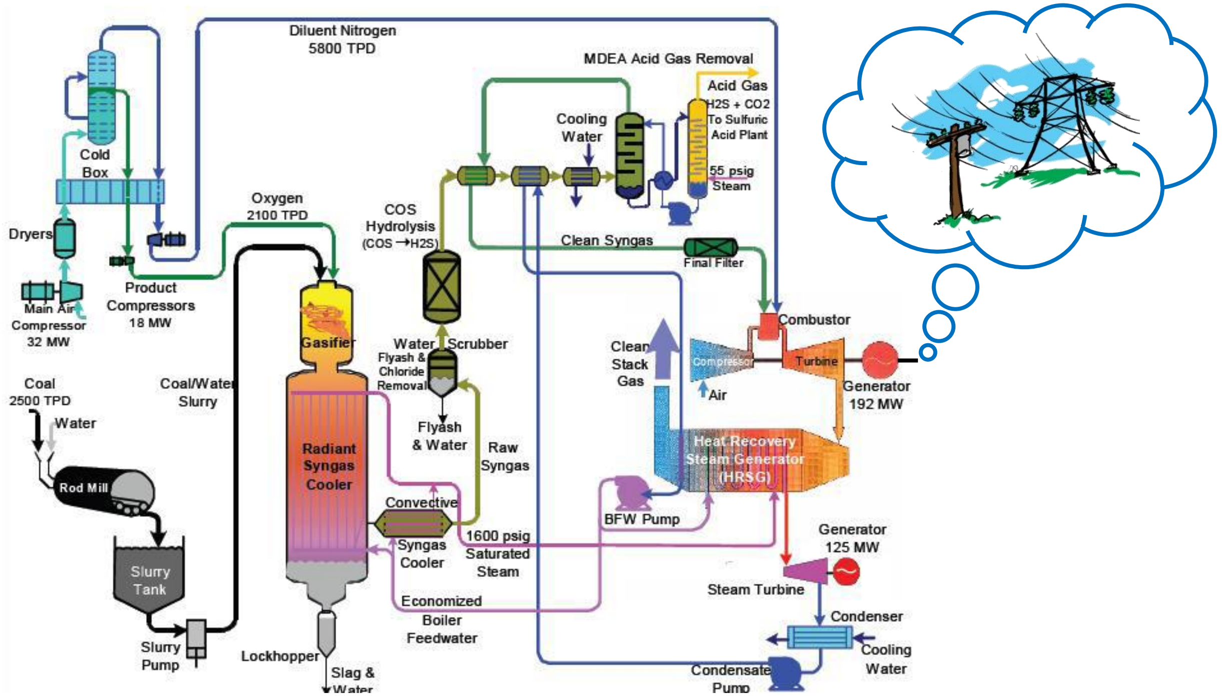
Energy system analysis capabilities are applied in isolation

Process-centric Modeling

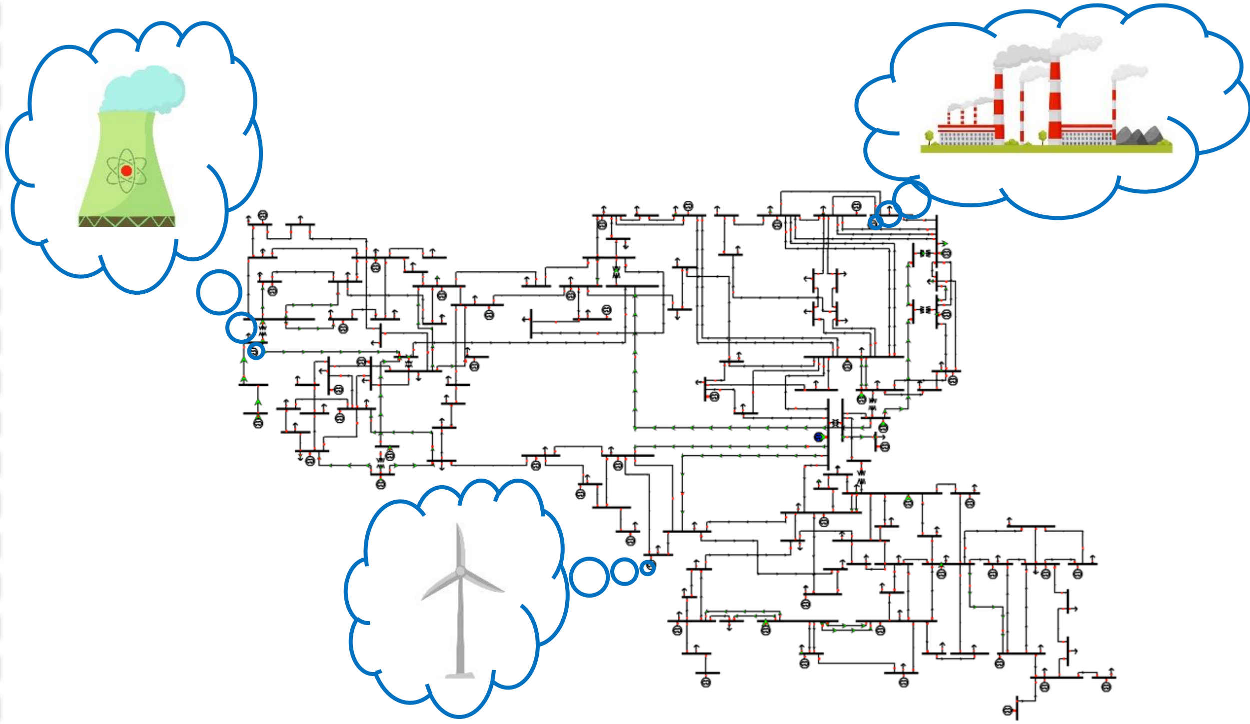
Detailed steady state or dynamic process models,
with the grid modeled as an infinite capacity bus



https://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/igcc-config

Grid-centric Modeling

Detailed power flow models,
with individual generators modeled as either
dispatchable point sources or stochastic "negative loads"



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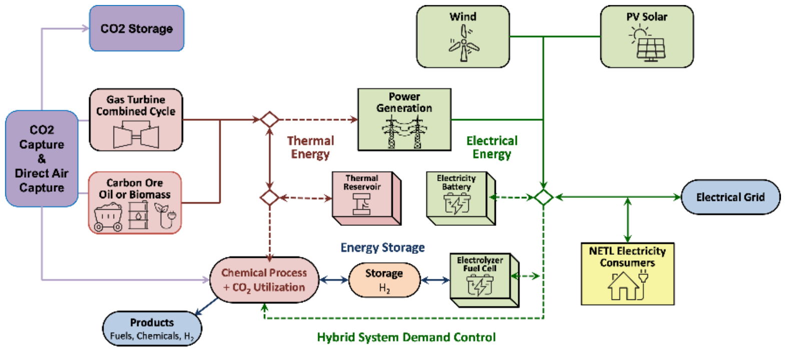
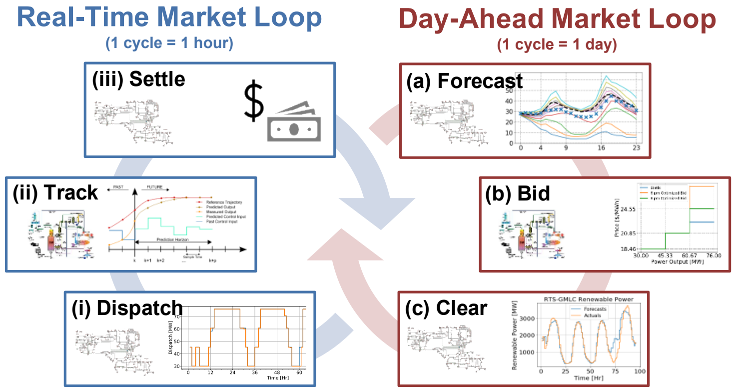
Challenge of increasingly integrated & dynamic grid/generation

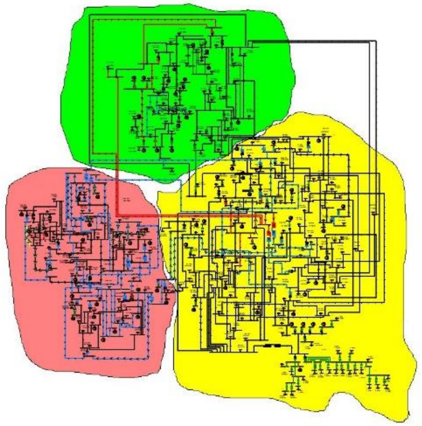
Generation & Process Modeling

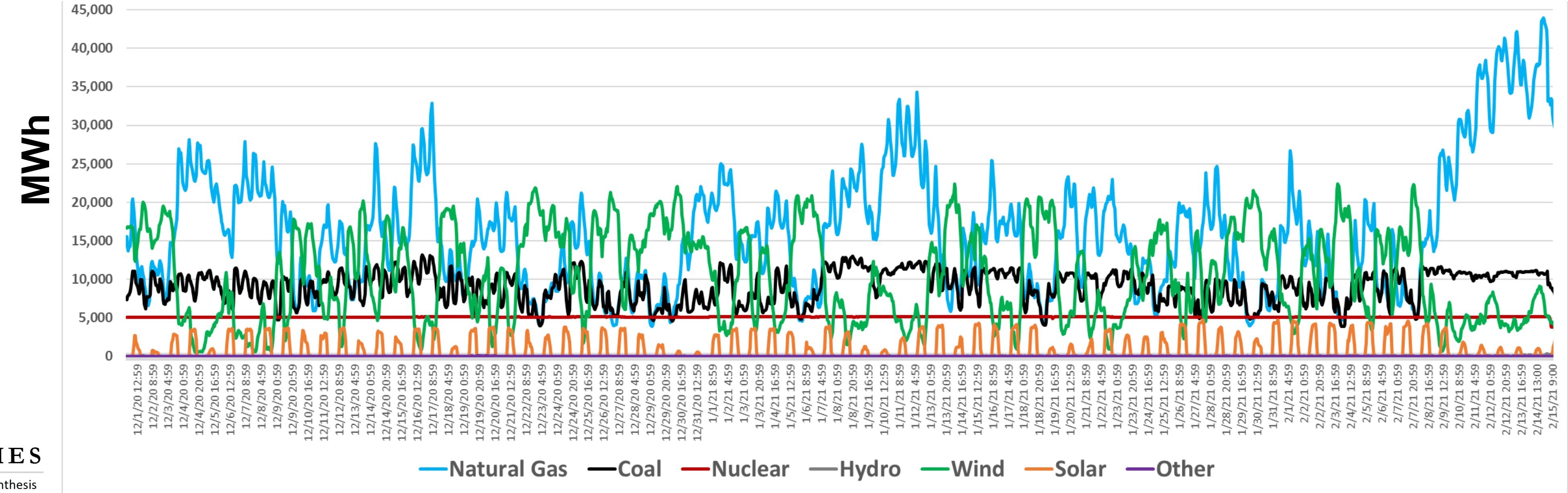
Integrated Resource-Grid Model

Grid Modeling









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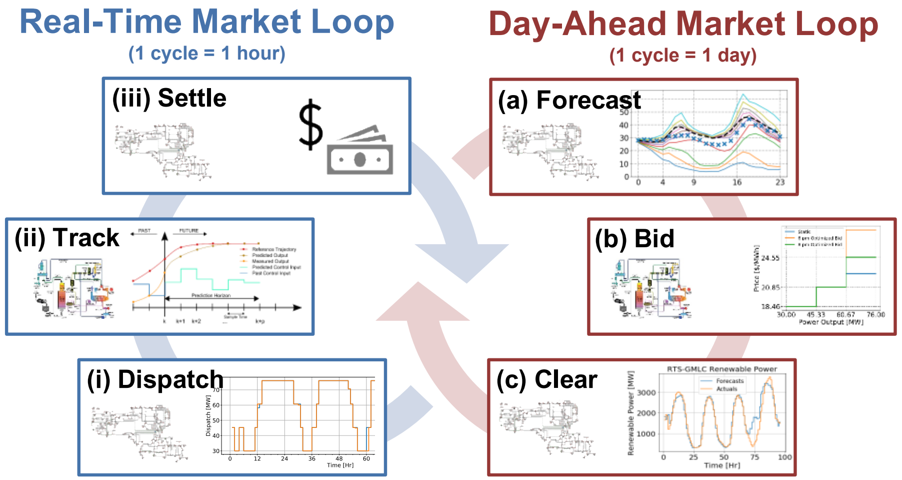
Multiscale Market-Based Optimization of IES

Multiscale Simulation to Quantify Grid/IES Interactions

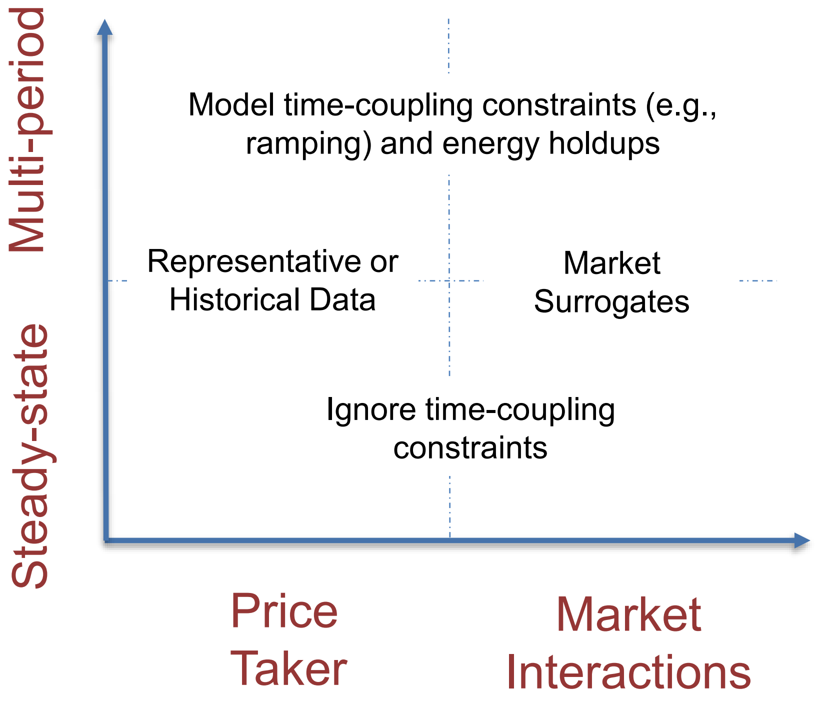


Data to refine market representation (e.g., prices, surrogates)

Candidate IES designs (i.e., IDAES models) to evaluate

Superstructure Optimization

Maximize Net Present Value



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Abstract Integrated Energy System

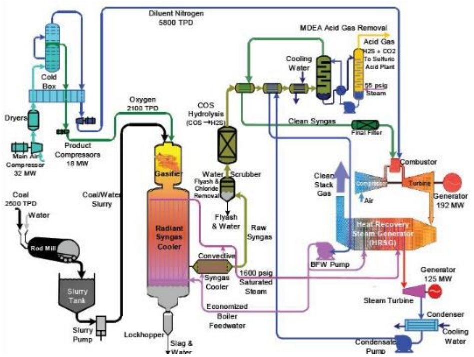
Integrated Energy System

Design Decisions: d

Operating Decisions: u

Net Power Output: δ

Steady-State Model (Constraints): $g(d, u, \delta) = 0$



Power δ →

← Price π

Energy Market

This abstraction is easy to extend to…

- ➢ multiple products (electricity, heat, H_2, chemicals)
- ➢ multiple market timescales (day ahead, real time, ancillary services, capacity)

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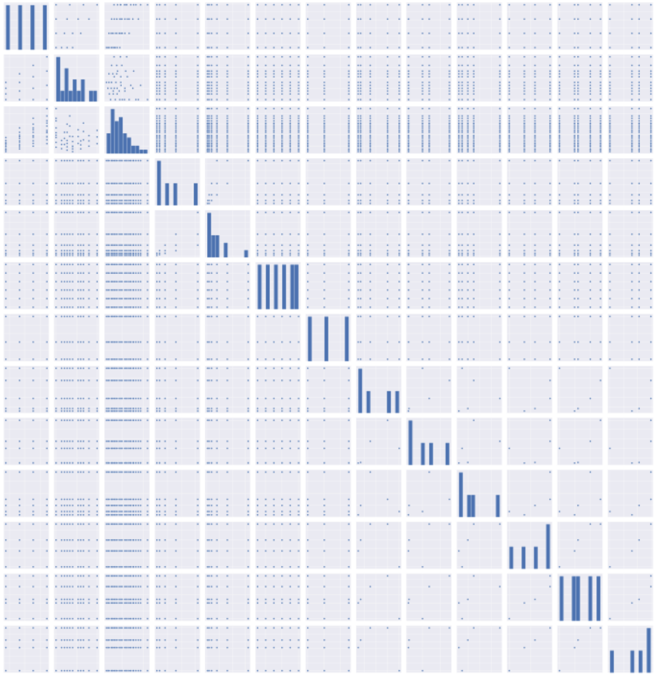
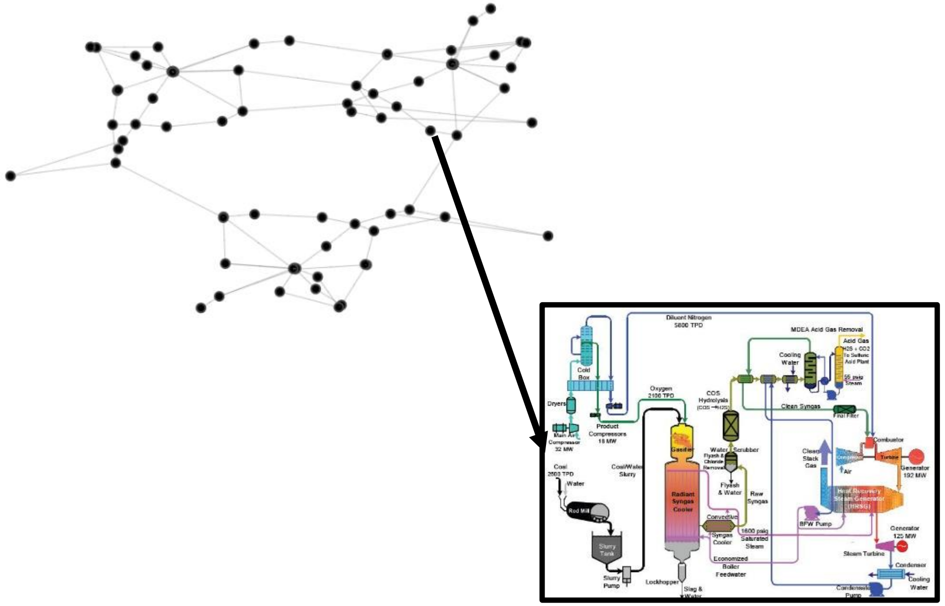
How would a new generator change market outcomes?

Simulation Design

	Market Inputs		
	Market Inputs	7	No Load Cost [$/hr]
1	PMax [MW]	8	Start Time Hot [Hr]
2	PMin [MW]	9	Start Time Warm [Hr]
3	Ramp Rate [MW/hr]	10	Start Time Cold [Hr]
4	Min Up Time [Hr]	11	Start Cost Hot [$]
5	Min Down Time [Hr]	12	Start Cost Warm [$]
6	Marginal Cost [$/MWh]	13	Start Cost Cold [$]

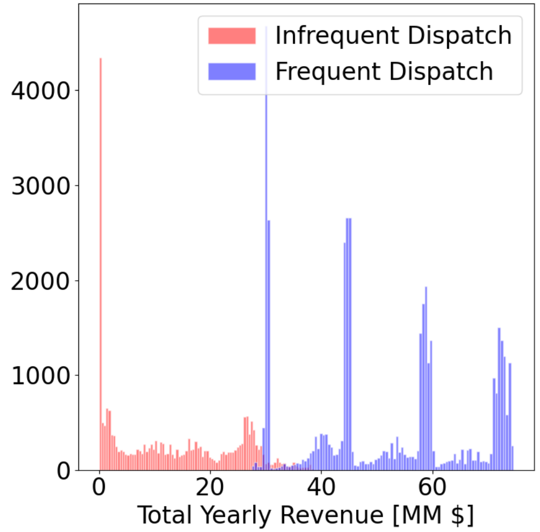


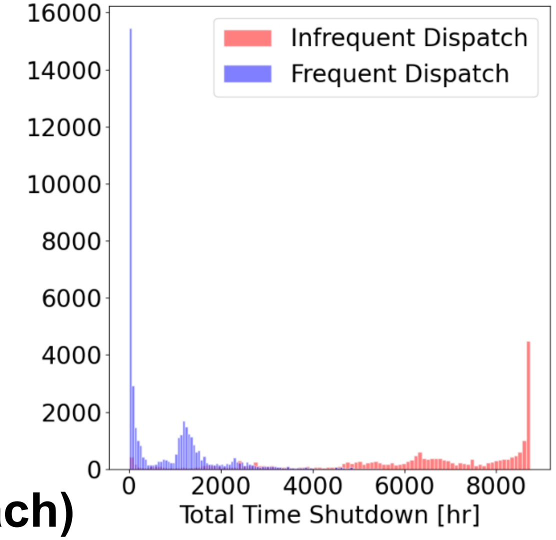
Production Cost Modeling: RTS-GMLC Test System



PRESCIENT

Revenue & Dispatch Results





64,800 1-year Prescient simulations (@ 3 hr each)

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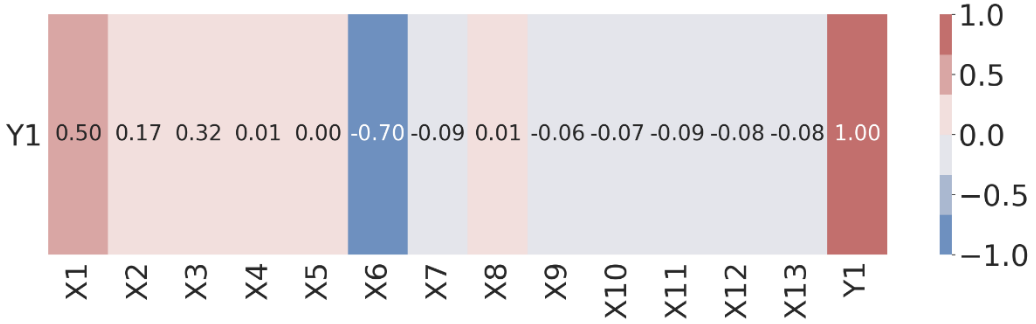
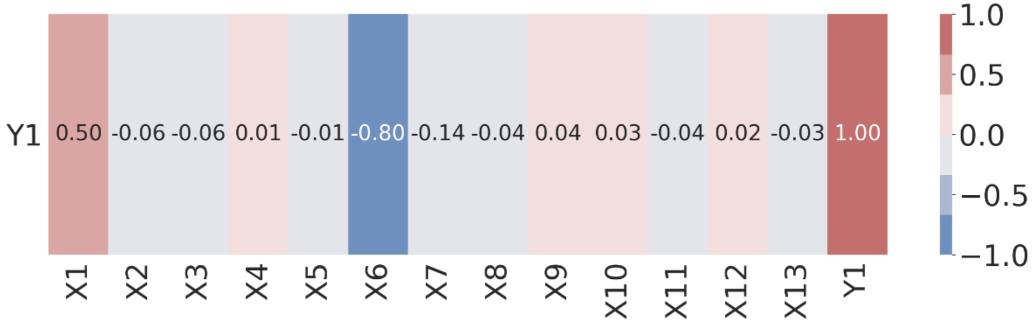
Global Sensitivity Analysis

	Market Parameters
X1	P_{max} [MW]
X2	P_{min} [MW]
X3	Ramp Rate [MW/hr]
X4	Min Up Time [Hr]
X5	Min Down Time [Hr]
X6	Marginal Cost [$/MWh]
X7	No Load Cost [$/hr]
X8	Start Time Hot [Hr]
X9	Start Time Warm [Hr]
X10	Start Time Cold [Hr]
X11	Start Cost Hot [$]
X12	Start Cost Warm [$]
X13	Start Cost Cold [$]
Y1	Revenue [MM$]

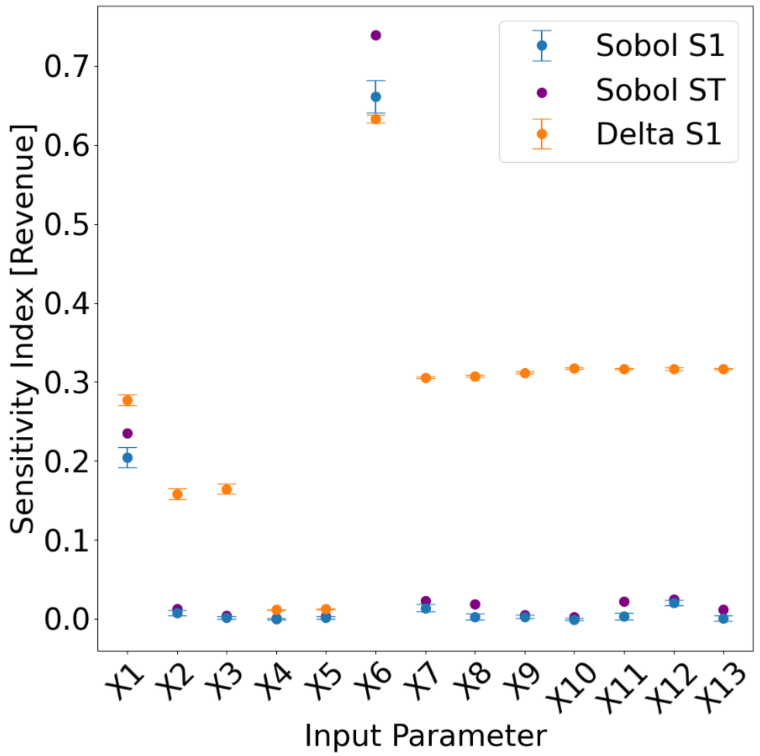
Spearman Correlations



PRCC (Ranked Partial Correlations)

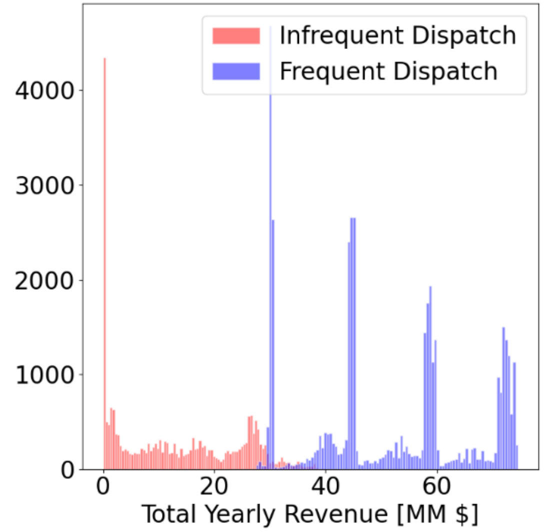


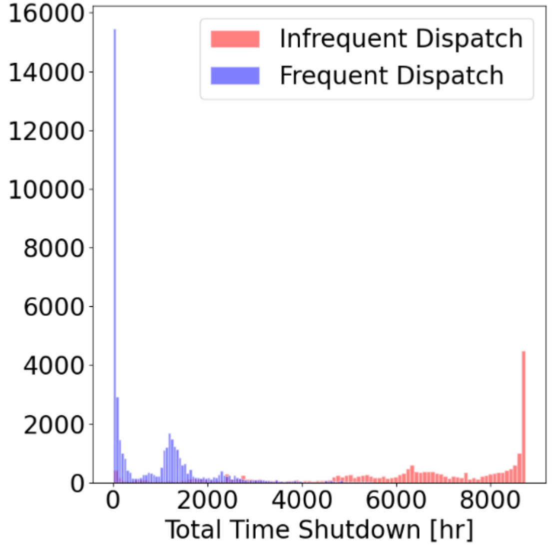
Sensitivity Indices



- Sensitivity analysis tends to confirm intuition
  - P_{max} and marginal cost describe most variation in output
  - However, all inputs improve overall surrogate fit

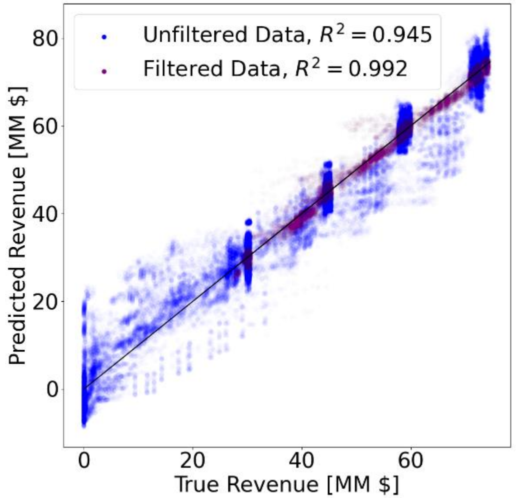
Surrogates Accurately Predict Market Outcomes

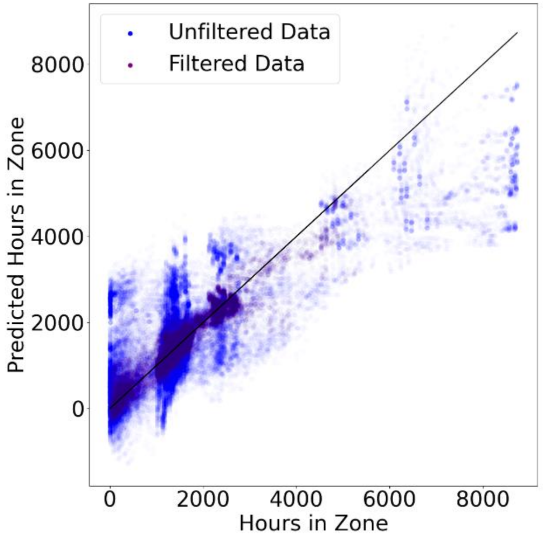




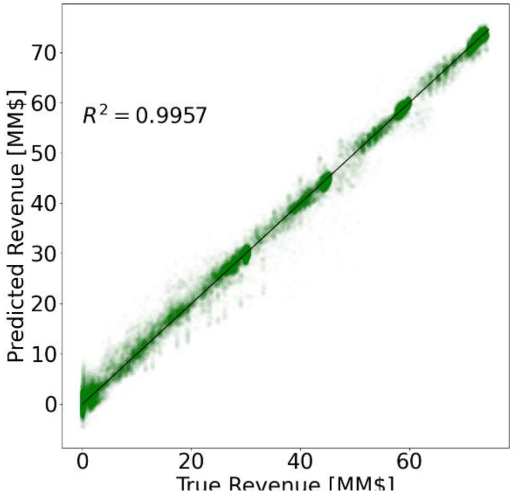
Fit Market Surrogates

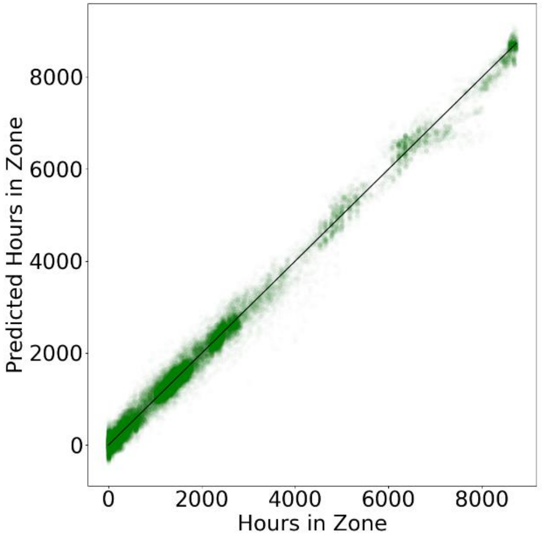
ALAMO
a black-box modeling tool





RAVEN K + TensorFlow





Steady-State Price Taker (Self-Schedule)

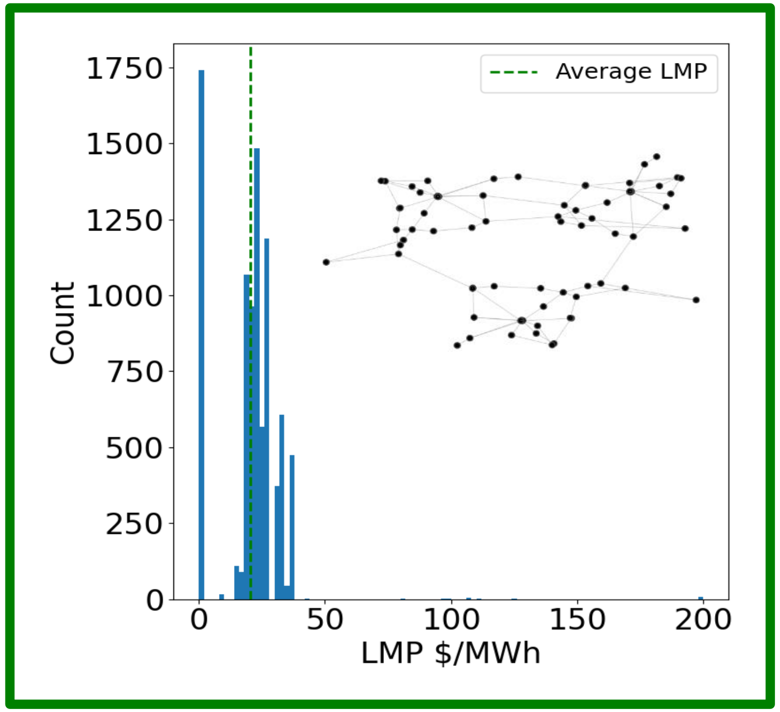
Weight / Frequency — Revenue — Cost (Operating + Capital)

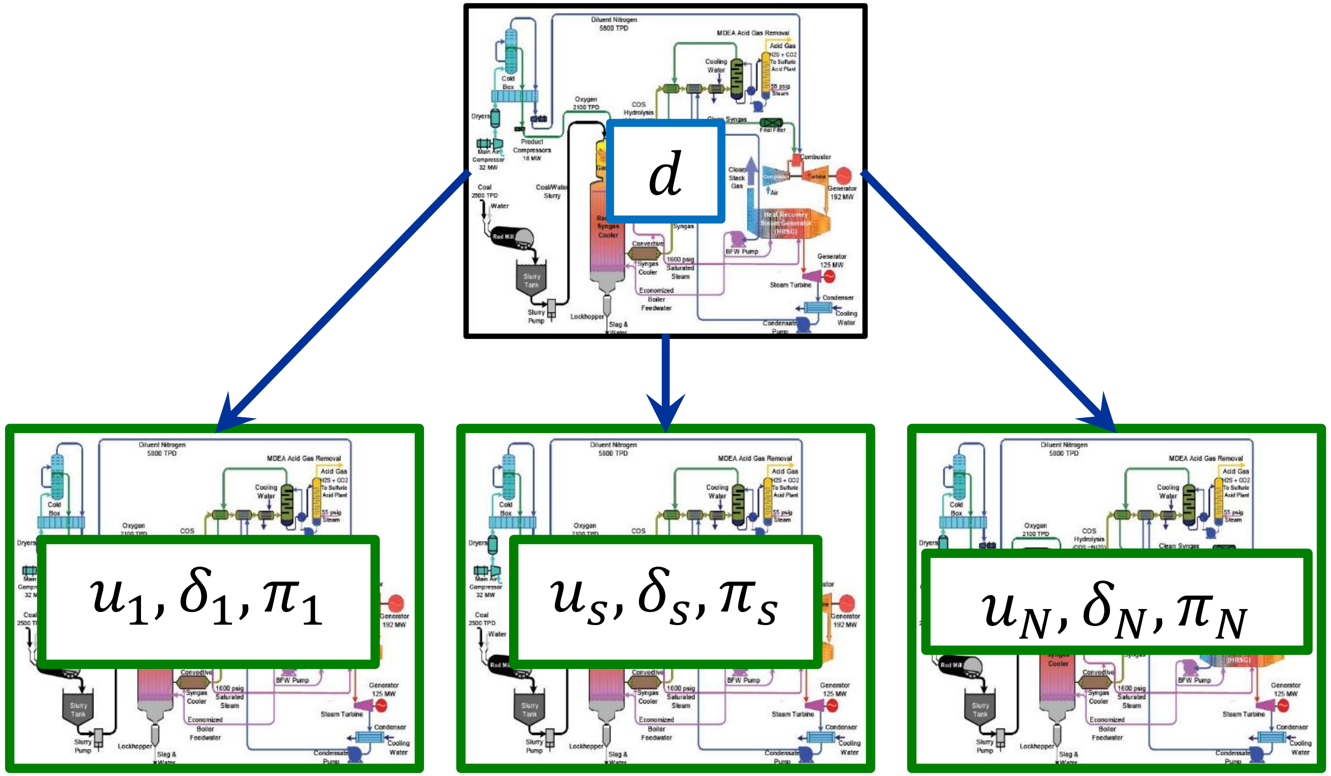
$$\max_{d,\boldsymbol{u},\boldsymbol{\delta}} \sum_{s\in S} \underbrace{w_s}_{\text{Weight / Frequency}}[\underbrace{R(d,u_s,\delta_s,\pi_s)}_{\text{Revenue}} - \underbrace{C(d,u_s,\delta_s)}_{\text{Cost (Operating + Capital)}}]$$

$$g(d,u_s,\delta_s) = 0, \qquad \forall s \in S$$

d	Design **decisions**
δ_s	Power output **decision** for scenario
u_s	Operating **decisions** for scenario
π_s	Scenario price (**data**)
$R()$	Revenue: function of decisions and prices
$C()$	Cost: function of decisions

Nominal RTS-GMLC Prices





Steady-State with Market Surrogates (Bid)

Revenue — Cost (Operating + Capital)

$$\max_{d,\boldsymbol{u},x} R(x) - \sum_{s \in S} w_s(x)[C(d,u_s,\delta_s)]$$

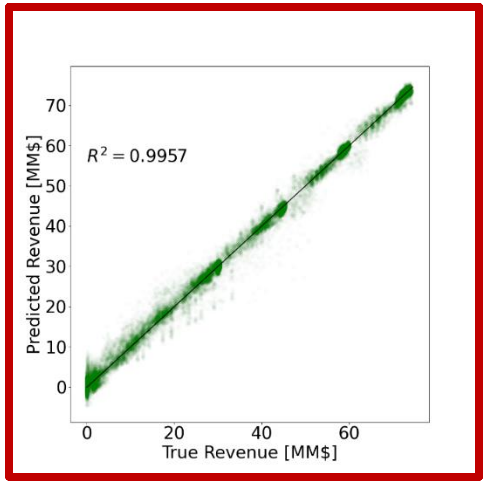
$$g(d,u_s,\delta_s) = 0, \qquad \forall s \in S$$ Process Model

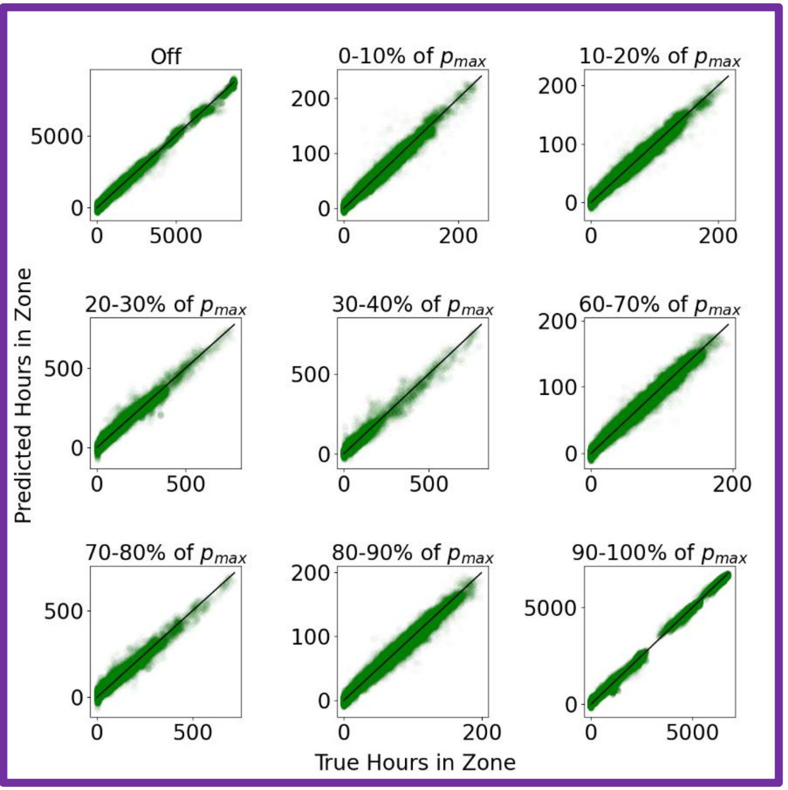
$$h(d,x) = 0$$ "Bid Rules"

$$R(x) = f_{rev}(x)$$ Revenue Surrogate

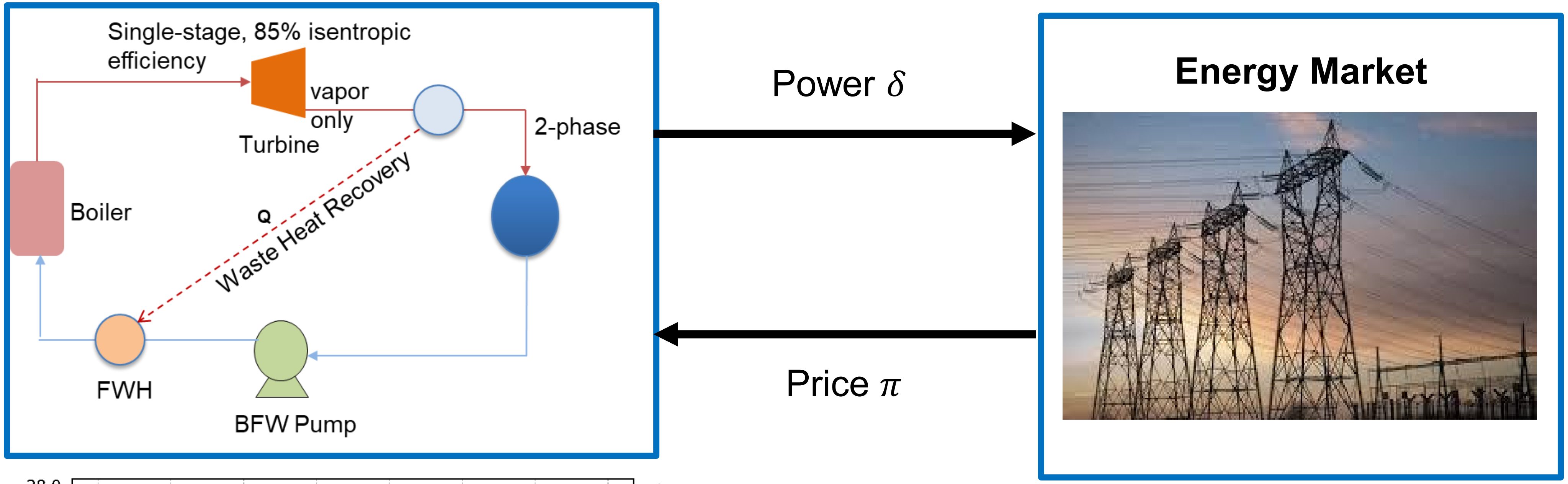
$$w_s(x) = f_s(x), \qquad \forall s \in S$$ Dispatch Surrogates

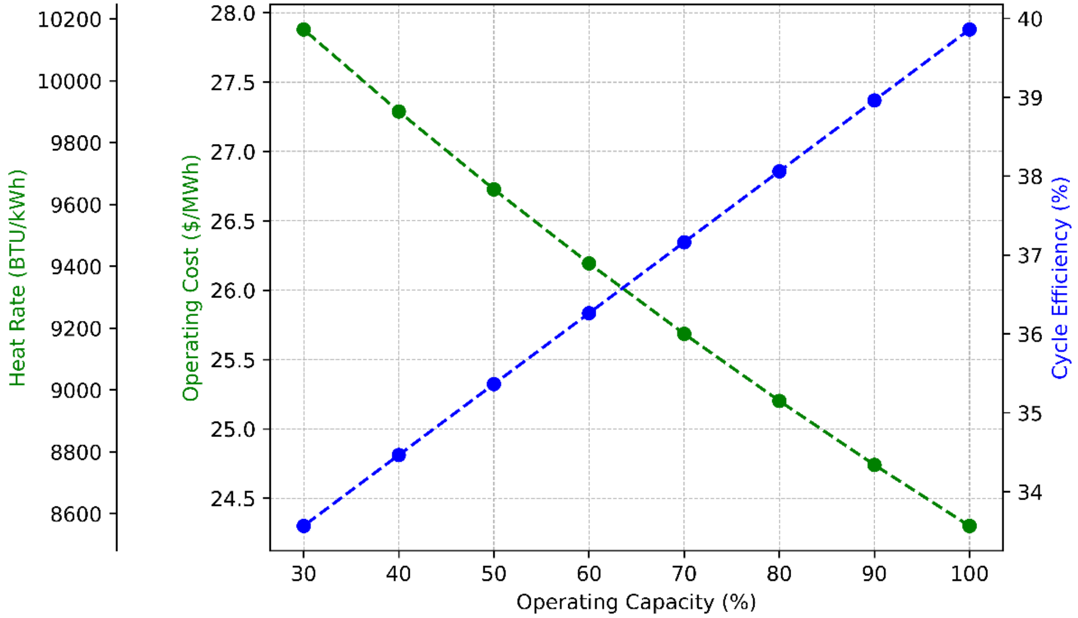
d	Design **decisions**
δ_s	Power output **data** for scenario
u_s	Operating **decisions** for scenario
x	Market Inputs (bid **decisions**)
$R()$	Revenue: function of market inputs
$C()$	Cost: function of decisions
w_s	Scenario weight: function of market inputs

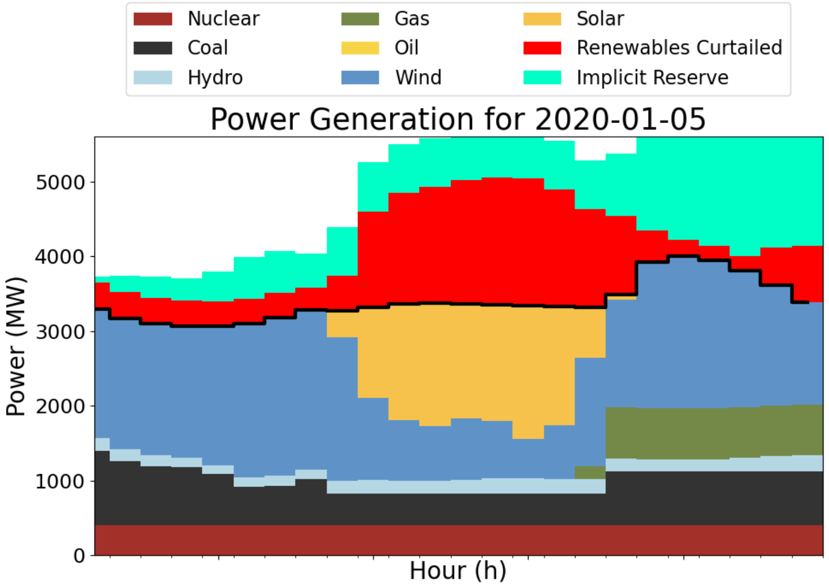




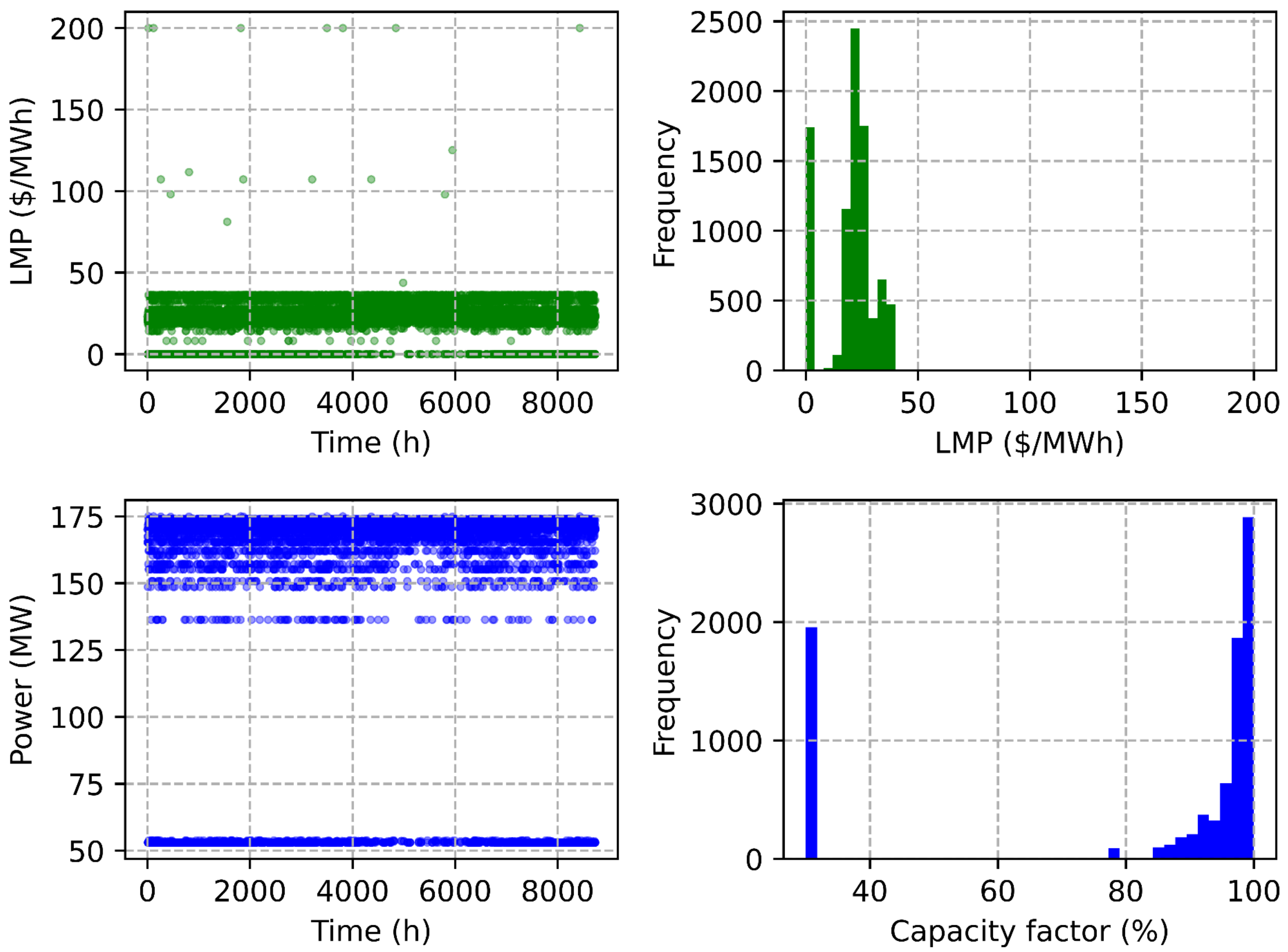
Example: Optimal Design of Rankine Cycle for RTS-GMLC







Steady-State Price Taker Results



P_{max}	175 MW
Marginal Cost	24 $/MWh
Revenue	**29.6 MM$/yr**
Opex	30.8 MM$/yr
Capex	404 MM$
20 year return	-428.8 MM$

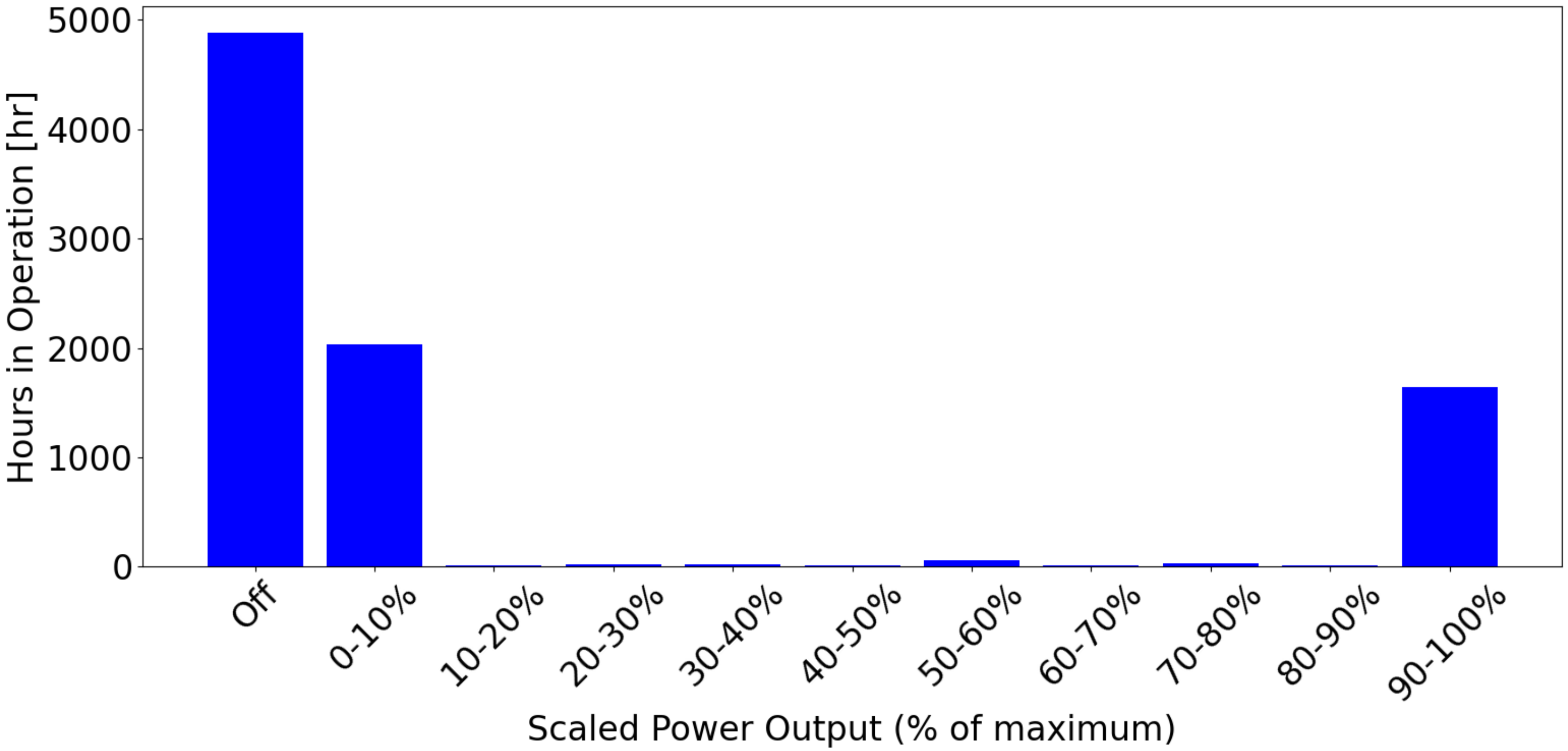
# Variables	419387
Solution Time	1846 sec (build) 49 sec (solve)

- Build small plant, operate at minimum power unless LMP exceeds operating cost
- Investment would require better prices (not surprising for RTS-GMLC system)

Surrogate Results

P_{max}	177.5 MW
Marginal Cost	24 $/MWh
Revenue	**13.5 MM$/yr**
Opex	12 MM$/yr
Capex	408 MM$
20 year return	-382 MM$

# Variables	738
Solution Time	13 sec (build) 336 sec (solve)

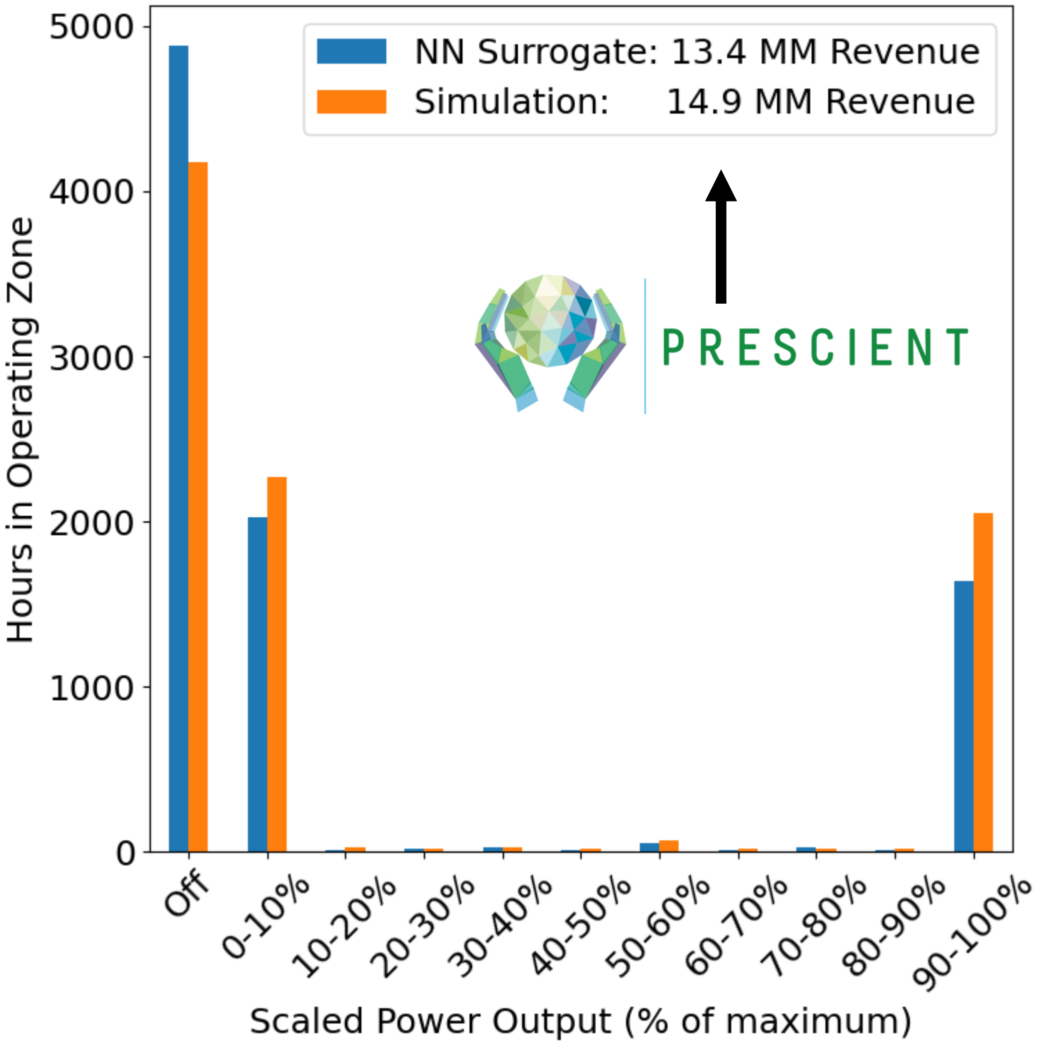


- ➢ Surrogate also builds small plant, but effectively captures shutdown operating modes
- ➢ Investment would still require better prices (but capturing shutdown helps)

Comparison of Results

	Price Taker	Surrogate	Verification
P_{max} [MW]	175	177.5	177.5
Marginal Cost [$/MWh]	24	24	24
Revenue [$MM/yr]	**29.6**	**13.5**	**14.9**
Opex [$MM/yr]	**30.8**	**12**	**14.5 (Rankine) 16.2 (Prescient)**
Capex [$MM]	404	408	408
20 year return [$MM]	-428.8	-382	-401

Verification of Surrogate Solution



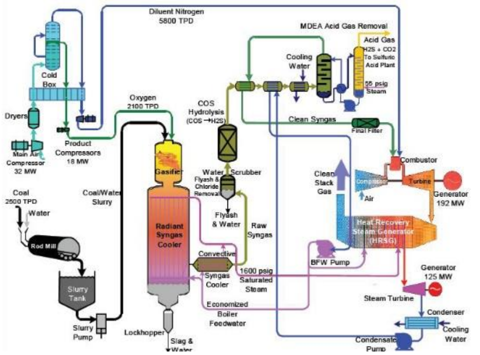
- ➢ Surrogate can capture startup/shutdown in steady state model, more realistic opex
- ➢ Surrogate solution is reasonably verified with Prescient simulation

Conclusions and Future Work

Integrated Energy System

Design Decisions: d
Operating Decisions: $u_{t_1..t_N}$
Net Power Output: $\delta_{t_1..t_N}$
Multi-Period Model:

$$h(d, u_{s,t}, \delta_{s,t}, u_{s,t+1}, \delta_{s,t+1}) = 0$$



Dispatch Schedule $\delta_{t_1..t_N}$ →

← Price Forecast $\pi_{t_1..t_N}$

Energy Market

- Surrogates can incorporate exogenous market uncertainty into conceptual design problems
- Steady-State problems can capture startup/shutdown effects using surrogate methodology
- Future work is developing **multi-period** formulations for IES design

	Price Taker	Market Interactions
Fully Dynamic	Long-Term Goal	
Multi-period	Representative Days	Multi-Period Dispatch Surrogates
Steady-state	Price Scenarios	Zone Dispatch Surrogates

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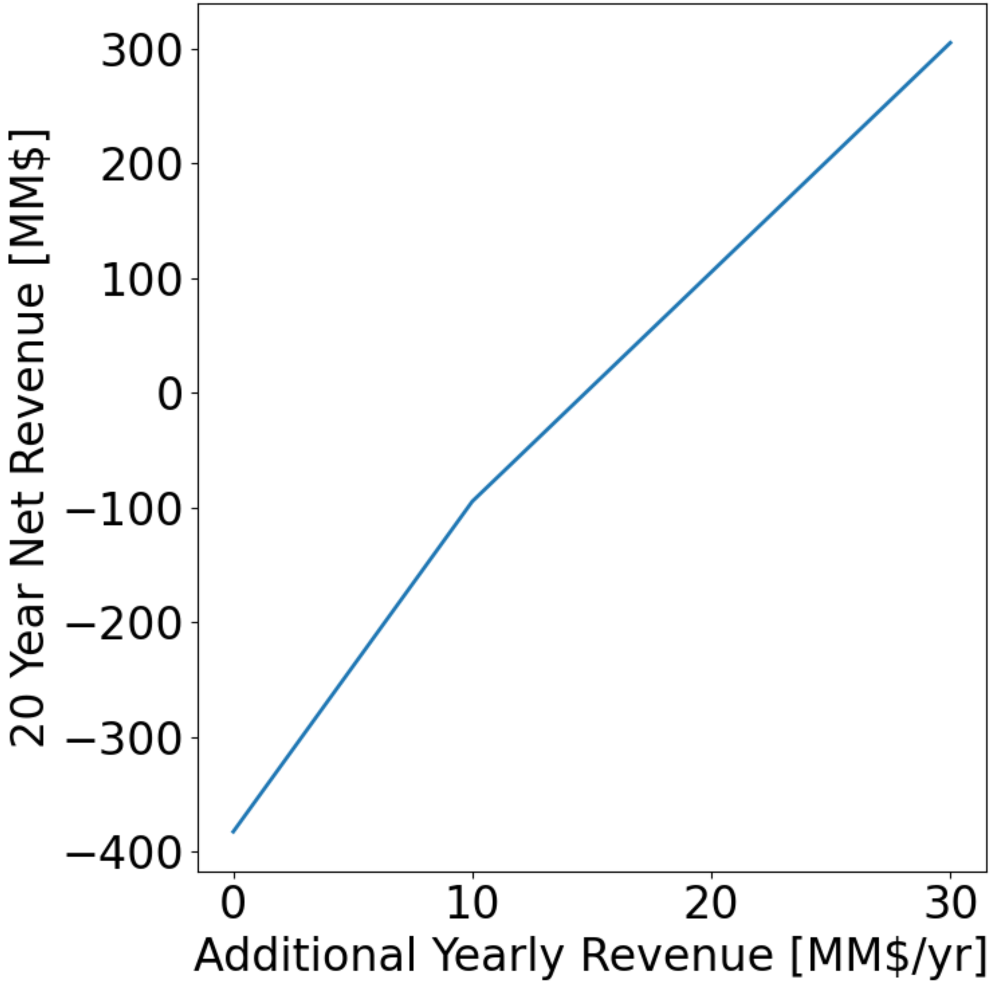
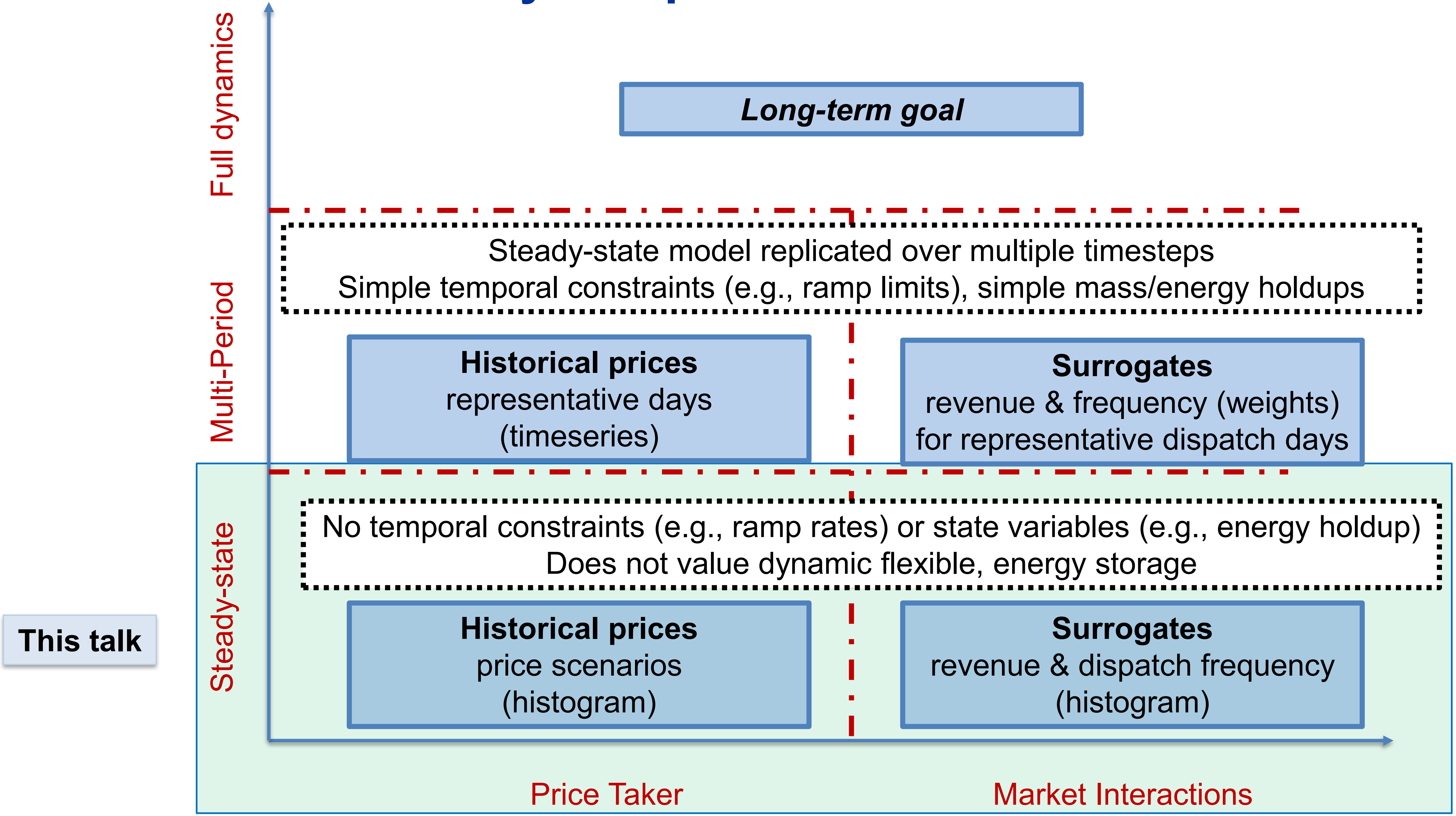
Additional Slides

Offset Results



Summary of Optimization Formulations



Multi-Period Price Taker (Self-Schedule)

Scenarios are timeseries, e.g., representative days

Weight / Frequency — Revenue — Cost (Operating + Capital)

$$\max_{d,\boldsymbol{u},\boldsymbol{\delta}} \sum_{s\in S} \sum_{t\in T} w_s \left[R(d, u_{s,t}, \delta_{s,t}, \pi_{s,t}) - C(d, u_{s,t}, \delta_{s,t}) \right]$$

Process Model

$$g(d, u_{s,t}, \delta_{s,t}) = 0, \qquad \forall s \in S, t \in T$$

Temporal Constraints

$$h(d, u_{s,t}, \delta_{s,t}, u_{s,t+1}, \delta_{s,t+1}) = 0, \qquad \forall s \in S, t \in T$$

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Multi-Period with Market Surrogates (Bid)

Revenue

Cost (Operating + Capital)

$$\max_{d,\boldsymbol{u},x} R(x) - \sum_{s \in S} \sum_{t \in T} w_s(x)\left[C\left(d, u_{s,t}, \delta_{s,t}\right)\right]$$

Process Model $\quad g\left(d, u_{s,t}, \delta_{s,t}\right) = 0, \quad \forall s \in S$

"Bid Rules" $\quad h(d, x) = 0$

Temporal Constraints $\quad h\left(d, u_{s,t}, \delta_{s,t}, u_{s,t+1}, \delta_{s,t+1}\right) = 0, \ldots$

Revenue Surrogate $\quad R(x) = f_{rev}(x)$

Multi-Period Dispatch Surrogate $\quad w_s(x) = f_s(x), \quad \forall s \in S$

Design Integration and Synthesis Platform to Advance Tightly Coupled Hybrid Energy Systems

Note: δ are representative days for market dispatch and are parameters (scenario data)