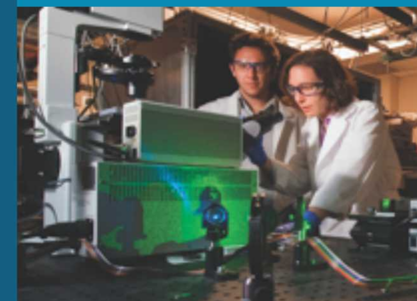
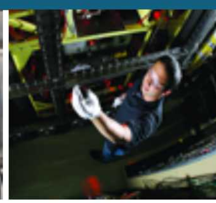
Sandia National Laboratories

SAND2019-8205C

Reassessing the Market: Computation Interface





PRESENTED BY

Dr. Anya Castillo

U.S. DEPARTMENT OF ENERGY NNSA

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Project Purpose

Targeted yet significant improvements in existing market and reliability constructs that leverages computational optimization capabilities.

Full Distribution Factor (FDF) Deliverable. Design and analysis of reactive power and voltage support approximations into existing Power Transfer Distribution Factor (PTDF) approaches

FDF Goal: Demonstrate the benefits of more accurate representations of power flow physics in real-time markets and related reliability processes

Continual Commitment and Dispatch (CCD) Deliverable 2. Design and analysis of a "continual commitment and dispatch" process intended to replace and integrate both existing market and reliability constructs.

CCD Goal: Demonstrate the benefits of how a simplified (but more computational demanding) process can yield significant improvements in overall system security, reliability and efficiency

Significance and Impact

Current State-of-the-Art:

1. Two-settlement system in the US; each market has own tariffs, day-ahead, intra-day and real-time processes.

- **Drawback:** Markets are becoming increasingly complicated in order to manage deviations in resource variability and other uncertainties

2. Nomograms (e.g., MISO Voltage and Local Reliability) to define a constraint relationship between power system MW variables

- **Drawback:** VAr/Voltage support becomes implicit in generator commitments/dispatch and congestion costs

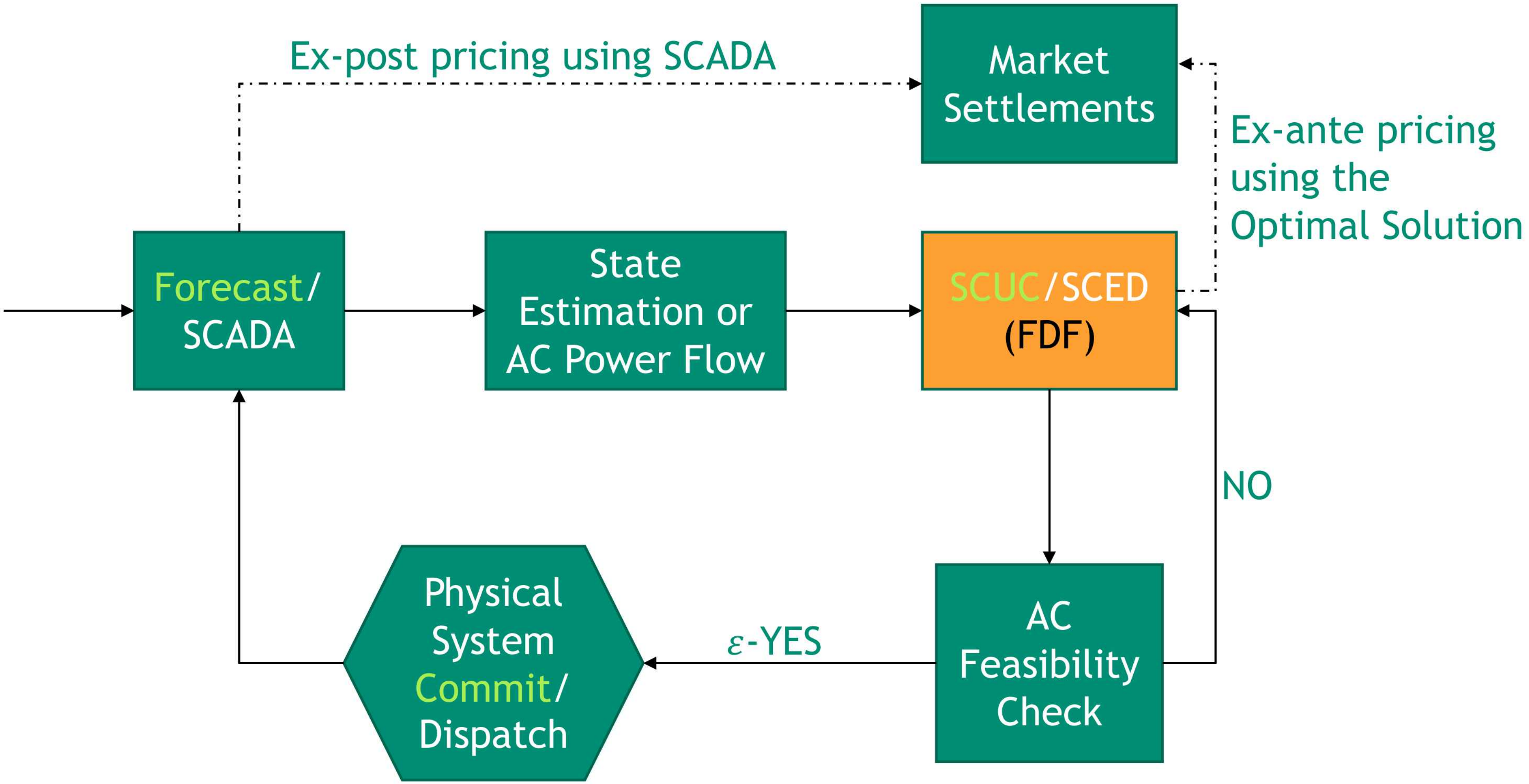
3. High Out-of-Market (Uplift) Payments: Prevents prices from reflecting the full cost of service and its associated costs are arbitrarily allocated to energy customers.

- **Drawback:** Uplift charges for VAr/Voltage support are not transparent

Our Approach Addresses the Drawbacks:

1. Scalable, linear FDF as an AC approximation
2. Representative price formation and cost allocation under multi-part nonconvex prices
3. Reliable, consistent and efficient CCD

Technical Approach: FDF Model



SCADA: Supervisory control and data acquisition (monitor, gather & process data)
SCUC: Security-Constrained (i.e., Line Limits, N-1, etc.) Unit Commitment
SCED: Security-Constrained Unit Commitment

Technical Approach: FDF Model

FDF Model

$$\min \quad f_0(\mathbf{p^g})$$

$$s.t.$$

$$\mathbf{1}^\top(\mathbf{p^g} - \mathbf{p^d}) = \mathbf{1}^\top \mathbf{p}^\ell$$

$$\mathbf{1}^\top(\mathbf{q^g} - \mathbf{q^d}) = \mathbf{1}^\top \mathbf{q}^\ell$$

$$\mathbf{p^f} = f_1(\mathbf{p^g}, \mathbf{p}^\ell)$$

$$\mathbf{q^f} = f_2(\mathbf{q^g}, \mathbf{q}^\ell)$$

$$\mathbf{p}^\ell = f_3(\mathbf{p^g})$$

$$\mathbf{q}^\ell = f_4(\mathbf{q^g})$$

$$f_5(\mathbf{p^f}, \mathbf{q^f}, \mathbf{p}^\ell, \mathbf{q}^\ell) \leq \widehat{\mathbf{T}}$$

$$\underline{\mathbf{V}} \leq f_6(\mathbf{q^g}, \mathbf{q}^\ell) \leq \overline{\mathbf{V}}$$

$$\underline{\mathbf{P}} \leq \mathbf{p^g} \leq \overline{\mathbf{P}}$$

$$\underline{\mathbf{Q}} \leq \mathbf{q^g} \leq \overline{\mathbf{Q}}$$

Proposed LP includes:

a) Voltage limits
b) VAr support
c) Thermal line limits
d) Real power flows and losses
e) Reactive power flows and losses
f) Real and reactive power dispatch

PTDF Model

$$\min \quad f_0(\mathbf{p^g})$$

$$s.t.$$

$$\mathbf{1}^\top(\mathbf{p^g} - \mathbf{p^d}) = \mathbf{0}$$

$$-\widehat{\mathbf{T}} \leq \mathbf{T}(\mathbf{p^f} - \mathbf{p^d}) \leq \widehat{\mathbf{T}}$$

$$\underline{\mathbf{P}} \leq \mathbf{p^g} \leq \overline{\mathbf{P}}$$

PTDF+L Model

$$\min \quad f_0(\mathbf{p^g})$$

$$s.t.$$

$$\mathbf{1}^\top(\mathbf{p^g} - \mathbf{p^d}) = \mathbf{1}^\top \mathbf{p}^\ell$$

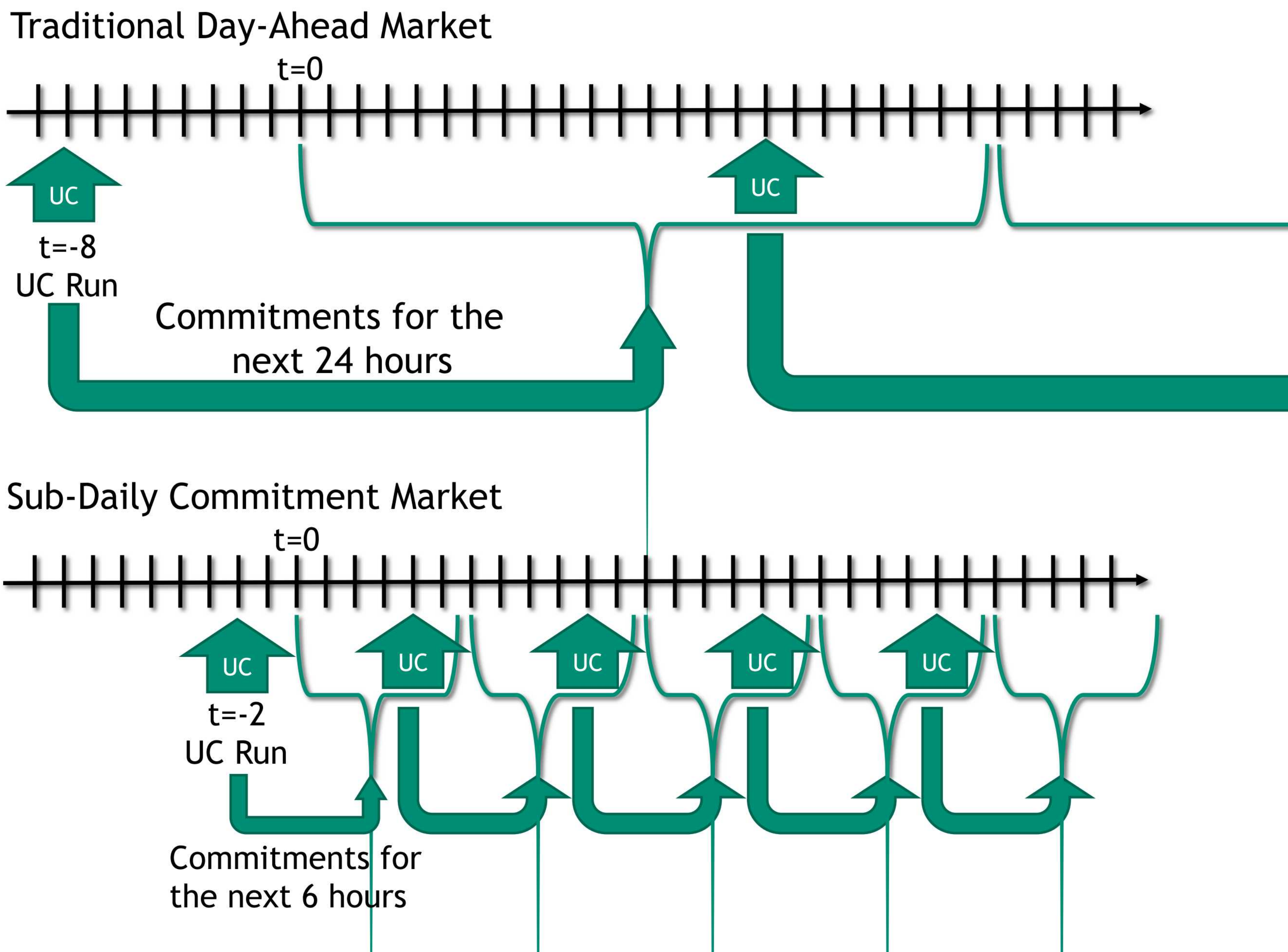
$$\mathbf{p}^\ell = \ell^0 + \mathbf{L}\mathbf{F}^\top(\mathbf{p^g} - \mathbf{p^d})$$

$$-\widehat{\mathbf{T}} \leq \mathbf{T}(\mathbf{p^f} - \mathbf{p^d} - \mathbf{D}\mathbf{p}^\ell) \leq \widehat{\mathbf{T}}$$

$$\underline{\mathbf{P}} \leq \mathbf{p^g} \leq \overline{\mathbf{P}}$$

(Litvinov et al., 2004)

Technical Approach: CCD Model



Technical Approach: CCD Pricing Model

Convex hull prices (CHP) can be computed by solving a linear program:

$$\min \sum_{g \in \mathcal{G}} c^g$$

subject to

(LP-CHP)

$$\sum_{g \in \mathcal{G}} (A^g p^g + B^g u^g) + N(s) = D \qquad (\pi^{\text{CH}})$$

$$(u^g, p^g, c^g) \in \text{conv}(\Pi^g), \ \forall g \in \mathcal{G}.$$

But we can always recover dual feasible (not optimal) prices for (LP-CHP) by solving:

$$\min \sum_{g \in \mathcal{G}} c^g$$

subject to

(LP-aCHP)

$$\sum_{g \in \mathcal{G}} (A^g p^g + B^g u^g) + N(s) = D \qquad (\pi^{\text{aCH}(\mathcal{R})})$$

$$(u^g, p^g, c^g) \in \mathcal{R}(\Pi^g), \ \forall g \in \mathcal{G}.$$

Technical Approach: CCD Pricing Model

Problem (LP-CHP) can be much larger than problem (LP-aCHP)

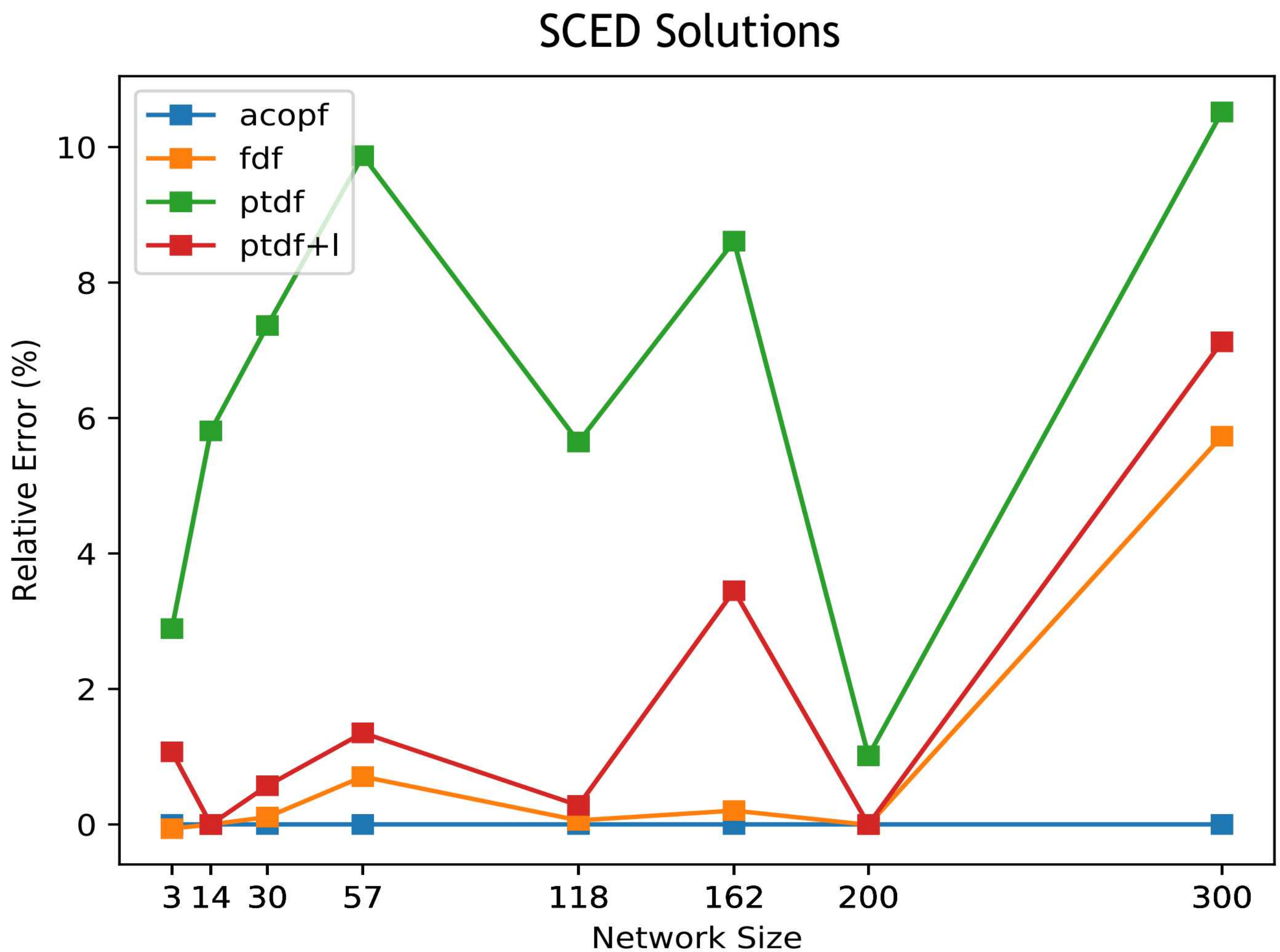
- Idea: generate Benders cuts separating feasible points of (LP-aCHP) from $\mathrm{conv}(\Pi^g), \ \forall g \in \mathcal{G}$.
- Repeat until the primal solution of (LP-aCHP) is feasible for (LP-CHP).

Since (LP-aCHP) (even with benders cuts) is necessarily a relaxation of (LP-CHP), this ensures the primal-dual pair of (LP-aCHP) is optimal for (LP-CHP).

Algorithm 1 (BENDERS CHP) Solves problem (LP-CHP) using Benders decomposition.

$\mathcal{G}^R \leftarrow \{g \in \mathcal{G} \mid g$ has irreduantant ramping constraints$\}$
$cuts \leftarrow True$
while $cuts$ **do**
  $cuts \leftarrow False$
  Solve master problem (LP-aCHP) with $\mathcal{R} = \mathcal{R}^*$
  for $g \in \mathcal{G}^R$ **do**
    Solve feasibility subproblem for g with $(\hat{u}^g, \hat{p}^g, \hat{c}^g)$ fixed from solution of (LP-aCHP)
    if feasibility subproblem is infeasible **then**
      add cut to (LP-aCHP)
      $cuts \leftarrow True$
return Dual values π of the system constraints

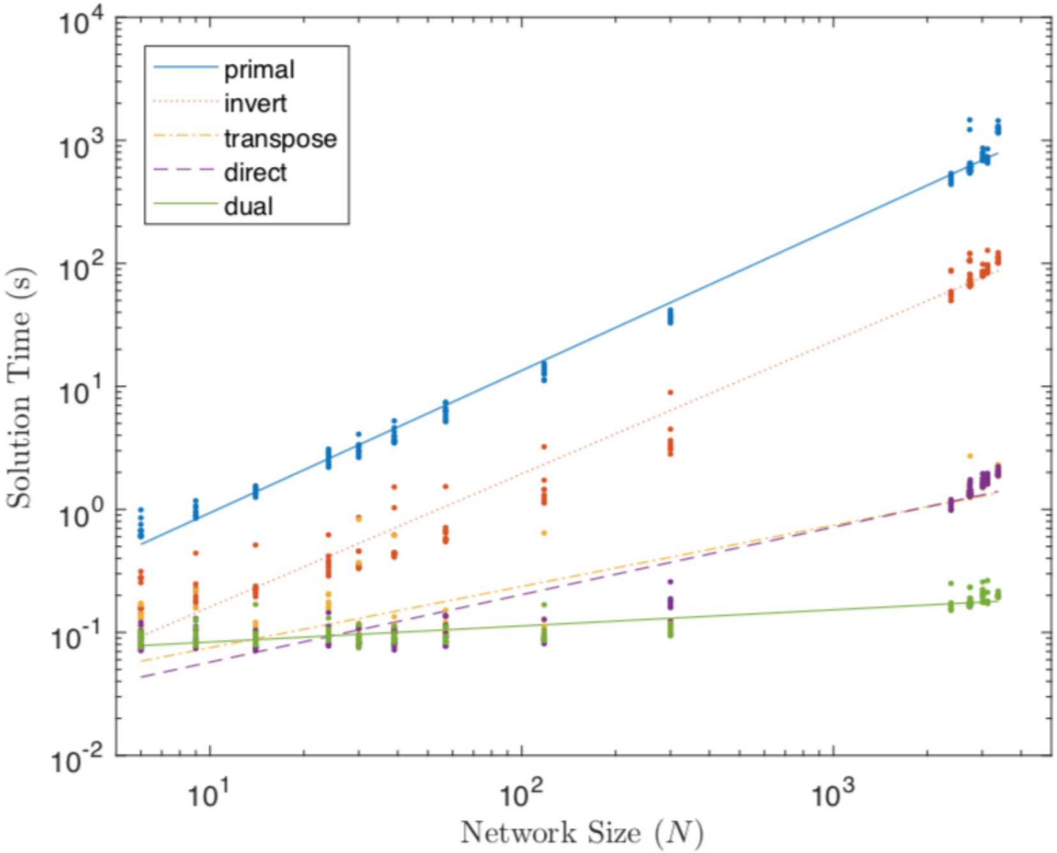
Technical Accomplishments: Preliminary FDF Performance



The relative error in objective value compared to the ACOPF solution demonstrates that the proposed FDF is a more accurate OPF approximation than current distribution factor approaches applied in practice.

(data: Coffrin, pglib-opf, v.17.08)

Technical Accomplishments: Scaling FDF Performance



Step 1. Initial State Estimation AC Base Point

Step 2. Calculate Sparse Distribution Factors with the 'Dual Method'

Step 3. Solve Sparse FDF Model

Step 4. Check all thermal limits and voltage limits are satisfied

Step 5. If not, re-initialize Step 1

The overhead time to construct the distribution factors increases with network size. Therefore we propose an approach that uses LP duals for matrix updates.

Technical Accomplishments: Preliminary CCD Results

	Production Cost	Savings (%)	Load Shedding	Savings (%)	Reserve Shortfall	Savings (%)
RUC every 24, schedule hr -8	$ 489,100,519	0.0%	159480	0.0%	66445	0.0%
RUC every 6, schedule hr -2	$ 487,786,469	0.3%	64931	59.3%	44608	32.9%
RUC every 4, schedule hr -2	$ 485,555,181	0.7%	66331	58.4%	44755	32.6%
RUC every 3, schedule hr -1	$ 484,560,041	0.9%	28187	82.3%	34343	48.3%
RUC every 1, schedule hr 0	$ 482,335,511	1.4%	3729	97.7%	15455	76.7%

Commitment decisions closer to real-time requirements enable more efficient procurement of reserves and thermal unit start-up/shut-down.

	Production Cost	Total Thermal Payments	Total Renewable Payments
RUC every 24, schedule hr -8	$ 489,100,519	$ 783,726,225	$ (162,293,607)
RUC every 1, schedule hr 0	$ 482,335,511	$ 579,115,875	$ 235,172,344

In high renewable penetration markets, it can be inefficient and unreliable to have renewables bid in their expected forecasts in the commitment market. In CCD markets, the risk of high variability decreases making ancillary service requirements like reserve and flexiramp available without over-commitments.

Technical Accomplishments: Preliminary CHP (CCD Pricing) Results

	Benders				EF
	Cut Time	Cuts Added	Iterations	Total Time	Time
2015-01-01 LW	15.6	63	6	64.1	*
2015-02-01 LW	47.1	90	18	105.6	*
2015-03-01 LW	38.6	90	12	83.7	*
2015-04-01 LW	48.0	59	12	102.5	*
2015-05-01 LW	188.7	131	47	310.4	*
2015-06-01 LW	67.3	89	16	135.8	*
2015-07-01 LW	106.7	178	12	163.2	*
2015-08-01 LW	137.8	247	23	218.0	*
2015-09-01 LW	480.5	1084	86	658.1	*
2015-10-01 LW	75.9	155	21	155.7	*
2015-11-02 LW	47.2	96	25	123.1	*
2015-12-01 LW	29.7	87	15	82.5	*
2015-01-01 HW	13.5	47	5	61.1	*
2015-02-01 HW	24.9	121	16	81.9	*
2015-03-01 HW	29.9	89	11	84.2	*
2015-04-01 HW	35.2	94	16	111.8	*
2015-05-01 HW	35.2	42	9	84.2	*
2015-06-01 HW	55.8	44	16	124.4	*
2015-07-01 HW	129.1	208	17	202.2	*
2015-08-01 HW	129.5	282	15	199.4	*
2015-09-01 HW	412.0	796	37	521.2	*
2015-10-01 HW	20.6	106	17	81.9	*
2015-11-02 HW	29.2	73	17	91.8	*
2015-12-01 HW	42.8	160	18	114.1	*

Proposed Benders Decomposition Method versus Extensive Form (EF) to Compute Convex Hull Pricing (CHP)

FERC Data Set:
- 48-Hour, Hourly Horizon
- FERC 900+ Generators
- Copperplate
- PJM Demand and Spinning Reserve Requirements
- PJM Wind Profiles (Low: LW and High: HW)

The problem was too large (275mm+ non-zeros in the constraint matrix) to solve the CHP directly (via EF) within a 2-hour timeframe. The proposed Benders approach computes exact CHP in less than 10 minutes for all but one.

Project Team

Anya Castillo, PhD (**PI**: arcasti@sandia.gov)

Sandia Team Members:

Bernard Knueven, PhD

Jean-Paul Watson, PhD (**POC**: jwatson@sandia.gov)

External Collaborators:

Brent Eldridge (PhD Candidate, Johns Hopkins University)

Ben Hobbs, PhD (Faculty, Johns Hopkins University)

Richard O'Neill, PhD (Economic Advisor, Federal Energy Regulatory Commission)

Jim Ostrowski, PhD (Faculty, University of Tennessee)

This project team integrates Sandia expertise in scalable nonlinear and discrete optimization techniques applied to power grid operations and market settlement analysis with complementary academic and regulatory expertise for developing state-of-the-art techniques in OPF approximations and rolling horizon continual UC and ED processes. The research funded on this project has resulted in numerous technical papers (1 published, 1 under review, and 4 drafting) and presentations (completed 2 invited talks).

Conclusion and Future Efforts

2018 Results.

1. FDF formulation results for network cases < 1k buses, with initial results done on sensitivity to different real and reactive demand loading factors.
2. Implementation of a novel 'dual method' to compute distribution factors for a subset of the network in order to scale the problem quickly with sparse matrix formulations.
3. CCD model results for current day (RUC every 24 hours, schedule hour -8) to increasingly aggressive continual rolling horizon variants (RUC every 1 hour, schedule hour 0) that demonstrate payment transfers between energy and ancillary markets, as well as thermal and renewable generators.
4. Efficient computation of exact convex hull pricing (CHP) for a fair and accurate comparison of multi-part pricing in current day and CCD processes.
5. 3 peer-review papers (2 under review and 1 published) and 2 invited talks

2019 Plans and Expectations.

1. Scale the FDF formulation with the proposed 'dual method' to solve OPF approximation quickly/accurately on large-scale networks.
2. Complete the comparison of current day and CCD processes for co-optimized energy and ancillary markets through dispatch and market settlement characteristics.
3. Publicly available Python code repositories on github.com to enable other researchers to leverage FDF and CCD capabilities.
4. 4 peer-review papers (works in progress)
5. Follow-on Proposal Submitted for FY20-FY22 (PI: Bernard Knueven, bknueve@sandia.gov)

Overall Impressions

Opportunities and Impact: There is a significant need to impact current inefficiencies such as: (1) two-settlement market design, (2) nomograms for VAr and voltage support, and (3) economic uplift (out-of-market) charges through computational advancements and advanced grid modeling initiatives.

Next Steps: Proposed in "Reactive Power and Ancillary Service Valuation and Procurement for Enhanced Security, Resilience, and Reliability" (PI: Bernard Kneuven bknueve@sandia.gov, FY20-FY22, $400k/year)

- Leverage existing work under current project to compute convex hull pricing for a multi-part market including ancillary services: voltage support, frequency regulation, spinning reserve and flexible ramp.
- Incorporate AC approximations/relaxations into Unit Commitment and compare to existing nomogram techniques (e.g., MISO voltage and local reliability approach)
- In collaboration with industry partner, develop valuations of reactive power dispatch, voltage support needs, and traditional ancillary services