SAND2019-4314C

Exceptional service in the national interest

Sandia National Laboratories

Advances and Opportunities in Optimization of Electrical Grid Operations

Carl D. Laird
PMTS, Center for Computing Research, Sandia National Laboratory
Associate Professor, School of Chemical Engineering, Purdue University

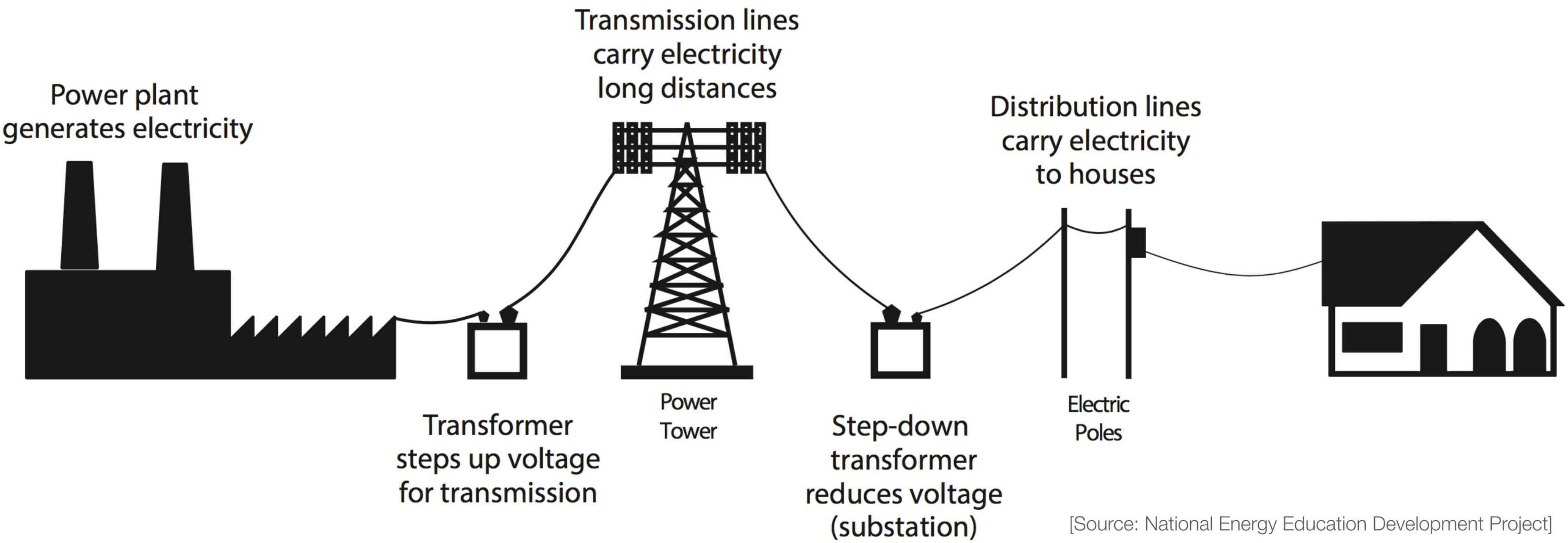
U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

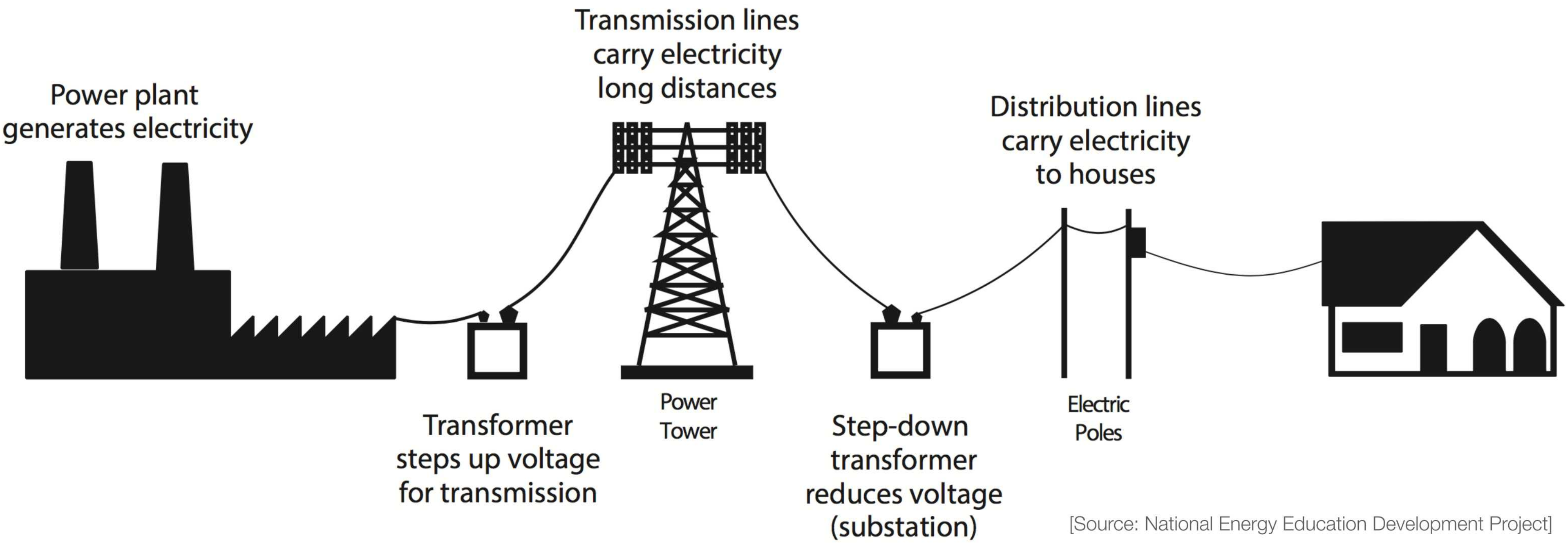
Electricity Supply and Delivery



[Source: National Energy Education Development Project]

Generation	Transmission	Distribution

Electricity Supply and Delivery



[Source: National Energy Education Development Project]

Generation	Transmission	Distribution
Wholesale (FERC)		Retail (States)

Characteristics of Electricity Generation Technologies

Sandia National Laboratories

Coal (> 30% of US power)

- High capital, low marginal cost
- High capacity

Nuclear (~20%)

- Flat load (~2 years)

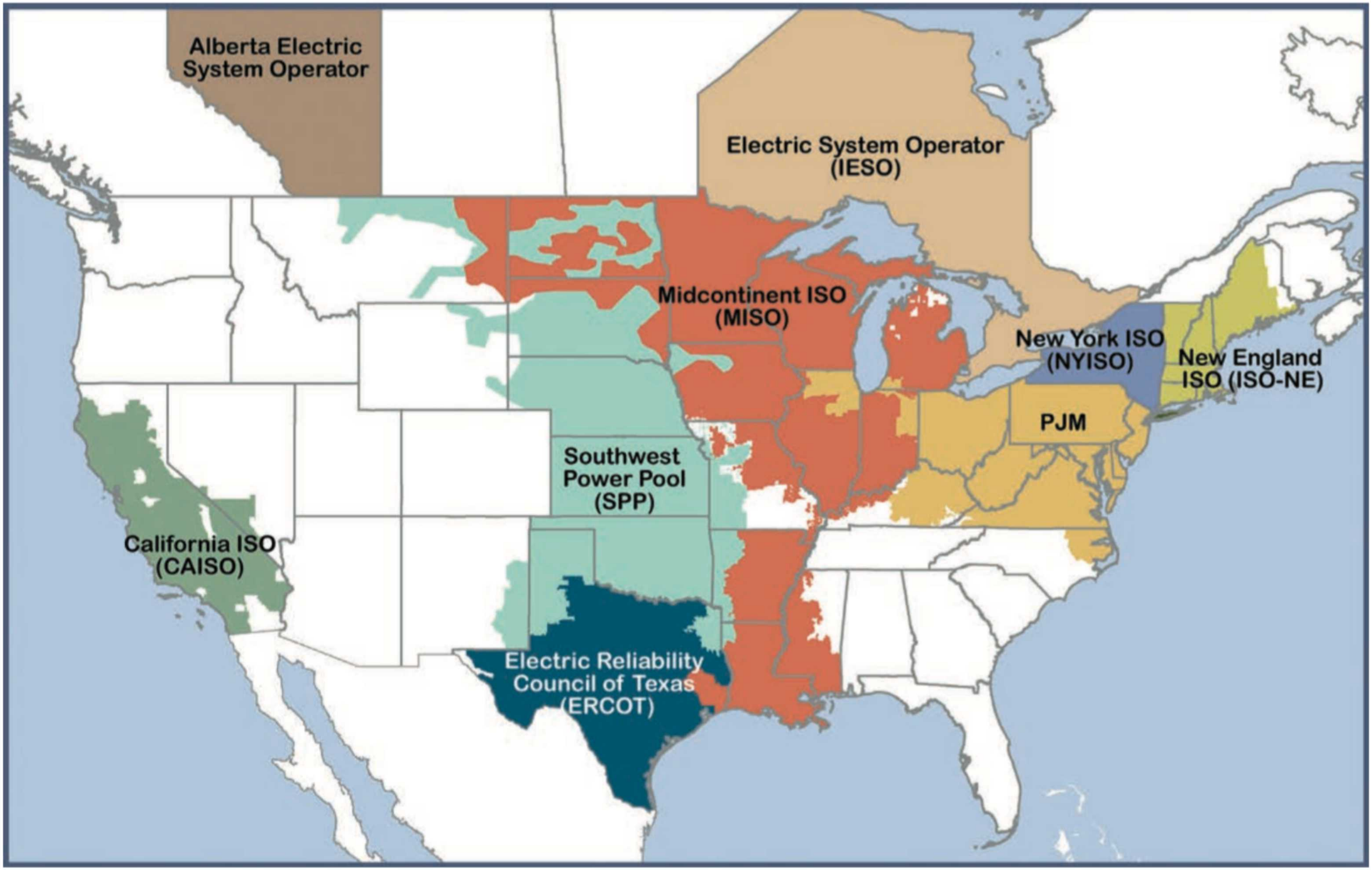
Natural Gas (~30% of US power)

- Steam: 300-1000 MW, long startup, limited flexibility
- Gas Turbine: 10-50 MW, high cost, quick start units
- Combined-cycle: High efficiency

Renewables

- E.g., geothermal, biomass, hydro, solar, wind
- Generation capacity not controllable (wind, PV)
- Increased variability during operation

North American Independent System Operators and Regional Transmission Organizations



Source: Velocity Suite, ABB

[Energy Primer,, A Handbook of Energy Market Basics, Staff Report, FERC]

Electricity Supply and Delivery

Independent System Operators:

- Ensure reasonable rates, terms, conditions in market
- Promote reliable, secure, efficient infrastructure

Challenges:

- Demand does not vary by price
- Little to no storage capacity
- Flow path governed by physics, not controlled

Demand must be exactly matched by generation
Cannot violate operating limits on lines/generators

Accurately forecast demand
Effectively commit and dispatch generating units
Quickly increase/decrease generator output

Electricity Supply and Delivery

Independent System Operators:

- Ensure reasonable rates, terms, conditions in market
- Promote reliable, secure, efficient infrastructure

Challenges:

- Demand does not vary by price
- Little to no storage capacity
- Flow path governed by physics, not controlled

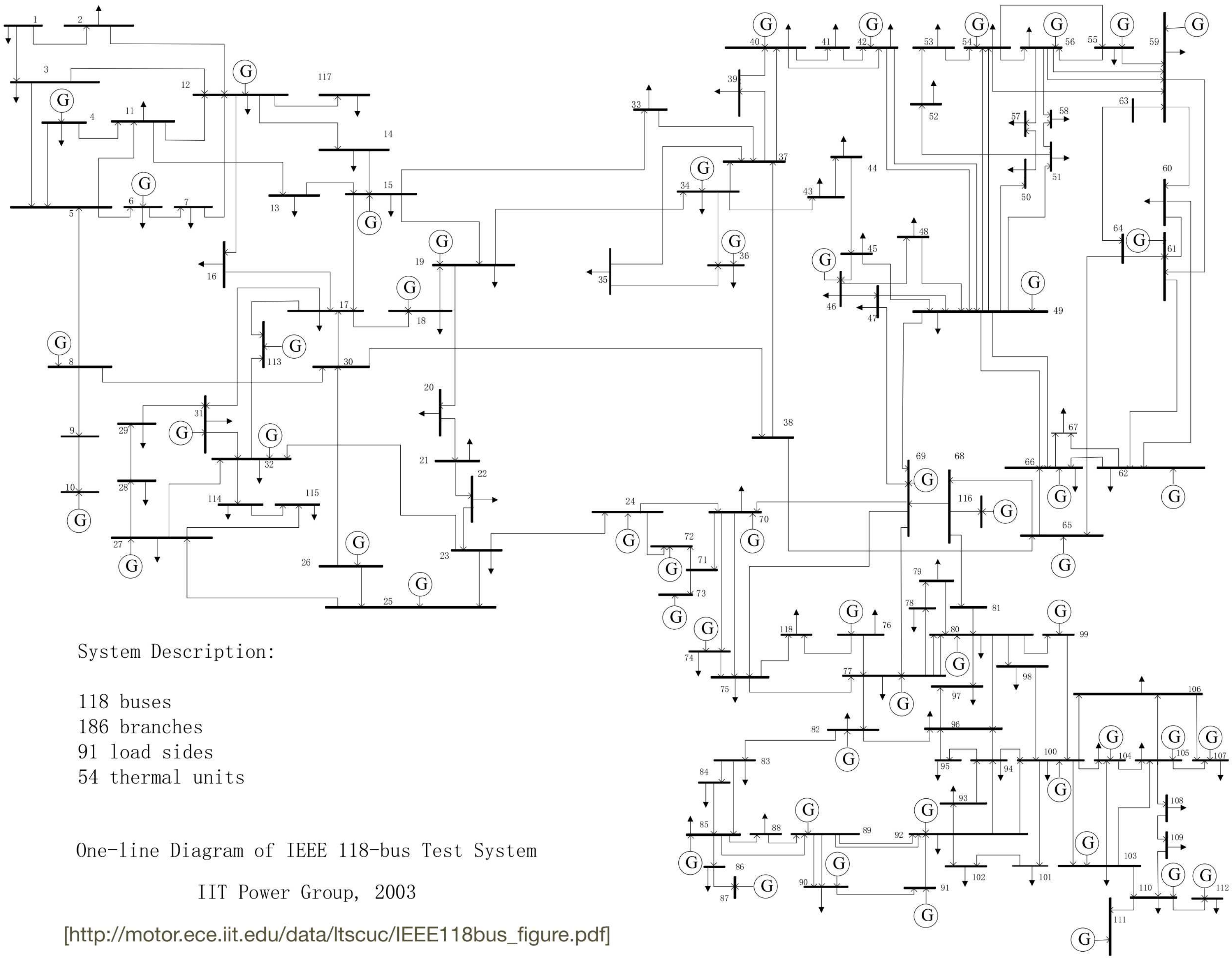
Demand must be exactly matched by generation
Cannot violate operating limits on lines/generators

Accurately forecast demand
Effectively commit and dispatch generating units
Quickly increase/decrease generator output

PSE Research Opportunities

ISO Transmission Network

Sandia National Laboratories



System Description:

118 buses
186 branches
91 load sides
54 thermal units

One-line Diagram of IEEE 118-bus Test System

IIT Power Group, 2003

[http://motor.ece.iit.edu/data/ltscuc/IEEE118bus_figure.pdf]

Transmission Network Models

Sandia National Laboratories

Power / current Balance

- Generation, demand, bus balances

PI transmission model

- Real/reactive power, IV relationships
- Line losses, other elements

Operating constraints

- Thermal limits on lines
- Generator limits, voltage / phase angle limits

Written in PQ, IV, rect, polar

Typical size: ~10,000 buses/lines

AC Power Flow

Nonlinear IV—> PQ
Full system constraints

DC Power Flow

linear approximation
(LP, MIP)
P, phase angle only

ISO OPF Applications: Unit Commitment

Sandia National Laboratories

- Day ahead unit commitment
  - Determine the On/Off schedule for generation units
  - Based on forecast demands
  - Include some model of the transmission network
  - Generator up/down time constraints, ramping limits
  - Used to determine wholesale pricing

- Formulations:
  - UC (MIP)
    - Copper-plate assumption
    - Ignores congestion (thermal limits)
  - SCUC+DCOPF (MIP)
    - Real power flows only
    - DCOPF assumptions (linearized model)
    - Can consider losses
    - AC feasibility tested on solution
  - SCUC+ACOPF (MINLP)
    - Includes real and reactive power dispatch
    - Nonlinear, non-convex model

ISO OPF Applications: Unit Commitment

Locational marginal pricing (LMP) determines spot prices for wholesale market

- Dual variable on the real power balance at network buses
- Considers marginal unit cost, network congestion, and power losses
- * Global solution highly desired…

Challenges:

- Committing least cost while maintaining reliability
- Demands (+ other parameters) are uncertain (Stoch. Prog.)
- AC feasibility tests remove optimality
- Need more accurate (nonlinear) models

ISO OPF Applications: Economic dispatch

Sandia National Laboratories

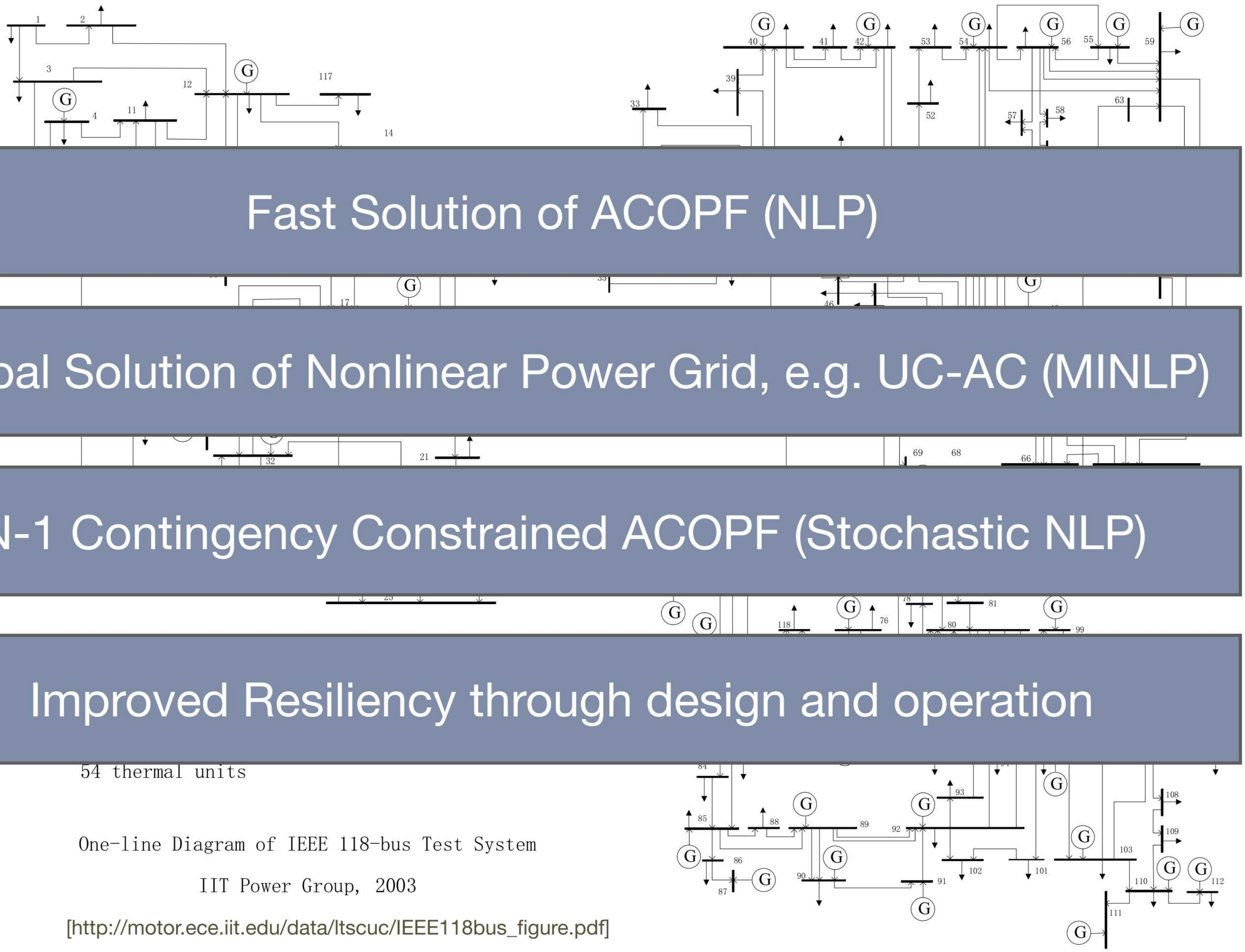
Real-time economic dispatch

- Run every hour (with 5-15 minute dispatch)
- Generator commitment (discrete decisions) fixed
- Solve for generator setpoints
- * Global solution highly desired…
- DCOPF formulation used with AC feasibility tests

Challenges:

- Desire more accurate models of generator and system capabilities (nonlinear ACOPF+)

Nonlinear Optimization for Power Grid Systems



Fast Solution of ACOPF (NLP)

Global Solution of Nonlinear Power Grid, e.g. UC-AC (MINLP)

N-1 Contingency Constrained ACOPF (Stochastic NLP)

Improved Resiliency through design and operation

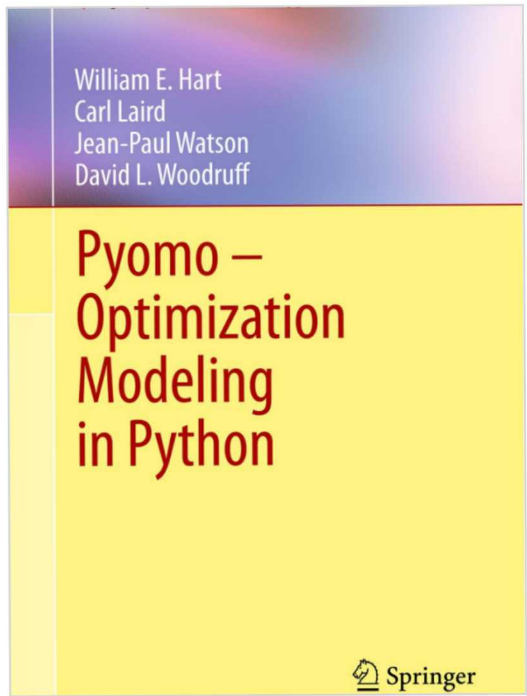
54 thermal units

One-line Diagram of IEEE 118-bus Test System

IIT Power Group, 2003

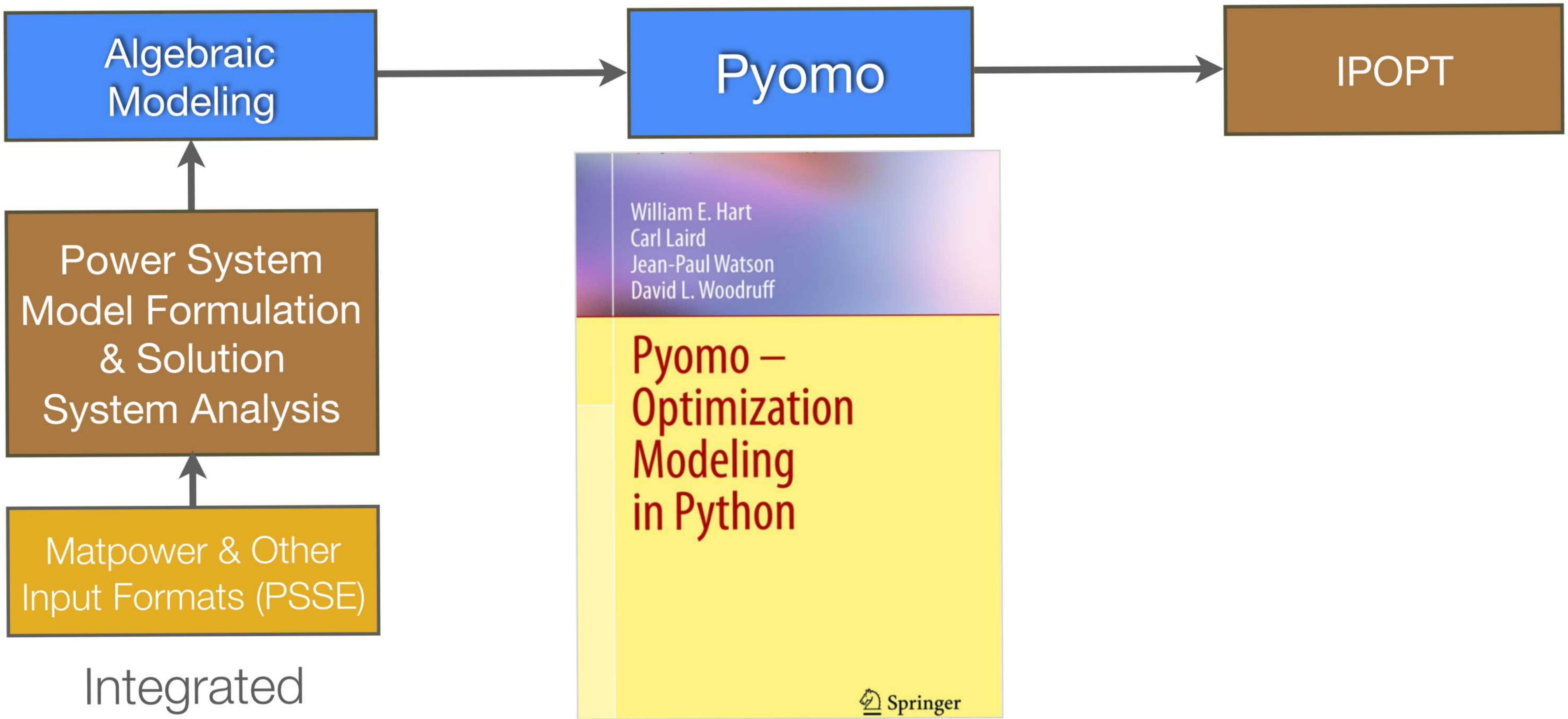
[http://motor.ece.iit.edu/data/ltscuc/IEEE118bus_figure.pdf]

Modeling Power Systems with Pyomo



Hackebeil, Hart, Laird,
Siirola, Watson, Woodruff,
and many others…

Modeling Power Systems with Pyomo



Integrated Python-based toolchain

Hackebeil, Hart, Laird, Siirola, Watson, Woodruff, and many others…

ACOPF Problem Formulation

Sandia National Laboratories

$$\min \quad \sum_{g \in \mathcal{G}} \text{GeneratorCost}_g(P_g, Q_g)$$

$$\begin{bmatrix} i^l_{fr} \\ i^l_{fj} \\ i^l_{tr} \\ i^l_{tj} \end{bmatrix} = Y^l_{br} \begin{bmatrix} v^l_{fr} \\ v^l_{fj} \\ v^l_{tr} \\ v^l_{tj} \end{bmatrix} \qquad \forall\, l \in \mathcal{L}$$

PI Transmission Model

$$P^l_t = (v^{bt(l)}_r \cdot i^l_{tr} + v^{bt(l)}_j \cdot i^l_{tj}) \qquad \forall\, l \in \mathcal{L}$$

$$Q^l_t = (v^{bt(l)}_j \cdot i^l_{tr} - v^{bt(l)}_r \cdot i^l_{tj}) \qquad \forall\, l \in \mathcal{L}$$

$$P^l_f = (v^{bf(l)}_r \cdot i^l_{fr} + v^{bf(l)}_j \cdot i^l_{fj}) \qquad \forall\, l \in \mathcal{L}$$

$$Q^l_f = (v^{bf(l)}_j \cdot i^l_{fr} - v^{bf(l)}_r \cdot i^l_{fj}) \qquad \forall\, l \in \mathcal{L}$$

$$S^l_t \geq (P^l_t)^2 + (Q^l_t)^2 \qquad \forall\, l \in \mathcal{L}$$

$$S^l_f \geq (P^l_f)^2 + (Q^l_f)^2 \qquad \forall\, l \in \mathcal{L}$$

Real Power, Reactive Power, Apparent Power Constraints From the Branches

$$0 = \sum_{l \in \mathcal{B}^b_{in}} P^l_t + \sum_{l \in \mathcal{B}^b_{out}} P^l_f + \sum_{d \in \mathcal{D}^b} P^d_L - \sum_{g \in \mathcal{G}^b} P^g_G + Y^b_{sh} \cdot [(v^b_r)^2 + (v^b_j)^2] \qquad \forall\, b \in \mathcal{B}$$

$$0 = \sum_{l \in \mathcal{B}^b_{in}} Q^l_t + \sum_{l \in \mathcal{B}^b_{out}} Q^l_f + \sum_{d \in \mathcal{D}^b} Q^d_L - \sum_{g \in \mathcal{G}^b} Q^g_G + Y^b_{sh} \cdot [(v^b_r)^2 + (v^b_j)^2] \qquad \forall\, b \in \mathcal{B}$$

Power Balance Constraints

$$v^b_m = (v^b_r)^2 + (v^b_j)^2 \qquad \forall\, b \in \mathcal{B}$$

Voltage Maximum/Reference

$$v^{ref}_j = 0$$

bounds on $v^b_m, P^g_G, Q^g_G, S^l_f, S^l_t$

ACOPF Solution with Pyomo/IPOPT

Sandia National Laboratories

Case Name	Number of Variables	Solution Time (CPU Seconds)
case4gs	67	0.015
case5	67	0.003
case9	95	0.004
case9Q	95	0.004
case6ww	105	0.004
nesta_case_14_ieee	194	0.007
case14	197	0.005
case30	399	0.028
case24_ieee_rts	416	0.016
case39	465	0.015
case57	767	0.015
case118	1832	0.037
case89pegase	1881	0.067
case300	4025	0.13
case30Q	4025	0.14
case2383wp	28456	2.6
case3012wp	35242	2.6

But global solution is highly desired…

Rectangular PQV Model

Power Balance

$$\sum_{l \in \mathcal{L}_b^{in}} P_{l,t}^t + \sum_{l \in \mathcal{L}_b^{out}} P_{l,t}^f + G_b^{sh} v_{b,t}^2 + P_{b,t}^D - \sum_{g \in \mathcal{G}_b} P_{g,t}^G = 0 \qquad \forall\, b,\ t$$

$$\sum_{l \in \mathcal{L}_b^{in}} Q_{l,t}^t + \sum_{l \in \mathcal{L}_b^{out}} Q_{l,t}^f - B_b^{sh} v_{b,t}^2 + Q_{b,t}^D - \sum_{g \in \mathcal{G}_b} Q_{g,t}^G - \sum_{sc \in \mathcal{SC}_b} Q_{sc,t}^{SC} = 0 \qquad \forall\, b,\ t$$

Power Flow

$$P_{l,t}^f = G_l^{ff} v_{b,t}^2 + G_l^{ft}(v_{b,t}^r v_{k,t}^r + v_{b,t}^j v_{k,t}^j) - B_l^{ft}(v_{b,t}^r v_{k,t}^j - v_{b,t}^j v_{k,t}^r) \qquad \forall\, l,\ t$$

$$Q_{l,t}^f = -B_l^{ff} v_{b,t}^2 - B_l^{ft}(v_{b,t}^r v_{k,t}^r + v_{b,t}^j v_{k,t}^j) - G_l^{ft}(v_{b,t}^r v_{k,t}^j - v_{b,t}^j v_{k,t}^r) \qquad \forall\, l,\ t$$

$$P_{l,t}^t = G_l^{tt} v_{k,t}^2 + G_l^{tf}(v_{k,t}^r v_{b,t}^r + v_{k,t}^j v_{b,t}^j) - B_l^{tf}(v_{k,t}^r v_{b,t}^j - v_{k,t}^j v_{b,t}^r) \qquad \forall\, l,\ t$$

$$Q_{l,t}^t = -B_l^{tt} v_{k,t}^2 - B_l^{tf}(v_{k,t}^r v_{b,t}^r + v_{k,t}^j v_{b,t}^j) - G_l^{tf}(v_{k,t}^r v_{b,t}^j - v_{k,t}^j v_{b,t}^r) \qquad \forall\, l,\ t$$

Safety Constraints

$$(P_{l,t}^f)^2 + (Q_{l,t}^f)^2 \leq (S_{l,t}^{max})^2 \qquad \forall\, l,\ t$$

$$(P_{l,t}^t)^2 + (Q_{l,t}^t)^2 \leq (S_{l,t}^{max})^2 \qquad \forall\, l,\ t$$

Bounds

$$(v_b^{min})^2 \leq v_{b,t}^2 \leq (v_b^{max})^2 \qquad \forall\, b,\ t$$

$$v_{b,t}^2 \equiv (v_{b,t}^r)^2 + (v_{b,t}^j)^2 \qquad \forall\, b,\ t$$

Rectangular PQV Model

Power Balance

$$\sum_{l \in \mathcal{L}_b^{in}} P_{l,t}^t + \sum_{l \in \mathcal{L}_b^{out}} P_{l,t}^f + G_b^{sh} v_{b,t}^2 + P_{b,t}^D - \sum_{g \in \mathcal{G}_b} P_{g,t}^G = 0 \qquad \forall\, b,\ t$$

$$\sum_{l \in \mathcal{L}_b^{in}} Q_{l,t}^t + \sum_{l \in \mathcal{L}_b^{out}} Q_{l,t}^f - B_b^{sh} v_{b,t}^2 + Q_{b,t}^D - \sum_{g \in \mathcal{G}_b} Q_{g,t}^G - \sum_{sc \in \mathcal{SC}_b} Q_{sc,t}^{SC} = 0 \qquad \forall\, b,\ t$$

Power Flow

$$P_{l,t}^f = G_l^{ff} v_{b,t}^2 + G_l^{ft}(v_{b,t}^r v_{k,t}^r + v_{b,t}^j v_{k,t}^j) - B_l^{ft}(v_{b,t}^r v_{k,t}^j - v_{b,t}^j v_{k,t}^r) \qquad \forall\, l,\ t$$

$$Q_{l,t}^f = -B_l^{ff} v_{b,t}^2 - B_l^{ft}(v_{b,t}^r v_{k,t}^r + v_{b,t}^j v_{k,t}^j) - G_l^{ft}(v_{b,t}^r v_{k,t}^j - v_{b,t}^j v_{k,t}^r) \qquad \forall\, l,\ t$$

$$P_{l,t}^t = G_l^{tt} v_{k,t}^2 + G_l^{tf}(v_{k,t}^r v_{b,t}^r + v_{k,t}^j v_{b,t}^j) - B_l^{tf}(v_{k,t}^r v_{b,t}^j - v_{k,t}^j v_{b,t}^r) \qquad \forall\, l,\ t$$

$$Q_{l,t}^t = -B_l^{tt} v_{k,t}^2 - B_l^{tf}(v_{k,t}^r v_{b,t}^r + v_{k,t}^j v_{b,t}^j) - G_l^{tf}(v_{k,t}^r v_{b,t}^j - v_{k,t}^j v_{b,t}^r) \qquad \forall\, l,\ t$$

Safety Constraints

$$(P_{l,t}^f)^2 + (Q_{l,t}^f)^2 \le (S_{l,t}^{max})^2 \qquad \forall\, l,\ t$$

$$(P_{l,t}^t)^2 + (Q_{l,t}^t)^2 \le (S_{l,t}^{max})^2 \qquad \forall\, l,\ t$$

Bounds

$$(v_b^{min})^2 \le v_{b,t}^2 \le (v_b^{max})^2 \qquad \forall\, b,\ t$$

$$v_{b,t}^2 \equiv (v_{b,t}^r)^2 + (v_{b,t}^j)^2 \qquad \forall\, b,\ t$$

Relaxation of Rectangular PQV Model

Second-Order Cone Programming (SOCP) relaxation

(Jabr, 2006, Kocuk, 2015)

$$c_{b,b,t} = (v^r_{b,t})^2 + (v^j_{b,t})^2 = v^2_{b,t}$$

$$c_{b,k,t} = v^r_{b,t} v^r_{k,t} + v^j_{b,t} v^j_{k,t} = |v_{b,t}||v_{k,t}| \cos\theta_{b,k,t}$$

$$s_{b,k,t} = v^r_{b,t} v^j_{k,t} - v^r_{k,t} v^j_{b,t} = -|v_{b,t}||v_{k,t}| \sin\theta_{b,k,t}$$

Relaxation of Rectangular PQV Model

Sandia National Laboratories

Power Balance

$$\sum_{l \in \mathcal{L}_b^{in}} P_{l,t}^t + \sum_{l \in \mathcal{L}_b^{out}} P_{l,t}^f + G_b^{sh} c_{b,b,t} + P_{b,t}^D - \sum_{g \in \mathcal{G}_b} P_{g,t}^G = 0 \quad \forall\, b,\ t$$

$$\sum_{l \in \mathcal{L}_b^{in}} Q_{l,t}^t + \sum_{l \in \mathcal{L}_b^{out}} Q_{l,t}^f - B_b^{sh} c_{b,b,t} + Q_{b,t}^D - \sum_{g \in \mathcal{G}_b} Q_{g,t}^G - \sum_{sc \in \mathcal{SC}_b} Q_{sc,t}^{SC} = 0 \quad \forall\, b,\ t$$

Power Flow

$$P_{l,t}^f = G_l^{ff} c_{b,b,t} + G_l^{ft} c_{b,k,t} - B_l^{ft} s_{b,k,t} \quad \forall\, l,\ t$$

$$Q_{l,t}^f = -B_l^{ff} c_{b,b,t} - B_l^{ft} c_{b,k,t} - G_l^{ft} s_{b,k,t} \quad \forall\, l,\ t$$

$$P_{l,t}^t = G_l^{tt} c_{k,k,t} + G_l^{tf} c_{b,k,t} + B_l^{tf} s_{b,k,t} \quad \forall\, l,\ t$$

$$Q_{l,t}^t = -B_l^{tt} c_{k,k,t} - B_l^{tf} c_{b,k,t} + G_l^{tf} s_{b,k,t} \quad \forall\, l,\ t$$

Bounds

$$(v_b^{min})^2 \leq c_{b,b,t} \leq (v_b^{max})^2 \quad \forall\, b,\ t$$

Second-Order Cone Constraints

$$c_{b,k,t}^2 + s_{b,k,t}^2 \leq c_{b,b,t} c_{k,k,t} \quad \forall\, l,\ t$$

Global Solution of ACOPF with Pyomo/IPOPT

Sandia National Laboratories

Table 1: Problem Size and Performance Results

Case Name	Optimal Solution	Optimality Gap (%)	CPU Time (s)	Iterations
Case6ww	3126.36	8×10^{-3}	0.26	4
Case14	8081.52	3×10^{-3}	0.43	3
Case30	574.52	0.0	0.95	5
Case39	41864.18	5×10^{-3}	1.21	3
Case57	41737.79	6×10^{-3}	7.29	12
Case89	5817.60	9×10^{-3}	46.2	44
Case118	129660.69	6×10^{-3}	18.5	14
Case300	719725.10	9×10^{-3}	82.7	49
NESTA Case6ww	3143.97	0.0	0.74	7
NESTA Case14	244.05	3×10^{-3}	0.22	3
NESTA Case30	204.97	0.0	0.57	4
NESTA Case39	96505.52	9×10^{-3}	3.00	8
NESTA Case57	1143.27	6×10^{-3}	9.62	20
NESTA Case89	5819.81	9×10^{-3}	55.8	57
NESTA Case118	3718.64	0.0	93.7	55
NESTA Case300	16891.28	0.0	138.2	26

Relaxation of SCUC+ACOPF (MISOCP)

$$\min \quad f^p + f^{su} + f^{sd}$$

$$A_g^2 (P_{g,t}^G)^2 + A_g^1 P_{g,t}^G + A_g^0 y_{g,t} \le c_{g,t}^p \quad \forall\, g,\, t$$

$$f^p = \sum_{g \in \mathcal{G}} \sum_{t \in \mathcal{T}} c_{g,t}^p,$$

$$f^{su} = \sum_{g \in \mathcal{G}} \sum_{t \in \mathcal{T}} \sum_{\tau \in \mathcal{S}_g} K_{g,\tau}^{su} \delta_{g,\tau,t}$$

$$f^{sd} = \sum_{g \in \mathcal{G}} \sum_{t \in \mathcal{T}} K_g^{sd} w_{g,t}$$

$$\sum_{t'=t-T_g^u}^{t} u_{g,t'} \le y_{g,t} \quad \forall\, g,\, t$$

$$\sum_{t'=t-T_g^d}^{t} w_{g,t'} \le 1 - y_{g,t} \quad \forall\, g,\, t$$

$$\sum_{b \in \mathcal{B}} P_{b,t}^D + P_t^R \le \sum_{g \in \mathcal{G}} P_{g,t}^a \quad \forall\, t$$

$$P_g^{G,min} y_{g,t} \le P_{g,t}^G \le P_{g,t}^a \le P_g^{G,max} y_{g,t} \quad \forall\, g,\, t$$

$$Q_g^{G,min} y_{g,t} \le Q_{g,t}^G \le Q_g^{G,max} y_{g,t} \quad \forall\, g,\, t$$

$$Q_{sc}^{SC,min} y_{sc,t} \le Q_{sc,t}^{SC} \le Q_{sc}^{SC,max} y_{sc,t} \quad \forall\, sc,\, t$$

$$\delta_{g,\tau.t} \le \sum_{t'=t-T_{g,\tau}^{su}}^{t+1-T_{g,\tau+1}^{su}} w_{g,t'} \quad \forall\, g,\, t,\, \tau$$

$$u_{g,t} = \sum_{\tau \in \mathcal{S}_g} \delta_{g,\tau,t} \quad \forall\, g,\, t$$

$$y_{g,t} - y_{g,t-1} = u_{g,t} - w_{g,t} \quad \forall\, g,\, t$$

+

$$\sum_{l \in \mathcal{L}_b^{in}} P_{l,t}^t + \sum_{l \in \mathcal{L}_b^{out}} P_{l,t}^f + G_b^{sh} c_{b,b,t} + P_{b,t}^D - \sum_{g \in \mathcal{G}_b} P_{g,t}^G = 0 \quad \forall\, b,\, t$$

$$\sum_{l \in \mathcal{L}_b^{in}} Q_{l,t}^t + \sum_{l \in \mathcal{L}_b^{out}} Q_{l,t}^f - B_b^{sh} c_{b,b,t} + Q_{b,t}^D - \sum_{g \in \mathcal{G}_b} Q_{g,t}^G - \sum_{sc \in \mathcal{SC}_b} Q_{sc,t}^{SC} = 0 \quad \forall\, b,\, t$$

$$P_{l,t}^f = G_l^{ff} c_{b,b,t} + G_l^{ft} c_{b,k,t} - B_l^{ft} s_{b,k,t} \quad \forall\, l,\, t$$

$$Q_{l,t}^f = -B_l^{ff} c_{b,b,t} - B_l^{ft} c_{b,k,t} - G_l^{ft} s_{b,k,t} \quad \forall\, l,\, t$$

$$P_{l,t}^t = G_l^{tt} c_{k,k,t} + G_l^{tf} c_{b,k,t} + B_l^{tf} s_{b,k,t} \quad \forall\, l,\, t$$

$$Q_{l,t}^t = -B_l^{tt} c_{k,k,t} - B_l^{tf} c_{b,k,t} + G_l^{tf} s_{b,k,t} \quad \forall\, l,\, t$$

$$(P_{l,t}^f)^2 + (Q_{l,t}^f)^2 \le (S_{l,t}^{max})^2 \quad \forall\, l,\, t$$

$$(P_{l,t}^t)^2 + (Q_{l,t}^t)^2 \le (S_{l,t}^{max})^2 \quad \forall\, l,\, t$$

$$(v_b^{min})^2 \le c_{b,b,t} \le (v_b^{max})^2 \quad \forall\, b,\, t$$

$$c_{b,k,t}^2 + s_{b,k,t}^2 \le c_{b,b,t} c_{k,k,t} \quad \forall\, l,\, t$$

Numerical Results: 48 hour look-ahead

Sandia National Laboratories

Case	Formulation	Upper Bound	Lower Bound	Gap (%)	CPU Time (s)	Iteration
Case6	MISOCP-Q	1017.63	1017.63	0.0%	10.1	3
	MISOCP	1017.63	1017.63	0.0%	14.6	4
	MILP-5	1017.63	1010.56	0.7%	1116.7	30*
	MILP-10	1017.63	1017.63	0.0%	453.5	9
Case24-1	MISOCP-Q	8953.23	8946.80	0.1%	995	5
	MISOCP	8951.49	8947.75	0.1%	1520	7
	MILP-5	–	8209.15	–	5762.8	30*
	MILP-10	–	8870.4	–	36000*	1
Case24-2	MISOCP-Q	8863.62	8855.38	0.1%	846	1
	MISOCP	8863.62	8854.28	0.1%	83	1
	MILP-5	–	6957.86	–	6108.4	30*
	MILP-10	–	8634.28	–	36000*	12
Case118	MISOCP-Q	–	8327.90	–	36000*	1
	MISOCP	8357.76	8329.13	0.3%	5551.0	1
	MILP-5	–	3984.62	–	36000*	1
	MILP-10	–	8175.10	–	36000*	1

MISOCP-Q: relaxation with quadratic cost functions and thermal limits
MISOCP: relaxation with linear under-estimators of cost functions
MILP-5 /10: linear relaxations with different segment points

Power Systems Resilience

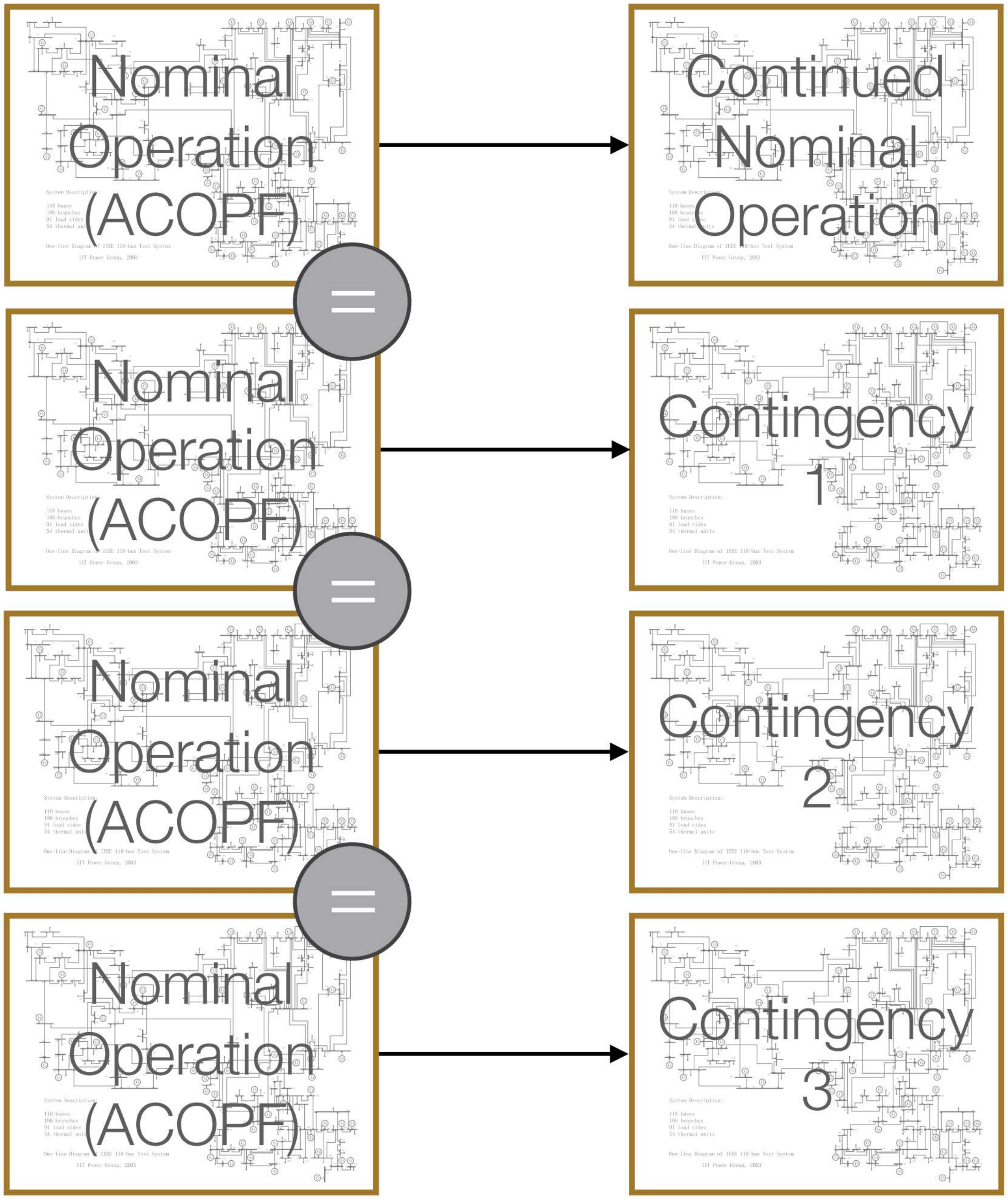
Transmission network performance vulnerable to:

- Inaccurate demand forecasts
- Weather events - transmission element failure
- Geomagnetic disturbances
- etc.

Optimization formulations for improving resilience:

- SP considering demand, weather, GMD uncertainty
- N-1 contingency constrained
- Adjust operating set point
- Perform system hardening or redesign

Contingency-Constrained ACOPF Problem



Nonlinear two-stage stochastic programming problem

AC power flow model for each scenario and stage

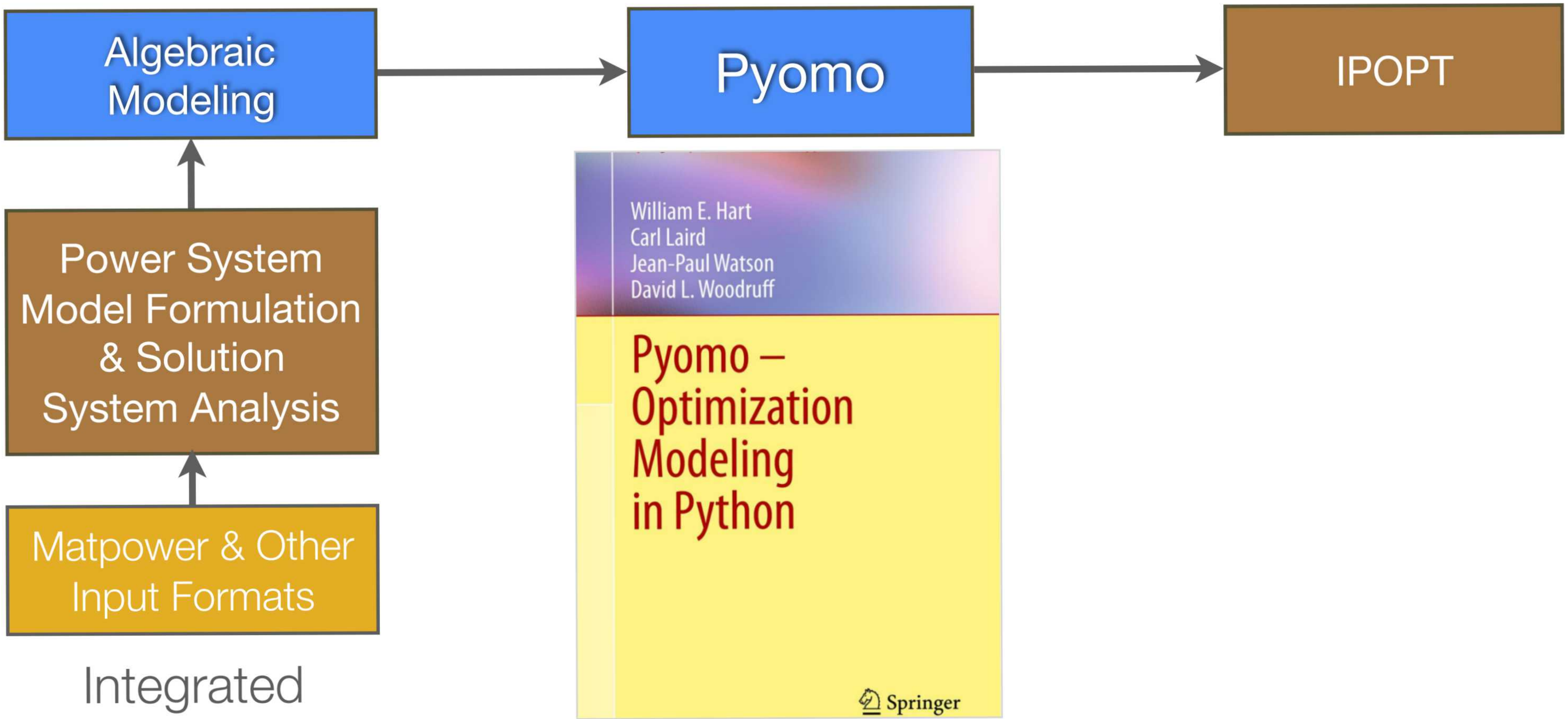
Contingency scenario for each transmission line

Penalty for inability to satisfy demands (infeasibility)

Ramping constraints for changes in generator set points

Very large-scale nonlinear programming problem (Millions of variables)

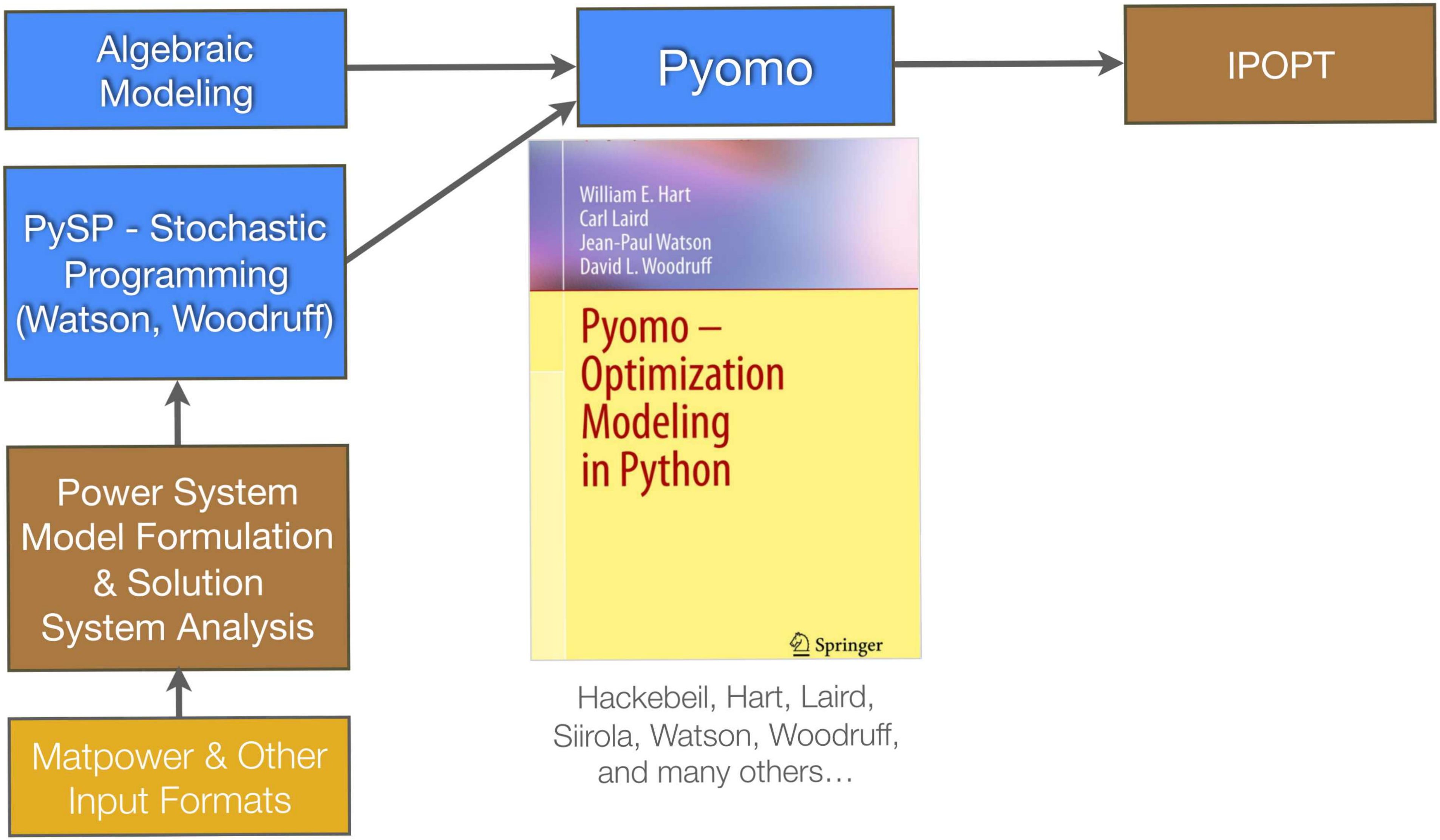
Building the model with Pyomo and PySP



Integrated Python-based toolchain

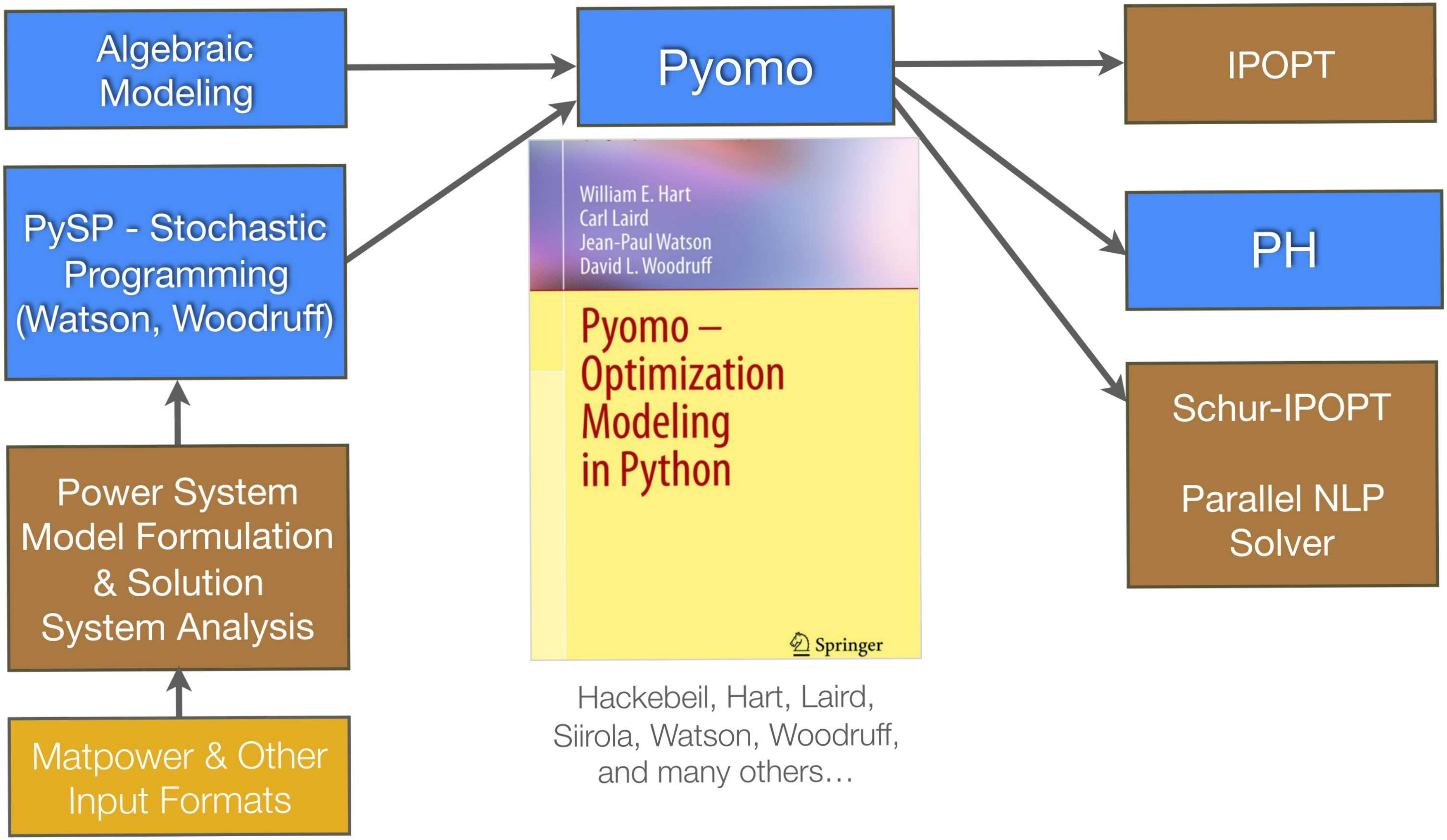
Hackebeil, Hart, Laird, Siirola, Watson, Woodruff, and many others…

Building the model with Pyomo and PySP



Hackebeil, Hart, Laird, Siirola, Watson, Woodruff, and many others…

Building the model with Pyomo and PySP



Hackebeil, Hart, Laird, Siirola, Watson, Woodruff, and many others…

Contingency-constrained ACOPF results

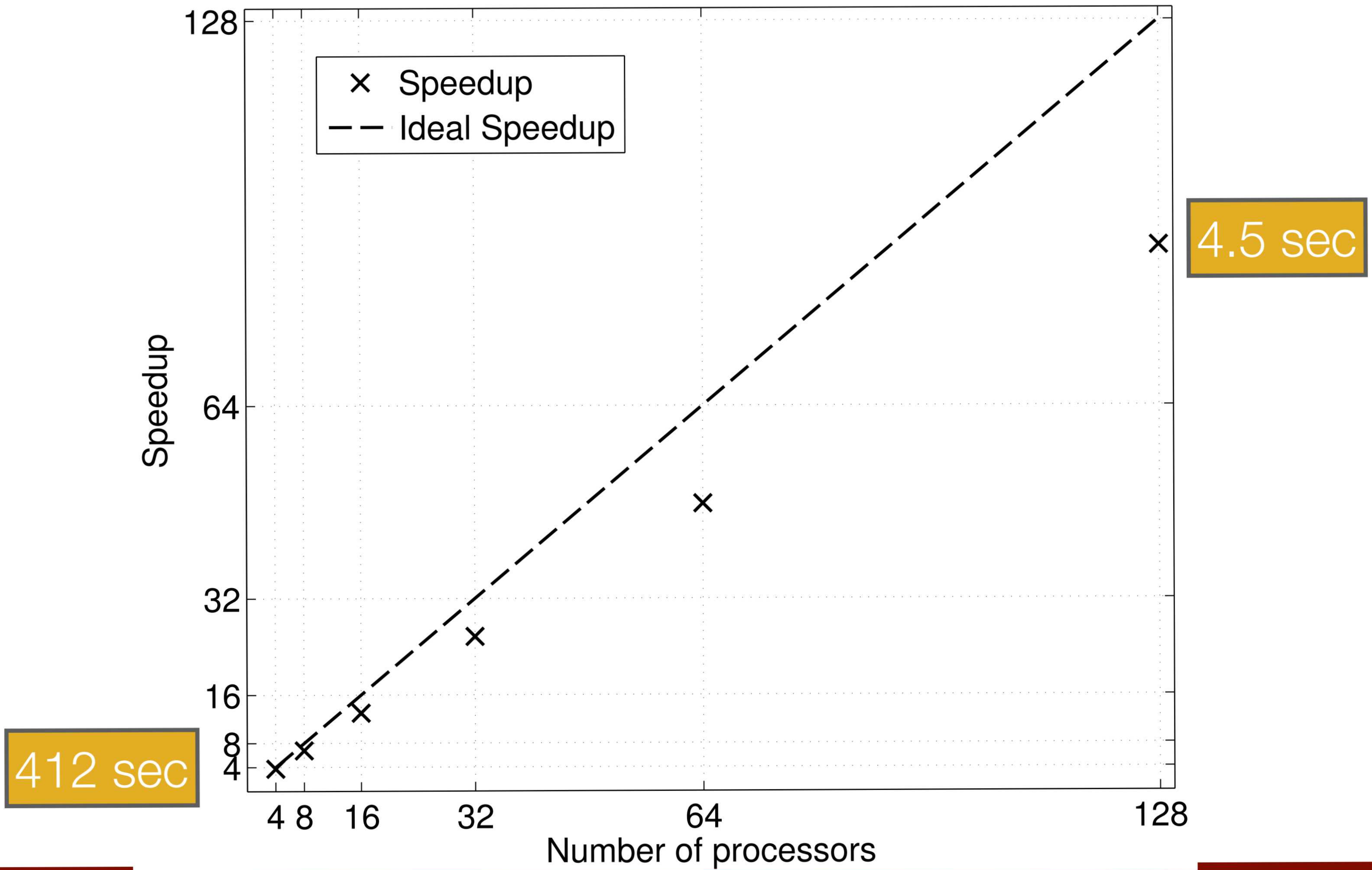
Problem data: case118 distributed with Matpower 4.1
- 118 buses, 54 active generators, and 186 branches

Multi-scenario problem with 128 scenarios in total
- Normal operating scenario and 127 contingencies
- Problem size: ~400,000 variables and ~385,000 constraints

Solution obtained in less than 5 seconds

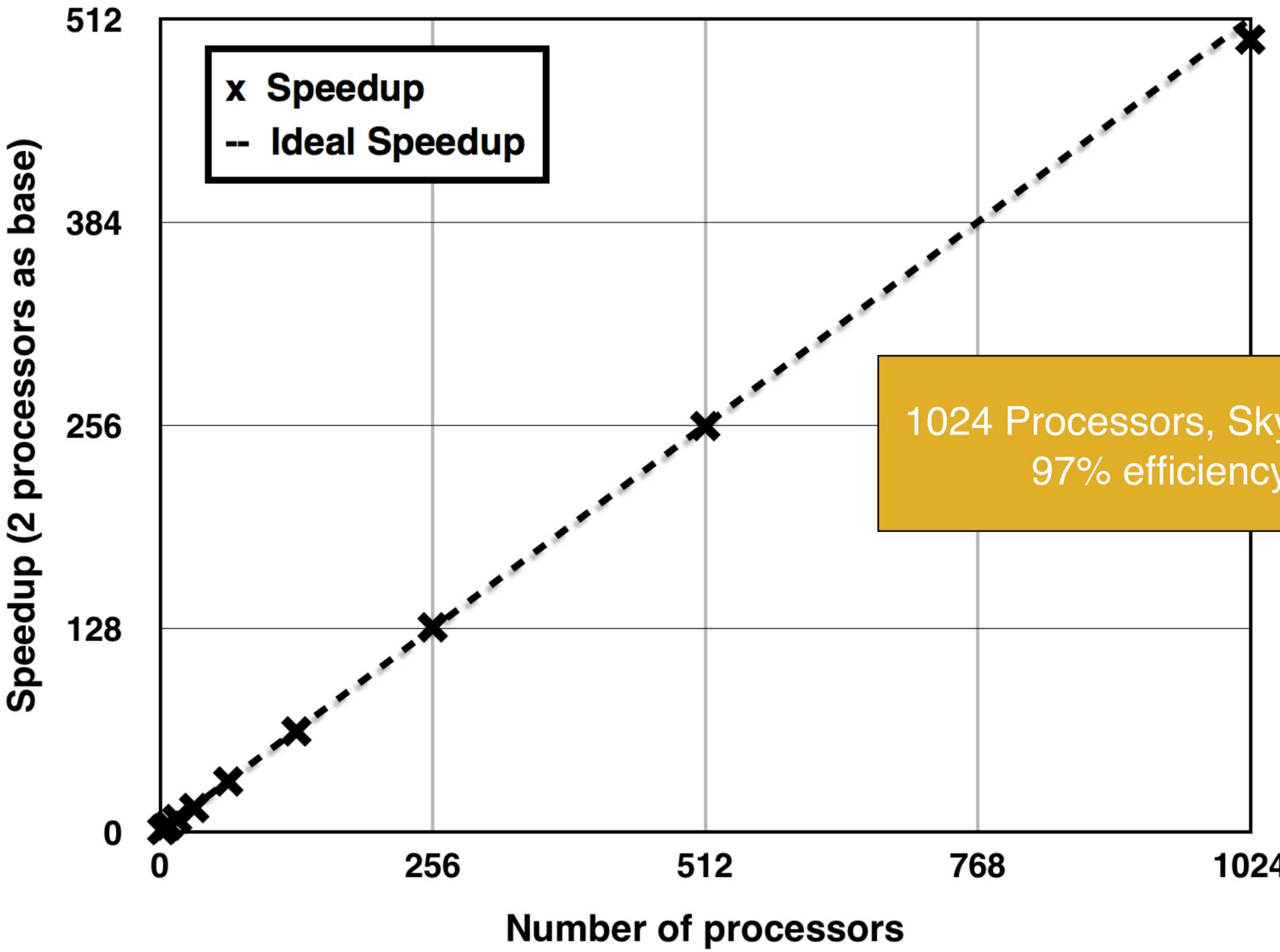
*Wall-clock time from the Red Mesa supercomputing cluster at Sandia National Lab.
Each node: 12 GB RAM, two 2.93 GHz quad-core, Nehalem X5570 processors

Contingency-constrained ACOPF results



Strong Scaling of Explicit Method in Schur-IPOPT

Sandia National Laboratories



1024 Processors, Skybridge, 97% efficiency

Research Opportunities

Forecasting:

- Wind, solar, demand

Generation:

- Impact of renewables
- Advanced systems for clean, efficient, energy production
- IDAES project with NETL

Improved optimization formulations for day-to-day operation

- Stochastic unit commitment
- Considerations of system nonlinearity - requires global/MINLP strategies
- Investigation of different (equivalent) formulations

Optimization formulations for design and operations

- Advisory tools for system reliability and resilience
- Introduction of new control elements
- Optimizing design of storage capabilities

Demand response

- Allow for controllable increase/decrease or shaping of demand

Dynamic systems optimization

- Include stability criteria and consider reliability rigorously

Acknowledgments

Students/Researchers

Arpan Seth
Yankai Cao
Alberto Benavides-Serrano
Jianfeng Liu
Michael Bynum
Todd Zhen
Santiago Rodriguez
Shu (Richard) Xu

Former Students/Postdocs

Yu Zhu
Ahmed Rabie
George Abbott III
Chen Wang
Sean Legg
Daniel Word
Angelica Wong
Xiaorui Yu
Gabriel Hackebeil
Jia Kang

Collaborators

W. Hart, **C. Silva-Monroy**, **J.P. Watson**,
K. Klise, **J. Siirola, Anya Castillo** - Sandia
D. Cummings - JHSPH
T. Haxton, R. Murray - EPA
Johan Akesson, Lund University
Sam Mannan, MKOPSC

Support

National Science Foundation Cyber-Enabled Discovery and Innovation (CDI)-Type II
National Science Foundation (CAREER Grant CBET# 0955205).
Sandia National Laboratories (DOE ASCR, EPA, PUB Singapore)