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Computational Challenges in Optimization for Electrical Grid Operations and Planning

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Take Away Message

- Improving and updating the electrical grid is interesting, challenging, & important
- There are a number of specific problems associated with this topic. I will give you just a few examples.
- These problems are excellent drivers for the development of tools and methods for solving stochastic MIPs & combinatorial problems.

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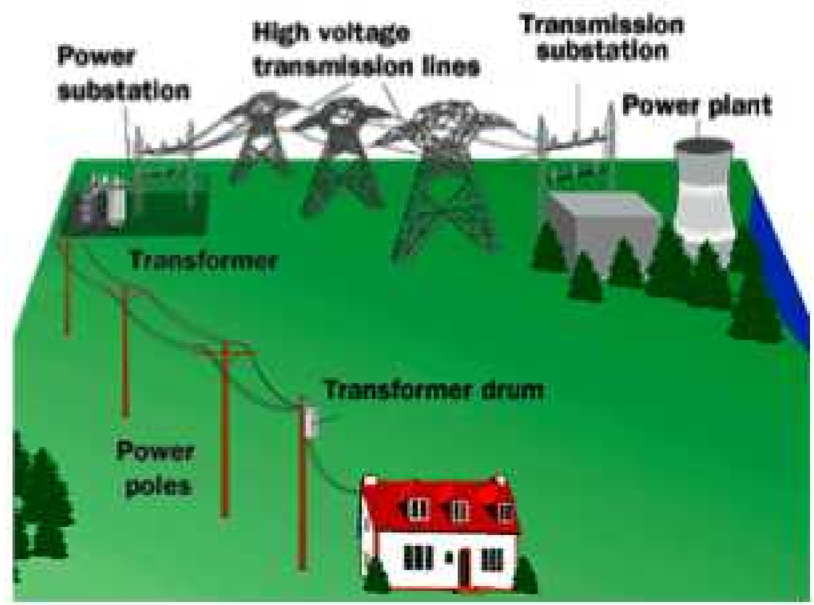
The Grid History

- 1882: First power system Pearl Street Station, NY (Edison)
- 1884: Introduction of AC transformer (Westinghouse)
- 1890’s: Edison and Westinghouse compete and AC becomes the norm (not DC)
  - Ability to increase and decrease voltages
  - Simpler, lower cost motors and generators
  - Standardization of frequency & voltage levels
- 1950’s: HVDC
- Since the 1950’s, there have been few changes
- Today & Future: Addition of computers, communications, distributed generation to form a smart (or smarter) grid
- Incorporation of renewable energy

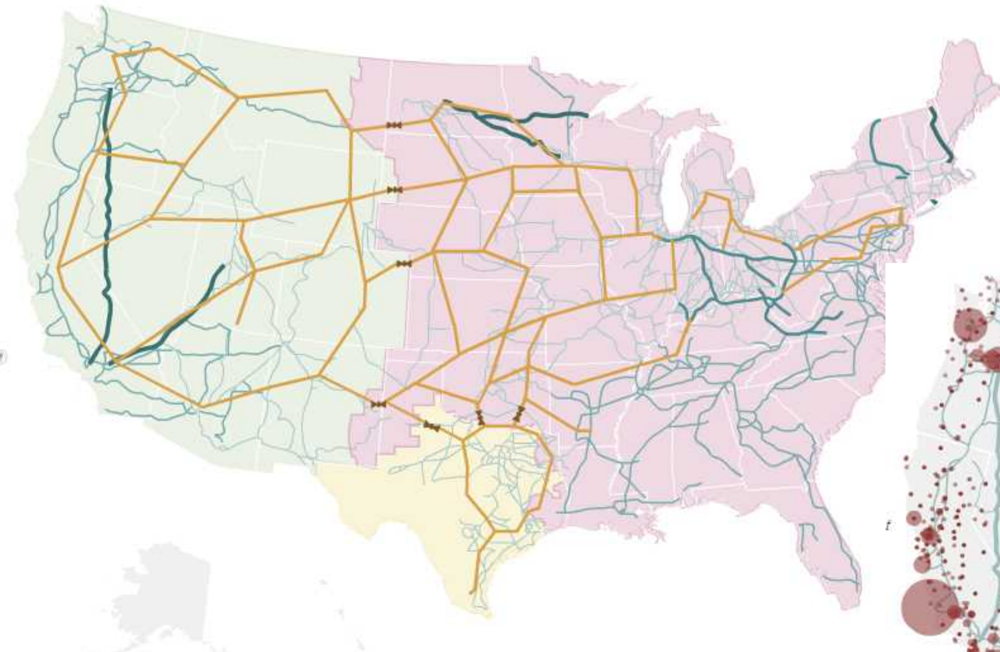
Pearl Street Power Station, NY

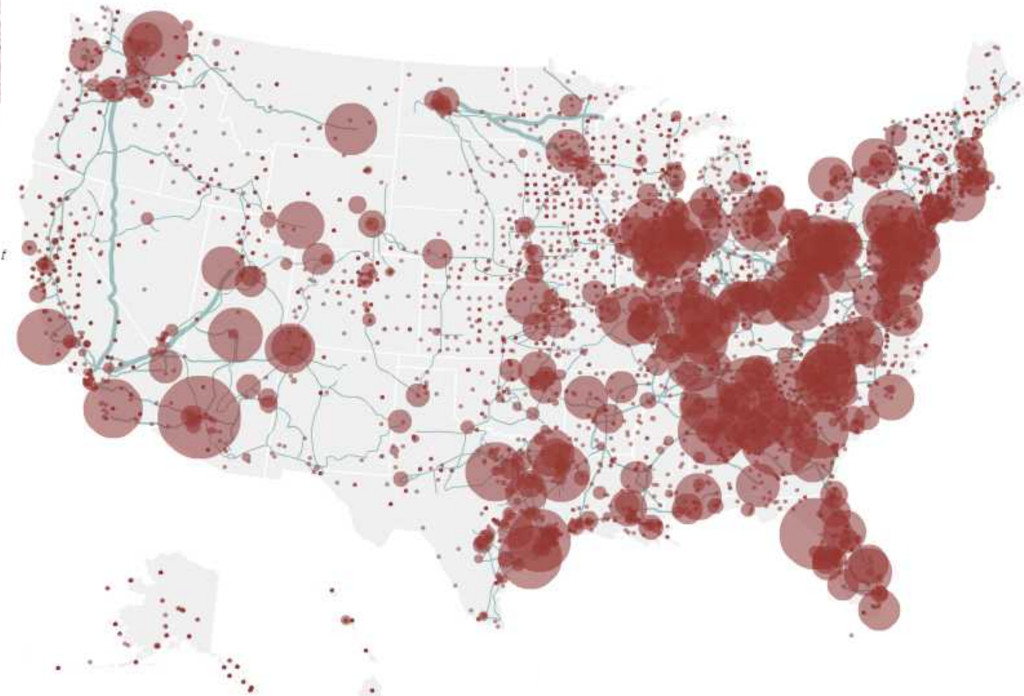
The Grid Make-Up

- Components
  - Generation (mostly centralized)
  - Transmission/distribution network: lines, transformers, regulators, switches, etc.
  - Utilization (loads)
  - Storage (little)
- Other physical components
  - Controls systems
  - Protection systems
  - Measurement
  - Communications
- It's a (complicated) graph!



The US Grid



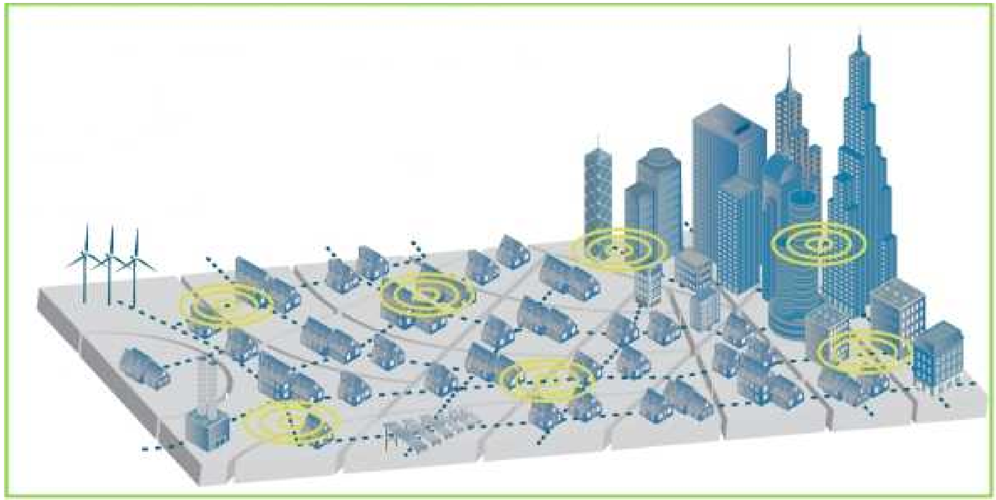


See NPR website for more details
(http://www.npr.org/templates/story/story.php?storyId=110997398)

Improving the Grid

Desired characteristics of the grid (as stated by the US Department of Energy):

- Self-healing from power disturbance events
- Enabling active participation by consumers in demand response
- Operating resiliently against physical and cyber attack
- Providing power quality for 21st century needs
- Accommodating all generation and storage options
- Enabling new products, services, and markets
- Optimizing assets and operating efficiently



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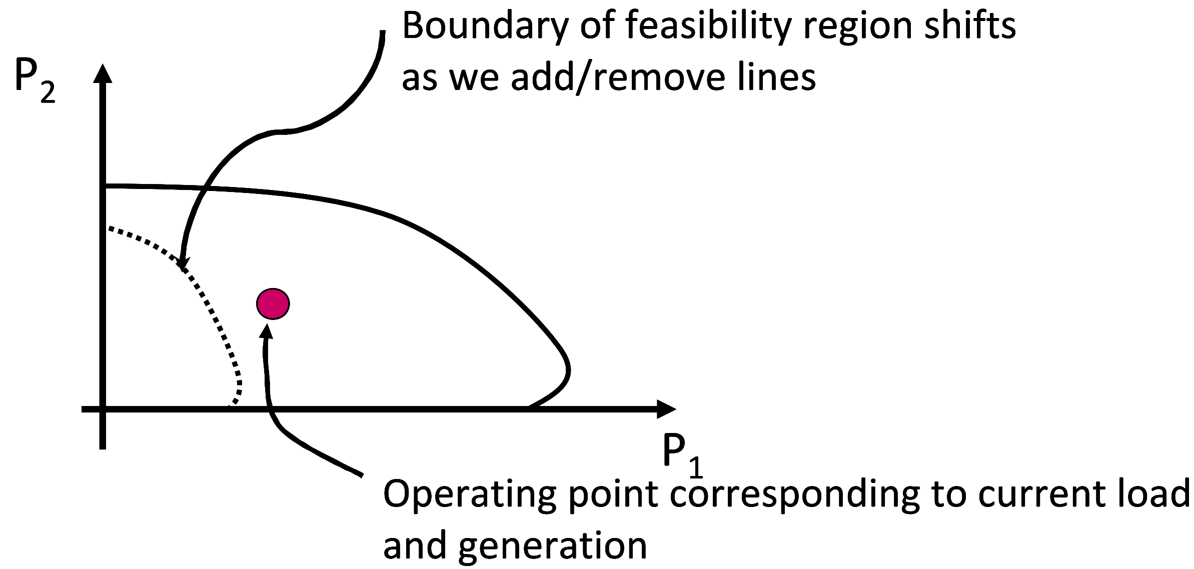
We are focusing on these issues…

- Analysis and reduction of system vulnerabilities
  - Natural risks: earthquake, hurricane, tsunami
  - Man-made: terrorism, sabotage, error
- Short term unit commitment & economic dispatch
- Long term transmission and generation (e.g. renewables) expansion planning
- The effects of uncertainties in and on the system

Vulnerability Analysis



- **Blackout corresponds to infeasibility of power flow equations.**
- **Cascading is initiated by a significant disturbance.**
- **Focus is detecting initiating events and analyzing the network for vulnerabilities**
- **Bilevel MINLP or combinatorial formulation**

Courtesy of: Ali Pinar, Richard Chen

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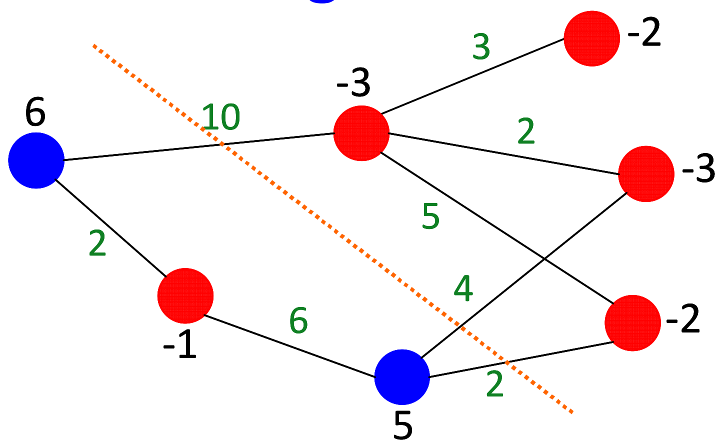
Vulnerability Analysis as Combinatorial Problem

- Given a graph *G=(V,E)* with weights on its vertices
  - negative for loads,
  - positive for generation,
- Find a partition of *V* into two loosely connected regions with a significant load/generation mismatch.



- Cut min. number of lines so that max flow is below specified bound.
- Shown to be NP-complete (Phillips 1991).

Two Planning Problems

- Generation Expansion: Examine the what, where, and when of adding new technologies
- Transmission Expansion: Examine the how and reliability of the bulk transfer of energy
- Commonly expressed as stochastic mixed-integer programs
- Both problems have 2-stage and n-stage forms
- (Severely) Complicating factors
  - With and without security constraints
  - DC versus AC power flow models
  - Linear, quadratic, or higher-order line loss models

The Generation Expansion Stochastic Program

Two-stage stochastic (mixed-integer) programming formulation

Objective:

$$\min \sum_y \left(\frac{\sum_g \left(c_g m_g^{\max} U_{g,y}\right) + \sum_s \pi_s \left(\sum_{t \in T_y} \left(\sum_g \left(l_{g,t,s} L_{g,t,s}\right) + p_u E_{t,s}\right)\right)}{(1+r)^y} \right) \quad (1)$$

Constraints:

$$\sum_g L_{g,t,s} + E_{t,s} = d_{t,s} \qquad \forall t,s \quad (2)$$

$$L_{g,t,s} \le n_g^{max} \left(u_g + \sum_{y \le Y_t} U_{g,y}\right) \qquad \forall g,t,s \quad (3)$$

$$\sum_y U_{g,y} \le u_g^{\max} \qquad \forall g \quad (4)$$

Jin and Ryan (2010)

Current Efforts in Generation Expansion

- Iowa State (Ryan, Industrial & Systems Eng.)
  - Multi-stage generation expansion problem
  - Uncertainty in future demand, fuel prices
  - 10-year planning horizon, mix of nuclear, wind, coal, combined-cycle…
  - Identify what to build, how many, and when

- North Carolina State (DeCarolis, Civil & Environmental Eng.)
  - Same fundamental problem as Iowa State
  - Key difference: Generators are modeled in terms of bulk power
  - Identify how many MW of capacity to build, and when

Stochastic Optimization and the Grid: Challenges

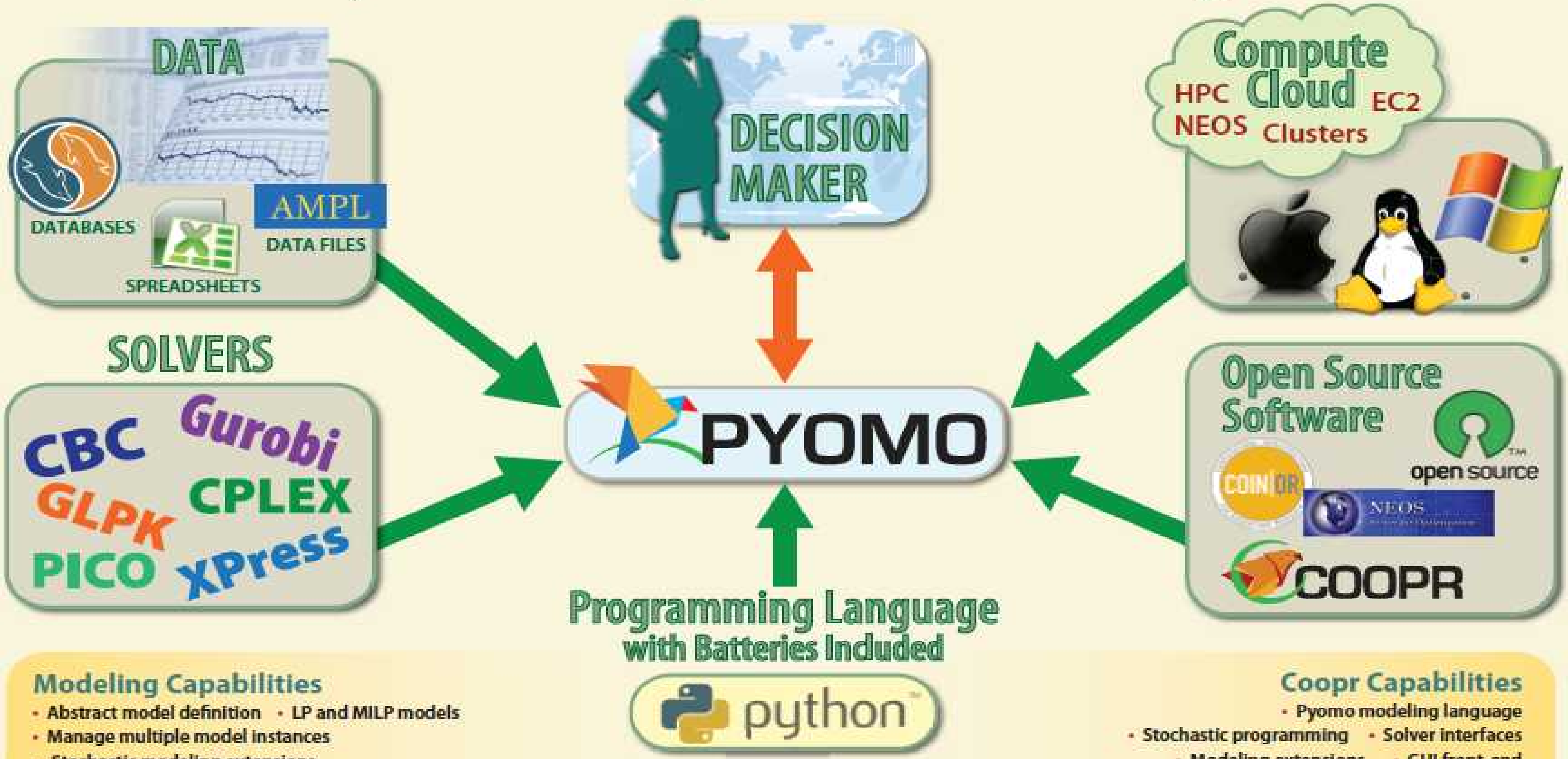
- **Challenge #1: Computation at regional and national scales**
  - **Most domain publications deal with "toy" problems**
  - **Few at-scale benchmarks widely available**
- **Challenge #2: Common definition of core operations and planning problems**
  - **Unit commitment literature is notoriously inconsistent**
  - **Makes algorithmic cross-comparison nearly impossible**
- **Challenge #3: Solving the *real* problem**
  - **Combining, e.g., unit commitment *and* transmission switching**
  - **Generation *and* transmission expansion**
  - **Unit commitment + transmission constraints + security constraints**

Stochastic Mixed-Integer Programming: The Algorithm Landscape

- The Extensive Form or Deterministic Equivalent
  - Write down the full variable and constraint set for all scenarios
  - Write down, either implicitly or explicitly, non-anticipativity constraints
  - *Attempt* to solve with a commercial MIP solver
    - Great if it works, but often doesn't due to memory or time limits
- Time-stage or "vertical" decomposition
  - Benders / L-shaped methods (including nested extensions)
  - Pros: Well-known, exact, easy for (some) 2-stage problems, parallelizable
  - Cons: Master problem bloating, multi-stage difficulties
- Scenario-based or "horizontal" decomposition
  - Progressive hedging / Dual decomposition
  - Pros: Inherently multi-stage, parallelizable, leverages specialized MIP solvers
  - Cons: Heuristic (depending on algorithm), parameter tuning
- Important: *Development of general multi-stage SMIP solvers is an open research area*

PYOMO

An Open-Source Optimization Modeling Tool



Modeling Capabilities

- Abstract model definition
- LP and MILP models
- Manage multiple model instances
- Stochastic modeling extensions

Key Features

- Parallel solver execution
- Extensible framework
- Interface to many data sources
- Portability
- Embedded in modern programming language
- Freely available
- Unrestricted open source license

Coopr Capabilities

- Pyomo modeling language
- Stochastic programming
- Solver interfaces
- Modeling extensions
- GUI front-end

Coopr Resources

- Coopr installer script
- Wiki documentation
- Examples
- Trouble tickets
- Mailing lists

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Ideas into Action

TO LEARN MORE VISIT >>

https://software.sandia.gov/pyomo

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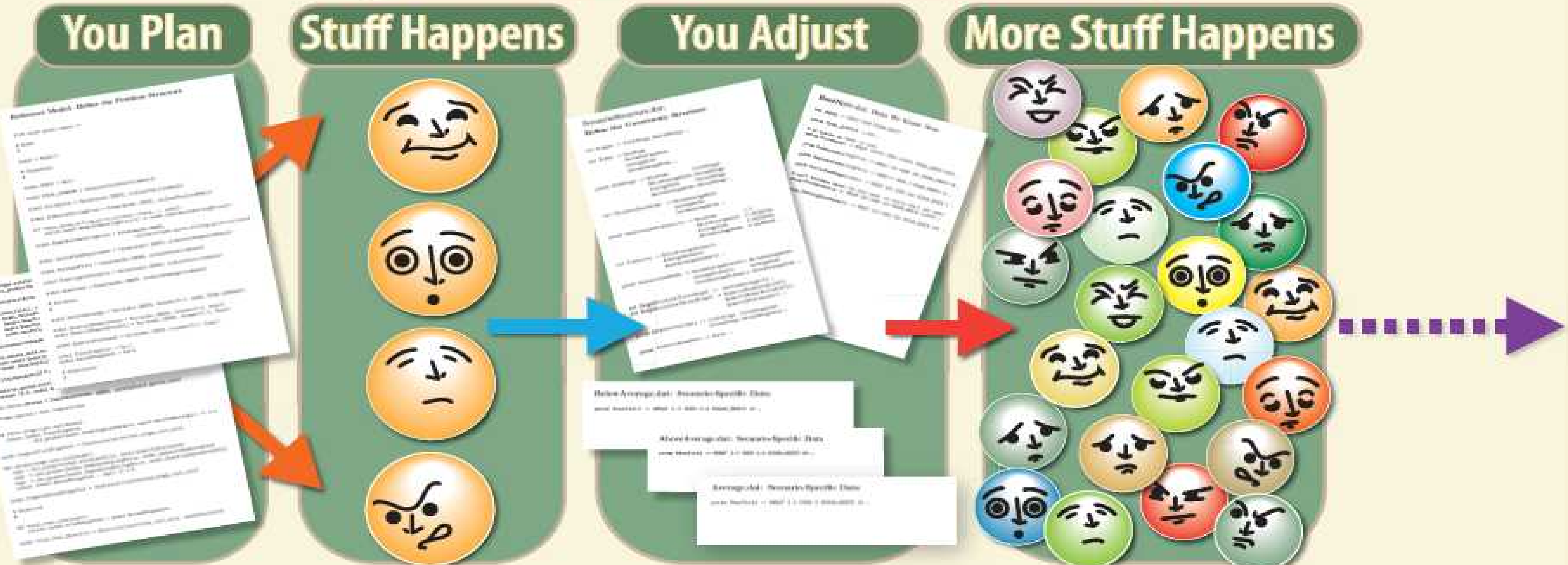
Hedging Against Uncertainty:
A Modeling Language and Solver Library



PYOMO

PySP: Stochastic Programming in Python

COOPR

Multi-Stage Planning for Uncertain Environments

- Explicitly capture recourse
- Uncertainty modeling framework
- Integrated solver strategies

What We Do:

- Mixed decision variables
  - Continuous
  - Integer/Binary
- General multi-stage
- Stochastic programming
  - Expected value
  - Conditional Value-at-Risk
  - Scenario selection
- Cost confidence intervals

How We Do It:

- Deterministic equivalent
- Scenario-based decomposition
  - Progressive Hedging
  - Customizable accelerators
- Algebraic modeling via Pyomo
- SMP and cluster parallelism
- Integrated high-level language support
- Multi-platform, unrestrictive license
- Open source, actively supported by Sandia
- Co-Managed by Sandia and COIN-OR

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TO LEARN MORE VISIT > https://software.sandia.gov/trac/coopr/wiki/PySP

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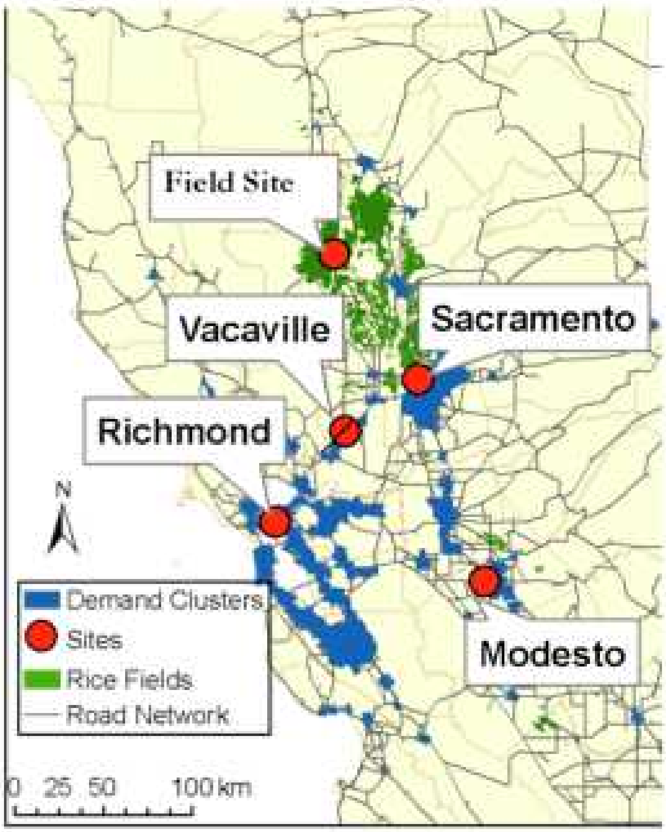
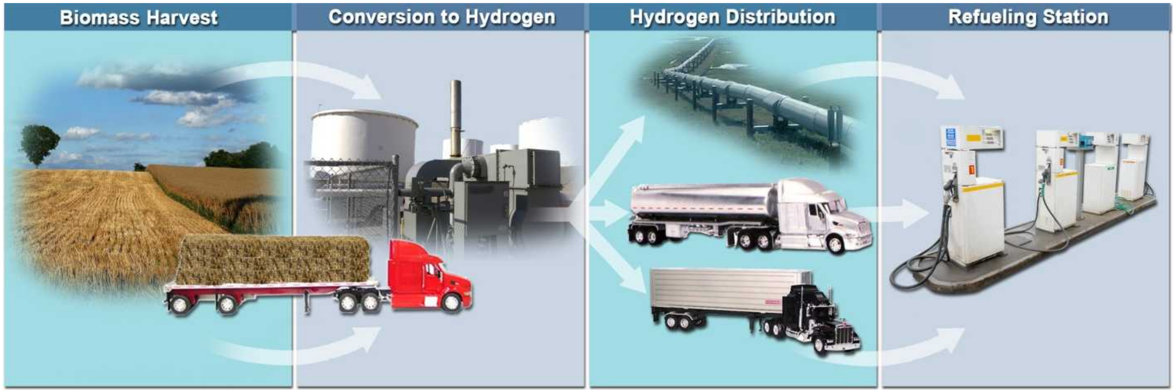
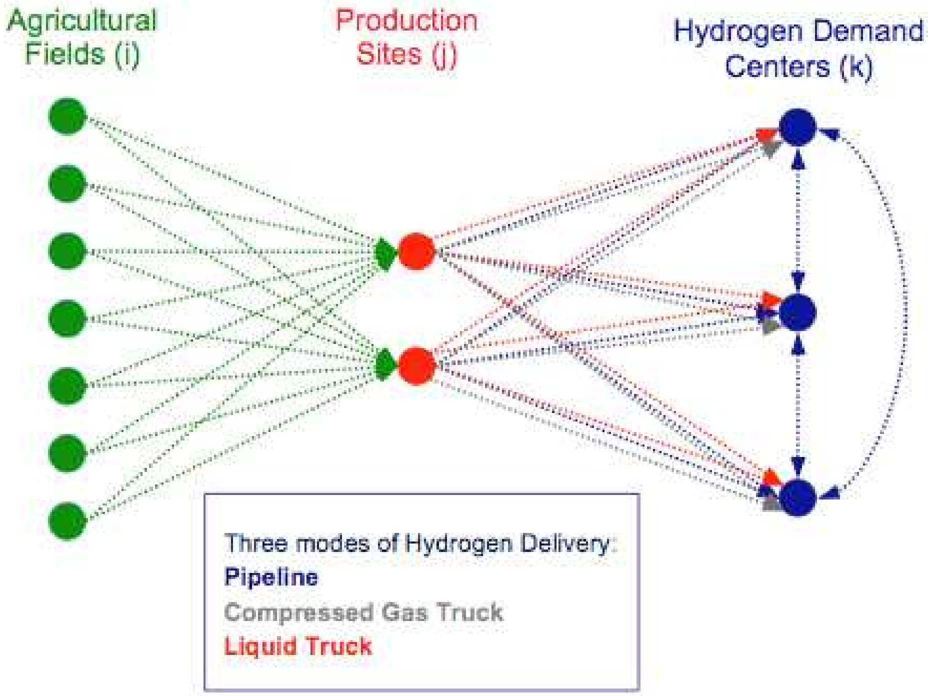
The Impact of Decomposition: Biofuel Infrastructure and Logistics Planning







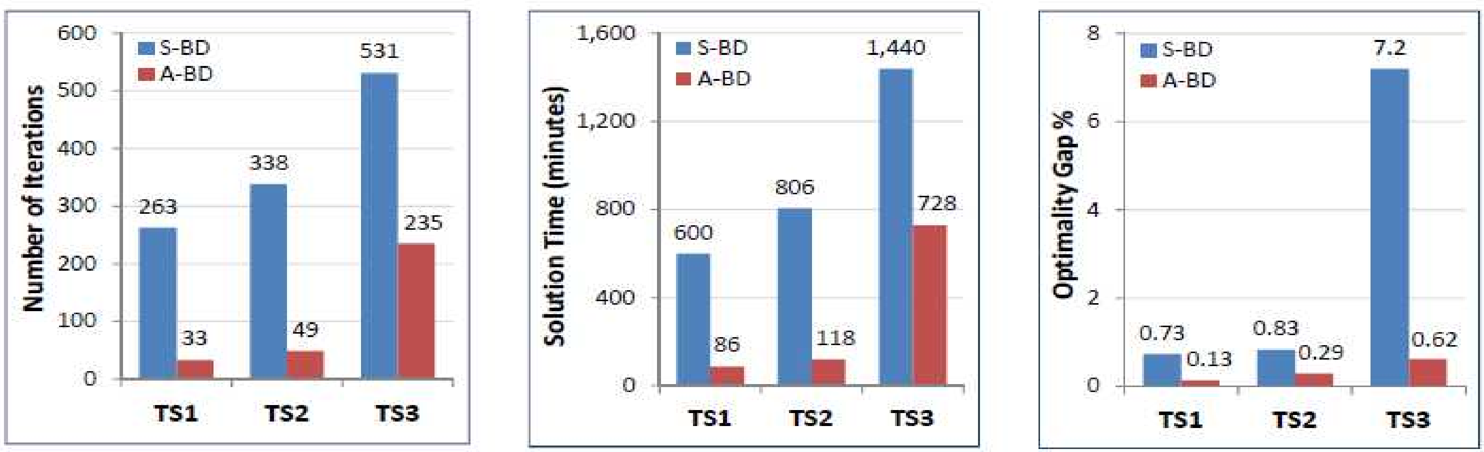
<u>Example of PH Impact:</u>

- Extensive form solve time: >20K seconds
- PH solve time: 2K seconds

Slide courtesy of Professor YueYue Fan (UC Davis)

Wind Farm Network Design

- Where to site new wind farms and transmission lines in a geographically distributed region to satisfy projected demands at minimal cost?
- Formulated as a two-stage stochastic mixed-integer program
  - First stage decisions: Siting, generator/line counts
  - Second stage “decisions”: Flow balance, line loss, generator levels
- 8760 scenarios representing coincident hourly wind speed, demand
- Solve with Benders: Standard and Accelerated



- Summary: A non-trivial Benders variant is *required* for tractable solution

Slide courtesy of Dr. Richard Chen (Sandia California)

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"Call for Participation"

- We have generic software available for computing confidence intervals on the optimal objective function values for stochastic (mixed-integer) programs
  - Multiple replication procedure demonstrates feasibility
  - There are numerous extensions that should and will be pursued

- Even with a straightforward computational procedure, we have quickly obtained key insights to a range of important, real-world stochastic programs
  - Often we are using more than enough scenarios (expected case minimization)
  - For some, we aren't using nearly enough (unit commitment)
  - For tail-oriented risk metrics, much work remains

- Software architectural challenges are identified by exposure to a broad user base
  - Different domains yield different challenges
  - Broader exposure yields more generic, robust implementations

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What's Next

- Study and quantify the gap between the combinatorial model and the nonlinear flow model
- Include vulnerability analysis as a constraint in decision making
- Improve scenario sampling
- Include renewables (wind, solar, geothermal) and the uncertainties associated with their generation
- Uncertainty analysis:
  - Characterize and assess importance of: modeling & data uncertainties and insufficient scenario coverage
  - Develop approaches that span time scales
  - Evaluate robustness of optimal solutions with respect to implementation uncertainties