CHANGING WHAT'S POSSIBLE

# Grid Optimization Workshop Introduction

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U.S. Department of Energy

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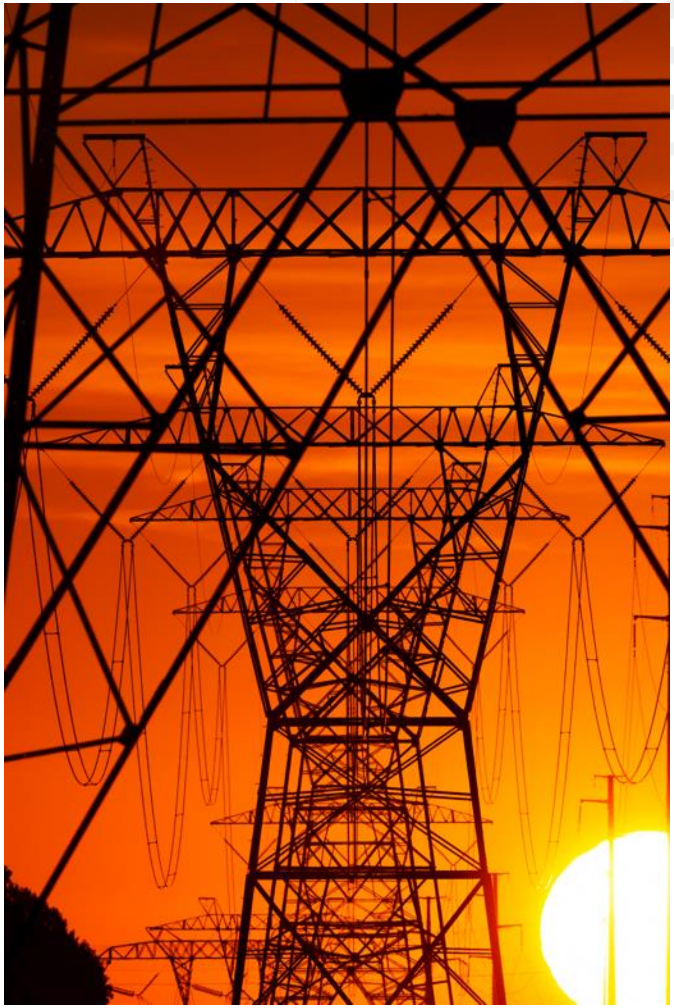
U.S. DEPARTMENT OF ENERGY

# New Grid Challenges and Opportunities

- **Many emerging grid challenges**
  – Aging infrastructure
  – Changing demand profiles
  – Increasing natural gas generation (including combined cycle plants)
  – Increasing wind and solar generation
  – Decentralization of generation

- **These challenges all make grid optimization more challenging.**



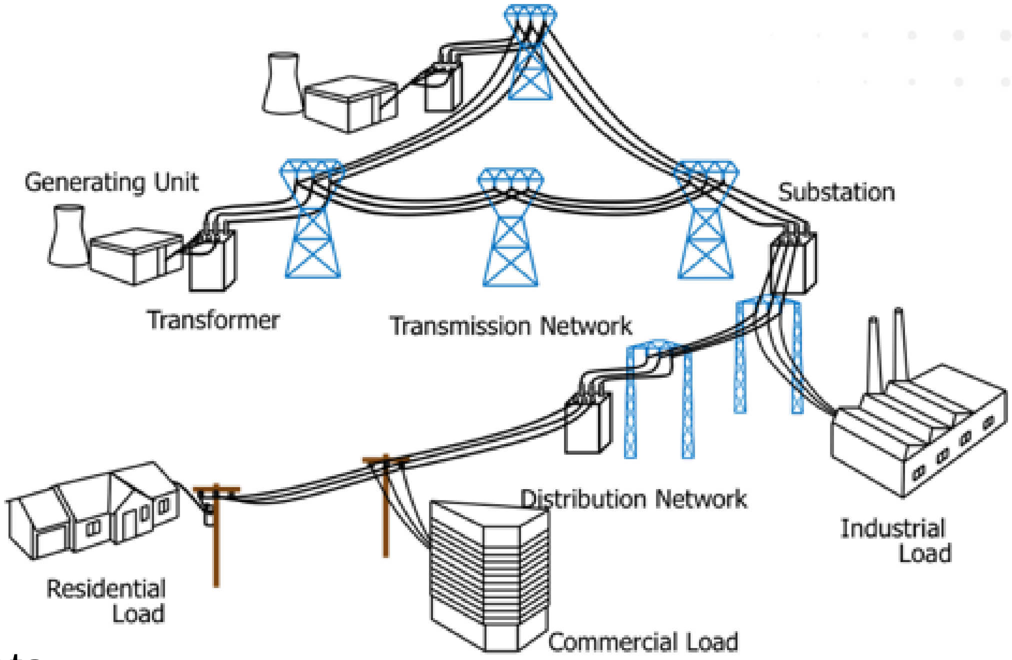
# New Opportunities for Grid Optimization

- **Advances in power electronics, computational technologies, and mathematics offer new opportunities for optimizing grid operations.**

*Power Flow Controllers*
- AC Power Flow Controllers
- High Voltage DC Systems

*Transmission Topology Optimization*
- Optimal line switching
- Corrective switching actions

*Energy Storage Optimization*
- Scheduling energy flows
- Coordination of diverse storage assets




*Responsive Demands*
- Scheduling large loads (eg. industrial loads)
- Mobilize large numbers of small assets

# GENI Program

## (Green Electricity Network Integration)

### Mission

Improve the efficiency and reliability of electricity transmission, increase the amount of renewable energy the grid can utilize, and provide energy suppliers and consumers with greater control over power.

| | |
|---|---|
| Kickoff Year | 2011 |
| Projects | 15 |
| Total Investment | $39 Million |
| Program Director | Tim Heidel (Rajeev Ram) |

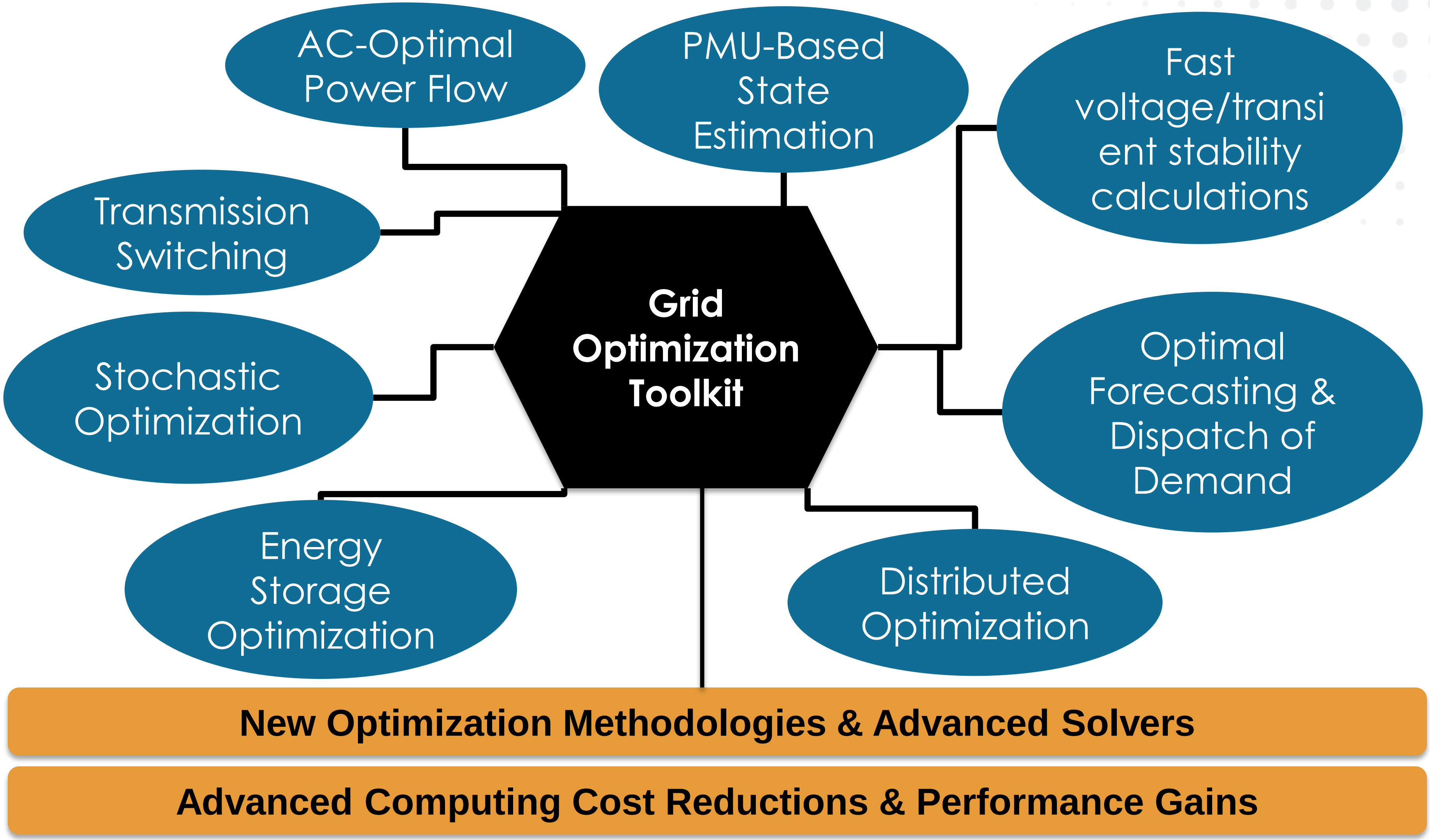
### Goals

- Enable 40% variable generation penetration
- >10x reduction in power flow control hardware (target < $0.04/W)
- >4x reduction in HVDC terminal/line cost relative to state-of-the-art

### Project Categories

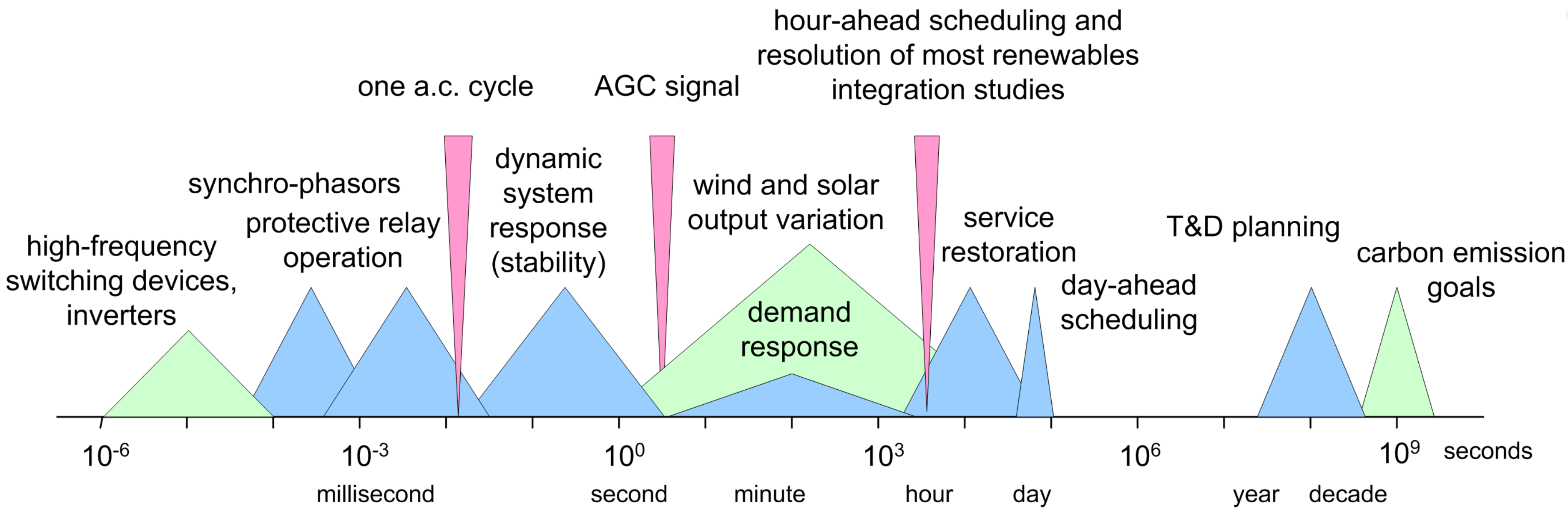
- Power Flow Controllers
  - Power flow controllers for meshed AC grids.
  - Multi-terminal HVDC network technologies.
- Grid Control Architectures
  - Optimization of power grid operation; incorporation of uncertainty into operations; distributed control and increasing customer optimization.

# Grid Optimization Opportunities



# Optimization of Grid Operations/Planning

- Optimizing grid power flows is central component to a variety of planning, operations, and market problems.




Source: Alexandra von Meier, CIEE

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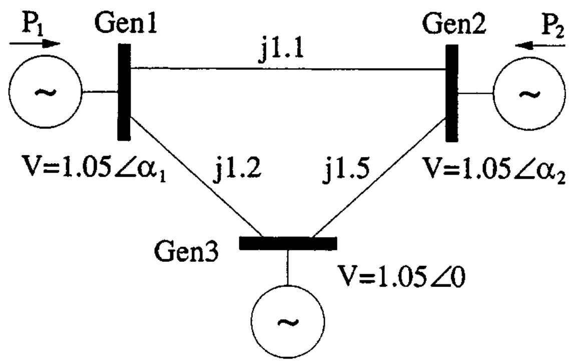
# OPF Problem Introduction

- Find steady state operation point (generator dispatch, control devices' set-points, demand levels) which minimizes generation cost
  - while satisfying system's safety and performance constraints
    - Generators' real and reactive powers limits
    - Line flow limits
    - Components input/output limits
    - Etc.

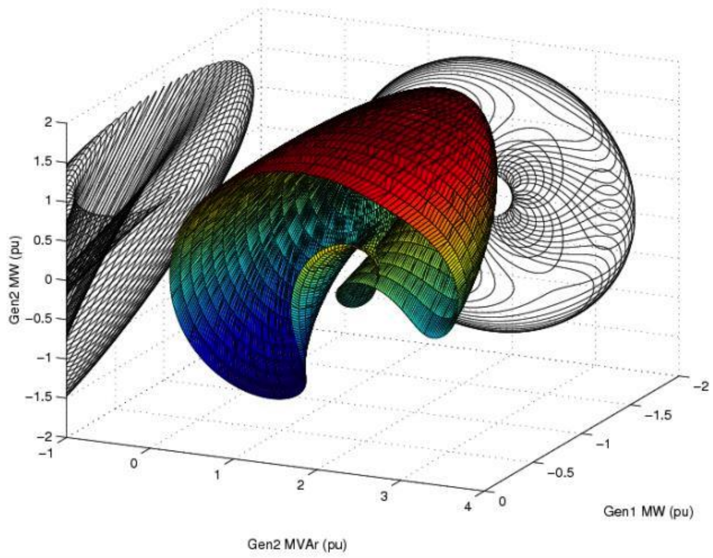
# Unit Commitment Problem (UC)

- **Objective**: Finding the optimal scheduling for using (committing) power generation units over a time interval (day(s))
  - to meet the forecast system load
  - and minimize generation cost
- **Variations**
  - ***Security*** Constrained Unit Commitment (SCUC)
  - Inclusion of line ***limit*** constraints
  - Inclusion of network transmission ***losses***
  - Existence of ***renewable*** energy source forecasts
  - Power generation ***cost functions***
    - Piecewise linear
    - Quadratic

# Optimal Power Flow (OPF) is ARPA-E Hard




3 Bus Example OPF Solution Space




Source: Hiskens et al. 2001

- Many non-convexities including multipart nonlinear pricing and electricity network and generation power flow constraints.
- Time complexity: NP-Hard
- Simplifying assumptions are required (and are used by industry) to achieve reasonable solutions within time constraints.

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# OPF Has Generated Substantial Interest

- Subject of substantial research and industry development:
  - 1000s of academic projects, papers
  - 100s of optimization methods/variants
  - Dozens of commercial OPF packages in use today (planning, markets, and operations)

- No commercial OPF tool today can fully utilize all network control capabilities (most tools do not simultaneously optimize real and reactive power flows)

- Most existing OPF tools do not guarantee a physical solution. (Feasibility of solution must be assessed separately.)

# Benefits of Faster, More Robust OPF

- Improved economic efficiency
  - Reduced power generation costs
  - Reduced transmission losses
  - Deferred new builds of transmission and generation

- Increased grid flexibility
  - Dynamic power routing (using FACTS devices)
  - Optimal transmission switching
  - Optimal utilization of energy storage
  - Demand side control
  - Autonomous control?

- Support for increasingly complex generation mix
  - Distributed generation
  - Variable renewable power integration

# Study of AC-OPF Potential in NY

- Annual economic dispatch savings from improved dispatch using AC-OPF.

| Case | Generation Cost [$/Hr] | Annual Savings |
|---|---|---|
| A (No voltage control) | 1205958 | Benchmark |
| B (NYCA x-former dispatch) | 1133203 | $637M **6%** |
| 00 | 1115321 | $794M**7.5%** |
| 01 | 1110705 | $834M |
| 02 | 1115025 | $796M |
| 03 | 1098848 | $941M |
| 04 | 1068956 | |
| 05 | 1063000 | |
| 06 | 1018623 | |
| 07 | 1110290 | $838M |
| 08 | 1094488 | $980M**9.2%** |

Benchmark System Operating Costs: $10.6B per year

Reference: Marija Ilic et al., "Modeling of Hardware-and Systems- Related Transmission Limits: The Use of AC OPF for Relaxing Transmission Limits to Enhance Reliability and Efficiency," FERC Staff Technical Conference, June 2013

# Benefits of Faster, More Robust OPF

| | 2012 Gross Electricity Production (GWh) | Production Cost ($Billion/Year)<br><br>MWh Cost<br><br>$57 | Savings ($Billion/Year)<br><br>5-10% increase in efficiency<br><br>5-10% |
|---|---|---|---|
| U.S. | 4,047,765 | $230.72 | $11.5-$23 |

Calculation Methodology Follows: Mary B. Cain, Richard P. O'Neill, Anya Castillo, "History of Optimal Power Flow and Formulations", FERC, December 2012

Electricity Consumption/Price Data: US Energy Information Administration (EIA) Annual Energy Report (2013)

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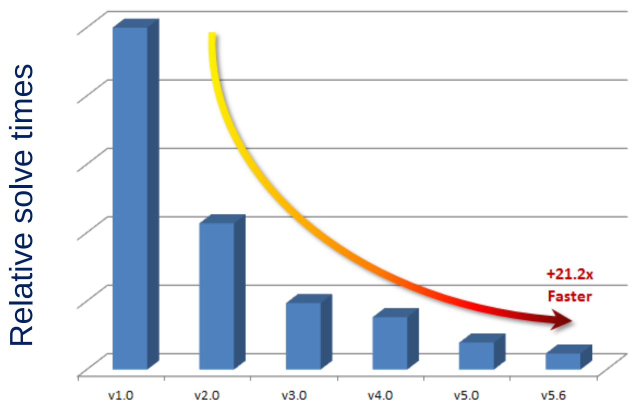
# Recent Advances (Why now?)

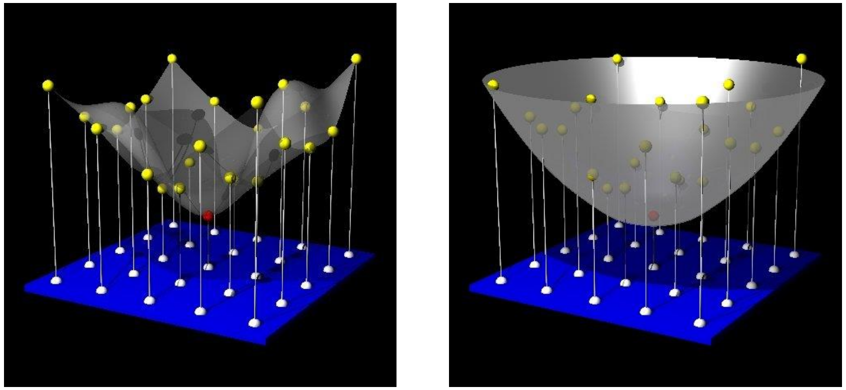
- Recent advances in the literature:
  - Rapid optimization solver improvements (especially MIP)
  - Continued reductions in advanced computing costs (including cloud computing)
  - Reevaluation of alternative problem formulations (see FERC papers)
  - Fast convex relaxations for OPF (SDP/QC/SOCP relaxations)
  - Distributed approaches to OPF (Convex relaxation and/or ADMM)

Gurobi (MIP) Improvement




Source: Gurobi

Convex Relaxation



http://www.idi.ntnu.no/~schellew/convexrelaxation/ConvexRelaxation.html

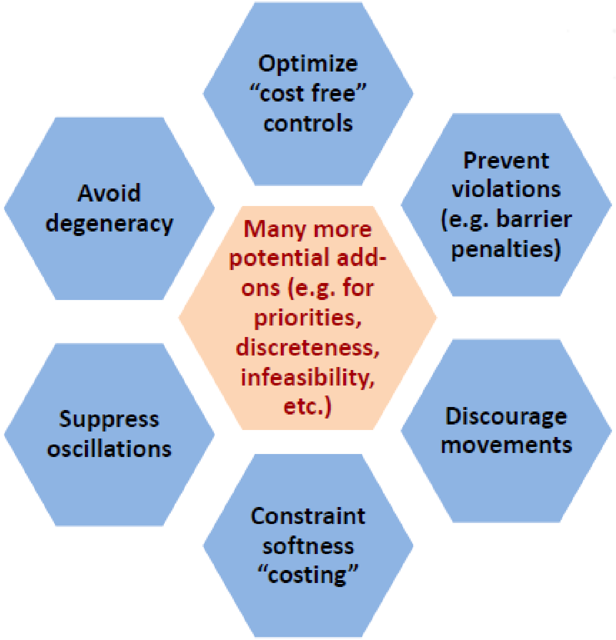
# OPF is hard in theory…

# and even harder in practice…

# Important Practical OPF Considerations

- Modern solutions are seldom able to provide useable engineering solutions
  - Security constraints (including multiple element contingencies) must almost always be considered
  - Degeneracy is common. (Control variables are subject to priorities and sharing rules.)
  - Infeasibility in real problems occurs routinely, how to handle this?

The objective function often requires a variety of add-ons to obtain an acceptable engineering solution:




**RESULT: Extensive heuristics are used to manage many of these practical challenges as well as to handle complex/discontinuous configurations, scheduling changes, and local controls.**



- Stott, B., & Alsaç, O. (2012, May). Optimal power flow–basic requirements for real-life problems and their solutions. White paper.

# OPF solutions are application dependent

Specific OPF application → Specific OPF mathematical formulation → Specific OPF solution methodology → Specific OPF software, full of problem-dependent heuristics

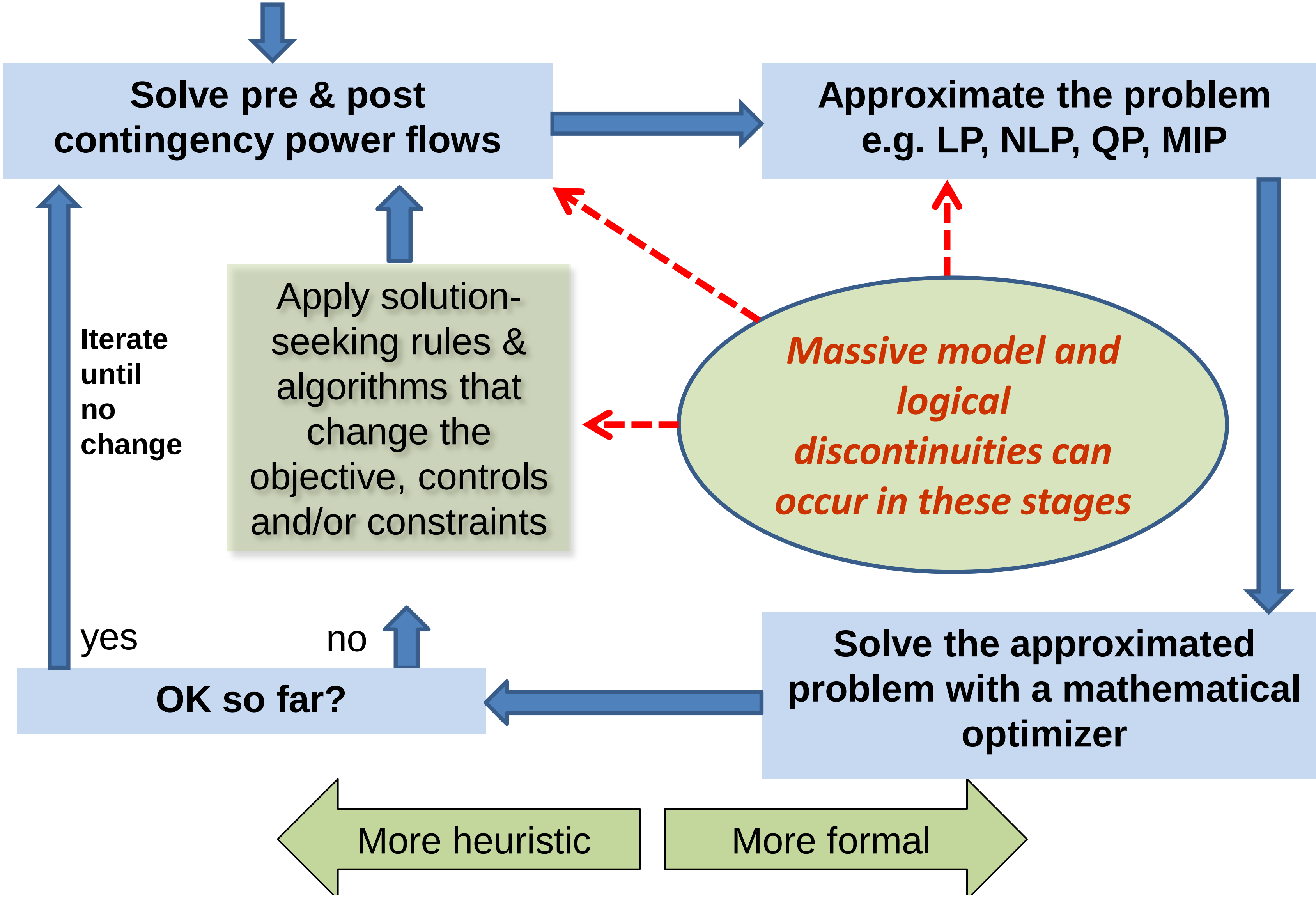
The unattainable ideal

One solution methodology for handling most OPF problems



Ongun Alsaç, Brian Stott, “Challenges Presented by Practical OPF Problem Formulations,” IEEE PES General Meeting, Washington, DC, July 2014

# A typical OPF calculation sequence

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Ongun Alsaç, Brian Stott, "Challenges Presented by Practical OPF Problem Formulations," IEEE PES General Meeting, Washington, DC, July 2014

# Examples of GENI Project Teams

## Stochastic Unit Commitment at Scale

PI: Jean-Paul Watson

Data: ISO New England

## Transmission Topology Control Algorithms

PI: Pablo Ruiz

Data: PJM Interconnection

## Scalable Real-time Decentralized Volt/Var Control

PI: Steven Low

Data: Southern California Edison

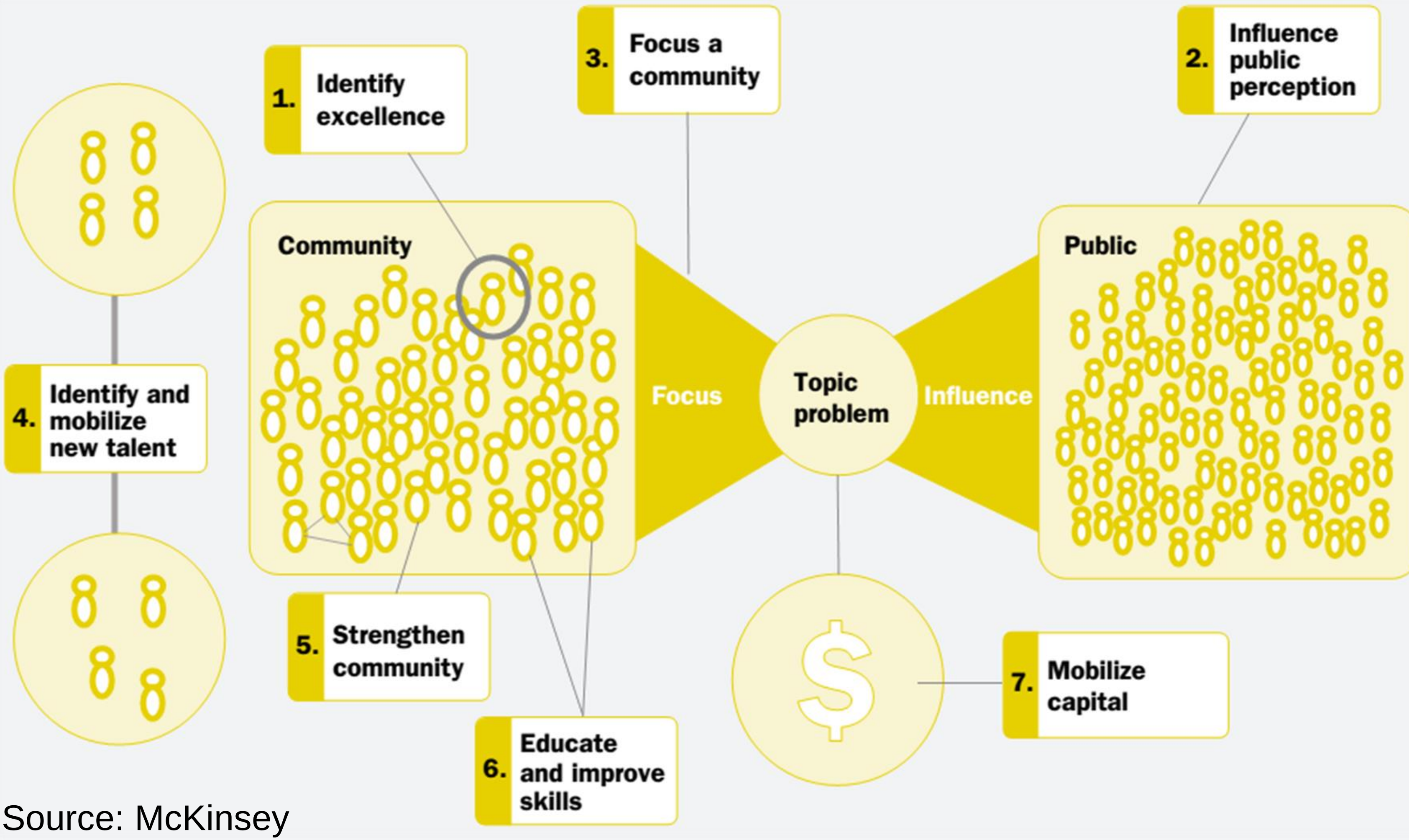
- **Realistic, large-scale datasets are extremely valuable but also extremely difficult, time consuming and expensive to collect and prepare for simulations.**

- **How do we know these teams have the best algorithms/methods for each problem?**

# How do we proceed?

# How do we maximize ARPA-E's impact?

# Why an *Inducement Prize Contest?*




Source: McKinsey

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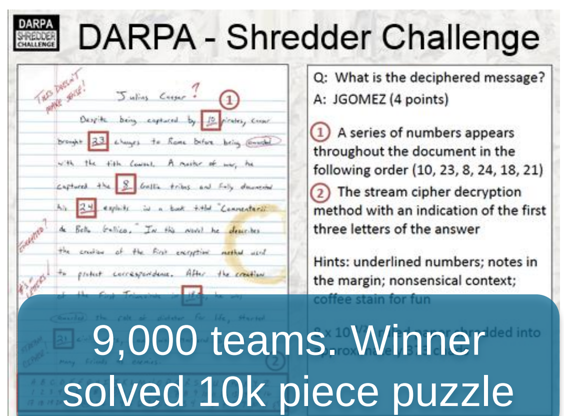
# Competition Success Stories

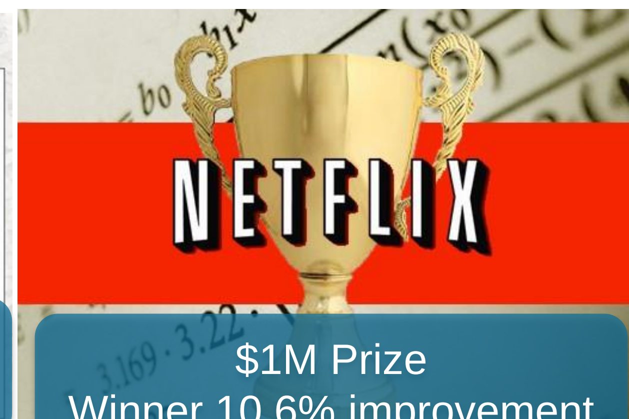

Longitudinal Prize of 1714


Found 10 balloons across U.S. in under 9 hours

Systems integration: SLAM+Planning+Mechatronics = Self-driving car



9,000 teams. Winner solved 10k piece puzzle



$1M Prize
Winner 10.6% improvement

# Power Related Competitions

Google/IEEE Little Box Challenge (2014-2015)


IEEE Forecasting Competition


Held in 2012 & 2014
40% reduction in RMSE

IEEE Competition on "Application of Modern Heuristic Optimization Algorithms for Solving Optimal Power Flow Problems"

Initial competition in 2014. Additional competition planned in 2015

IEEE PES Power & Energy Society™

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# An OPF Competition?

## "Power System Description"

- Synthetic (non-sensitive) dataset with at least the following information:
  - Network topology (incl. realistic line limits, voltage limits, etc.)
  - Generator locations and characteristics (physical limits and cost curves)
  - Contingency lists (incl. complex multi-element contingencies
  - Other control device characteristics (LTC, PST, Capacitor Banks, Power Flow Control Devices, Etc. (Locations, setpoints, etc.).
  - Controllable demand/Demand Response
  - Energy Storage
  - Etc.

## "Scenarios"

- At least 1 full year of hourly (10,000+) snapshots including at least the following information:
  - Demand characteristics (at each bus)
  - Wind/Solar generation
  - Transmission and Generation Availability
  - Other temporary constraints(?)

All participants required to use this dataset.

Participants develop new modeling approaches and solution algorithms using provided datasets.

Participants submit solutions

- ARPA-E evaluates and scores solutions (semi-automated, quantitative, transparent scoring required);
- A public "leader board" is maintained during the competition.

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# Selected Unanswered Questions

- Which difficult grid optimization problem, if solved more optimally (solution quality, robustness, time to solution, etc.) than possible today, could have the greatest impact on grid operations?
- How do we ensure participation that leads to maximum impact?
- How should new optimization methods and/or solutions be evaluated?
- How can testing/evaluation be designed to capture solution time, convergence robustness, and other important solution method attributes?
- What MUST be included in the “power system description” and “scenarios” datasets?

# We hope this workshop will give us some answers

# (or at least point us in the right direction)

# Workshop Format

- **Breakout Session #1: "The Most Impactful Application..."**
  - Discussion: Thursday 1:00pm-2:30pm
  - Readout: Thursday 3:00pm-3:30pm
- **Breakout Session #2: "So You Want to Run a Competition?"**
  - Discussion: Thursday 3:45pm-5:15pm
  - Readout: Friday 8:15am-8:45am
- **Breakout Session #3: "Show Me the Data"**
  - Discussion: Friday 9:00am-10:30am
  - Readout: Friday 11:00am-11:30am

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