CHANGING WHAT'S POSSIBLE

ARPA-E Electricity Research Programs

Tim Heidel

Program Director

Advanced Research Projects Agency – Energy (ARPA-E)

U.S. Department of Energy

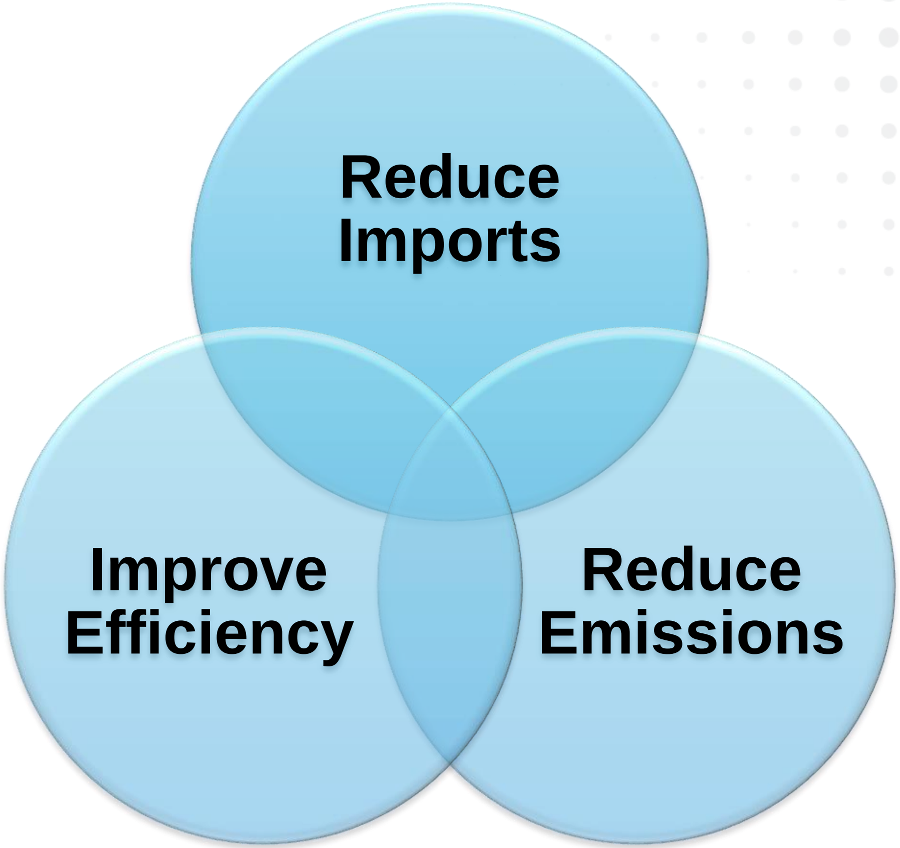
DOE Electricity Advisory Committee Meeting
Arlington, VA, March 26, 2015

U.S. DEPARTMENT OF
ENERGY

The ARPA-E Mission

Ensure America's

- National Security
- Economic Security
- Energy Security
- Technological Competiveness



Reduce Imports

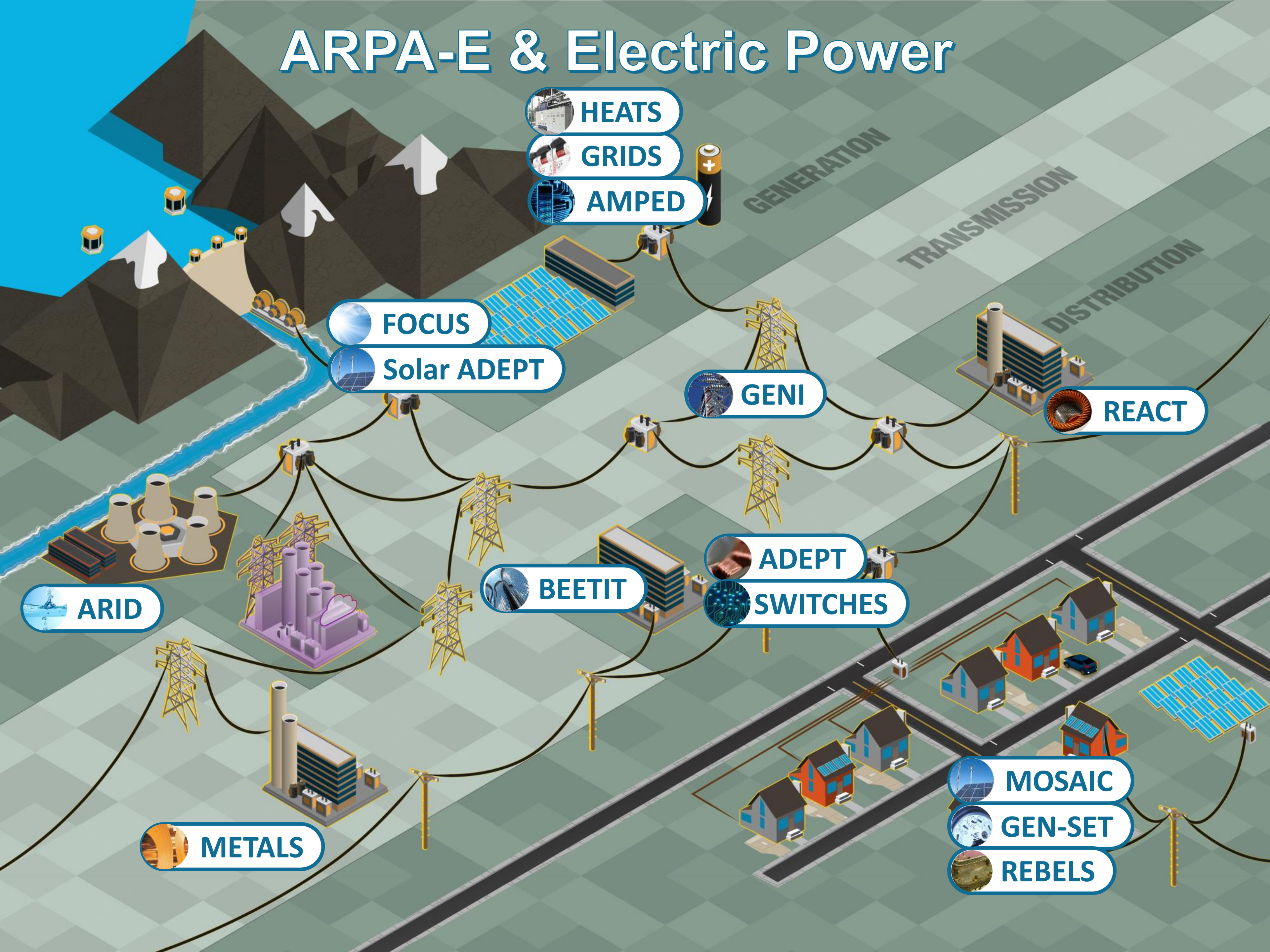
Improve Efficiency

Reduce Emissions

Catalyze and support the development of transformational, disruptive energy technologies

CHANGING WHAT'S POSSIBLE

ARPA-E & Electric Power



HEATS

GRIDS

AMPED

FOCUS

Solar ADEPT

GENI

REACT

ARID

BEETIT

ADEPT

SWITCHES

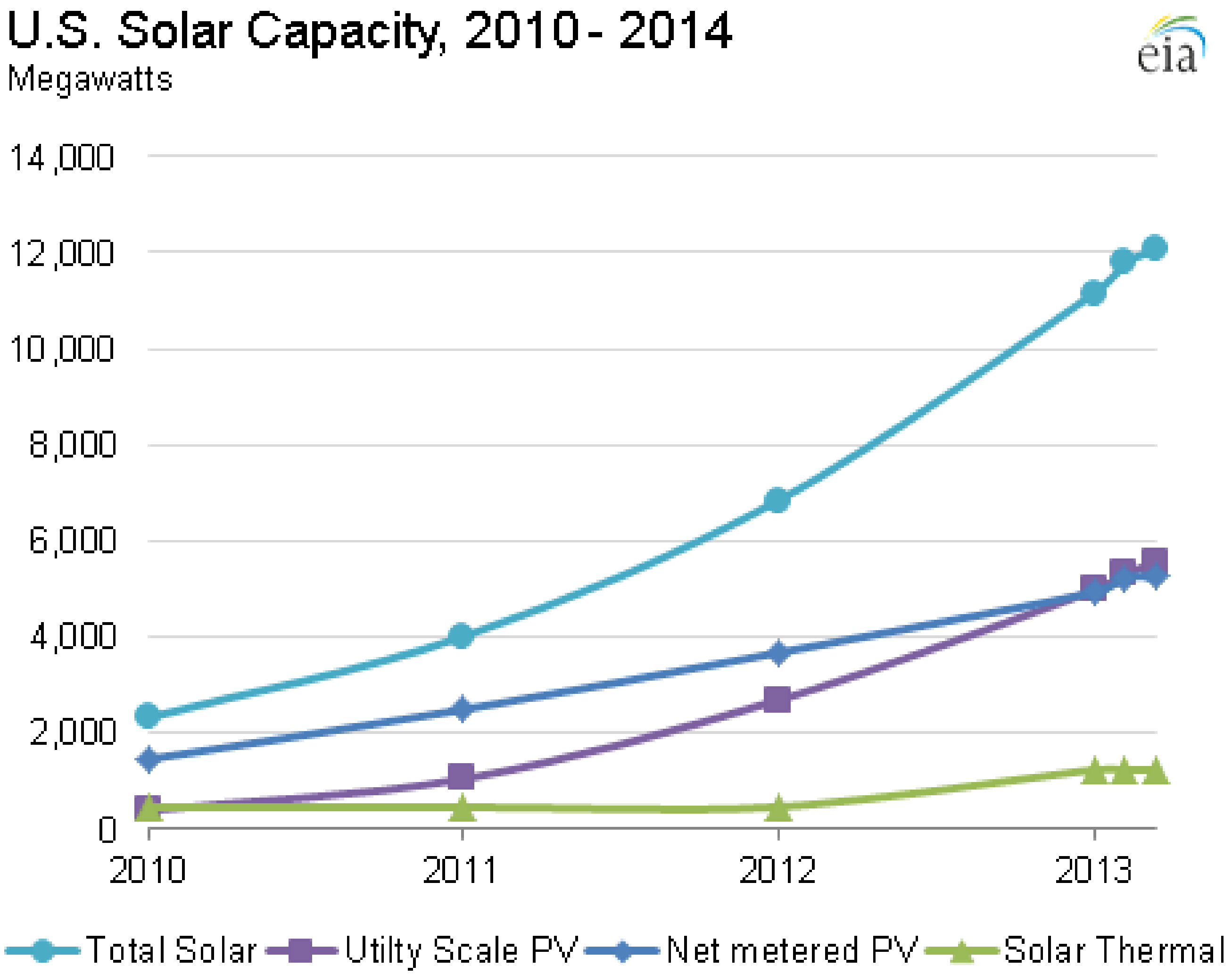
METALS

MOSAIC

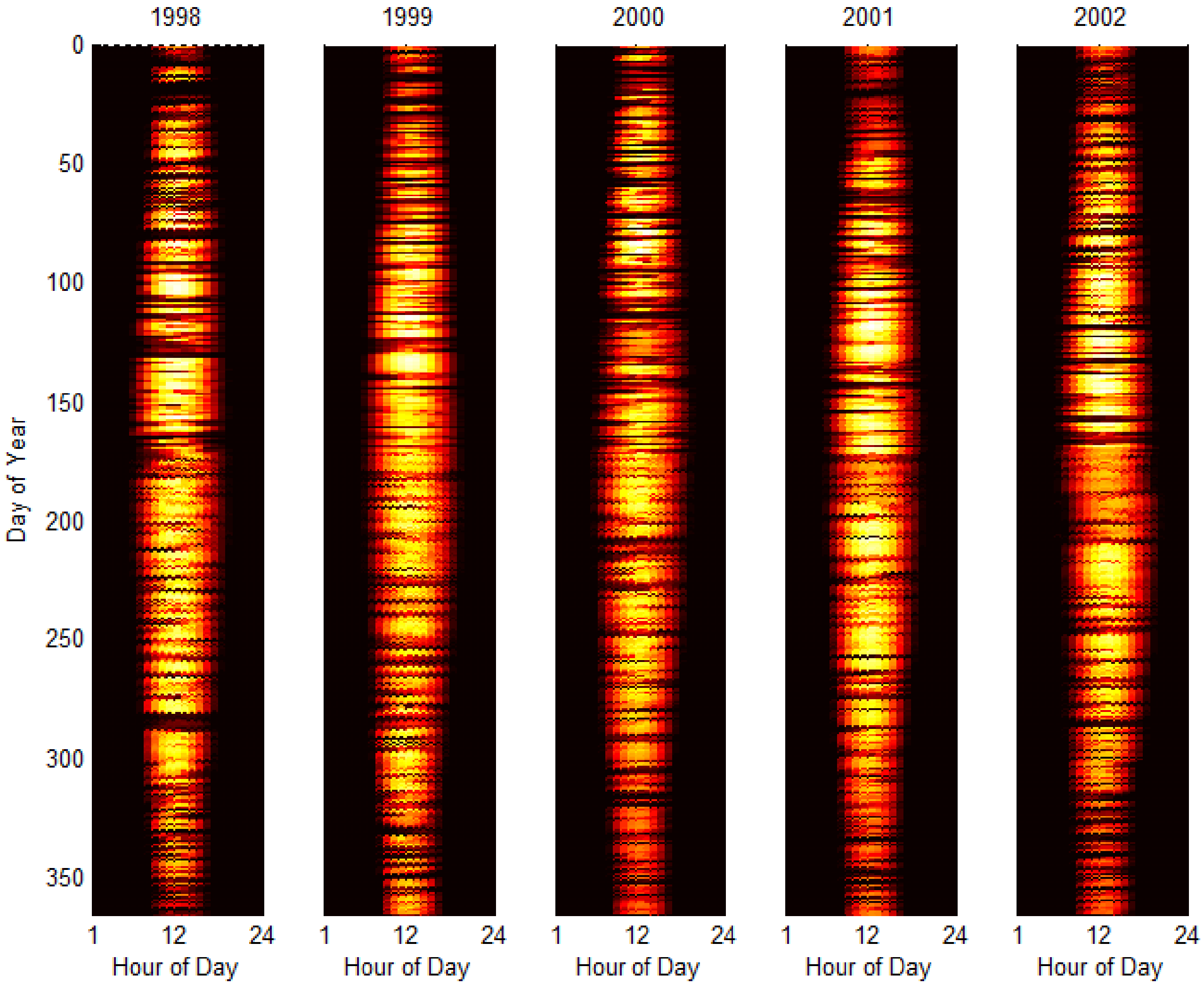
GEN-SET

REBELS

U.S. Installed Solar Capacity



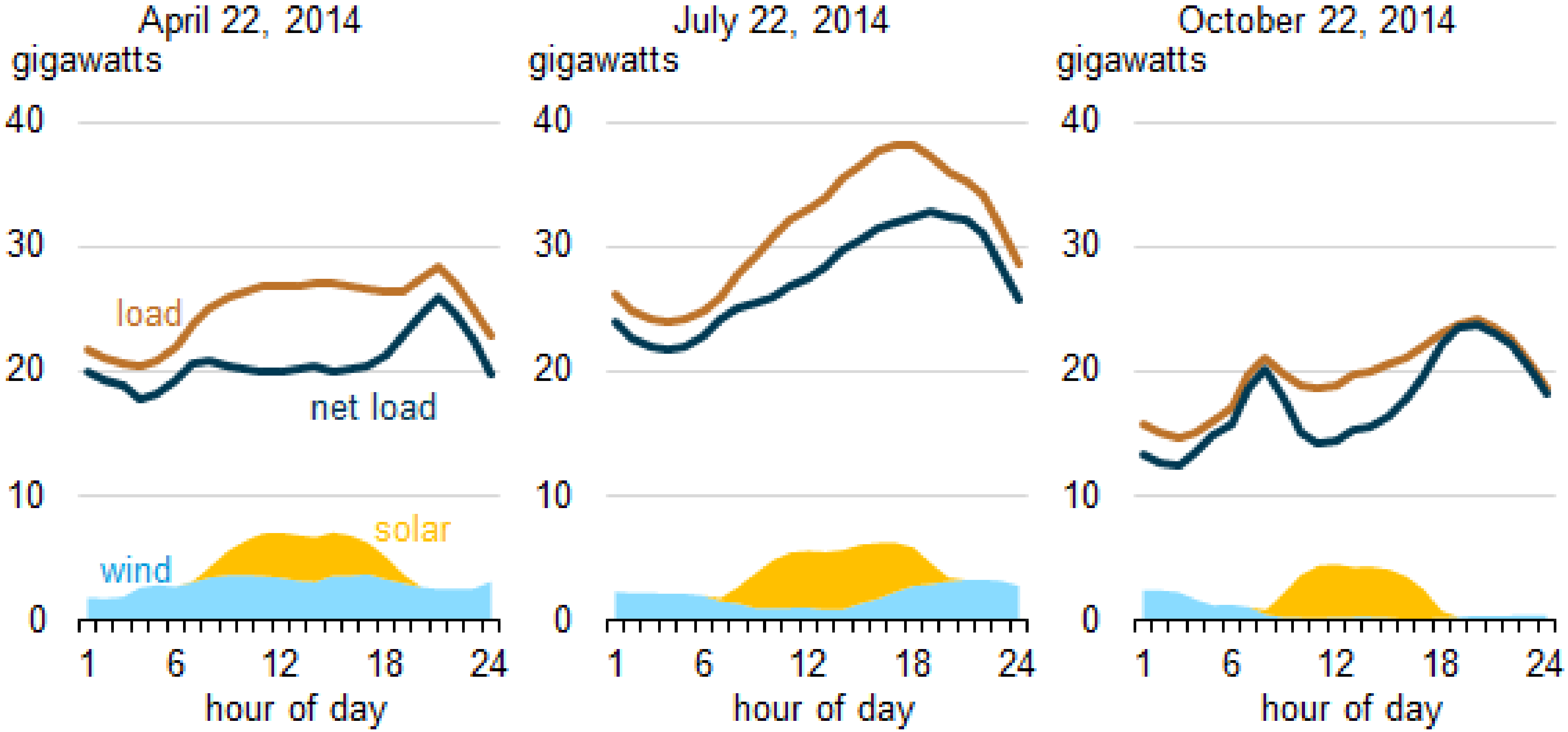
Variability & Uncertainty



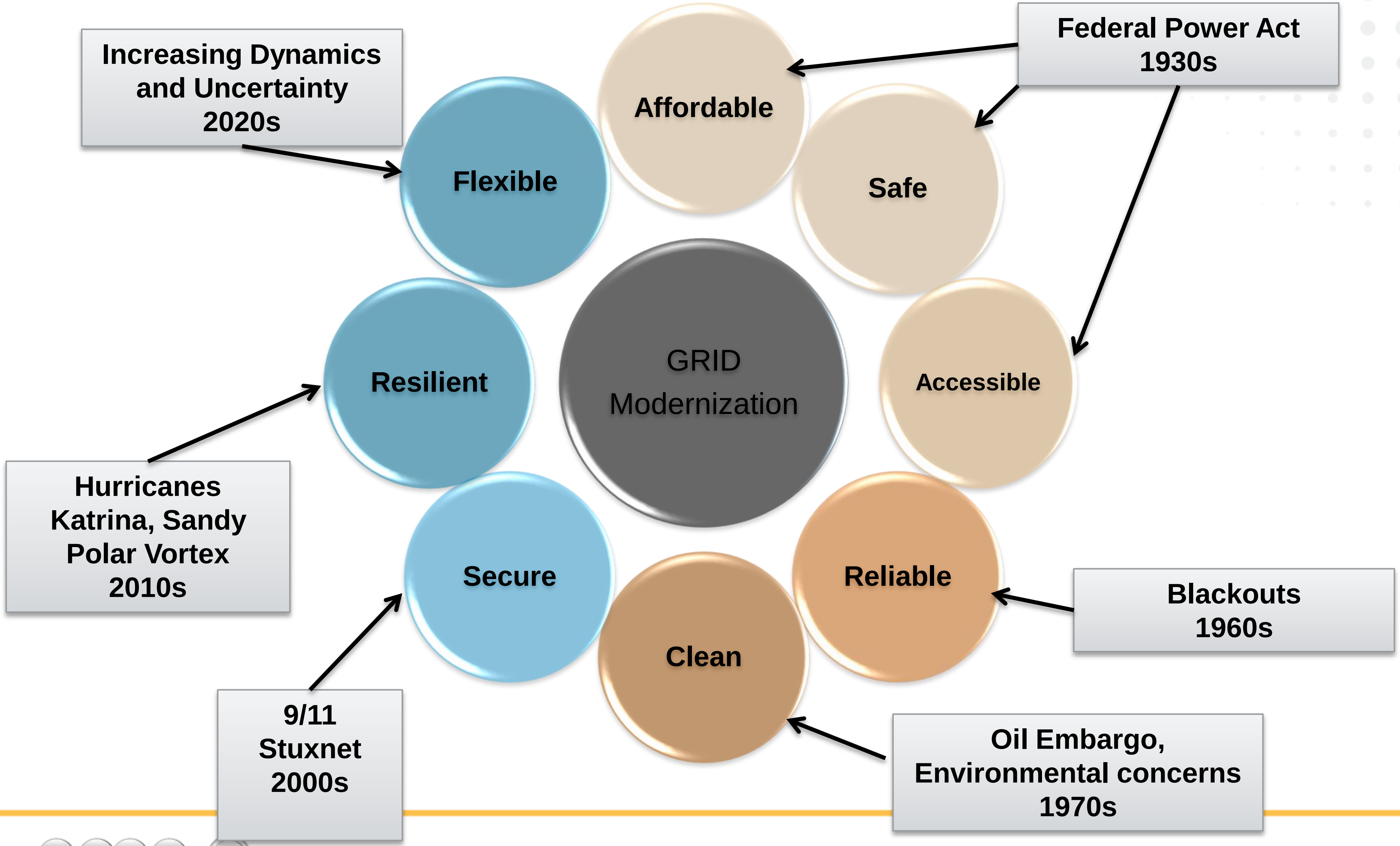
Source: National Solar Radiation Database

Variability & Uncertainty

CAISO load, net load, and wind and solar output on example weekdays during 2014



Evolution of Grid Requirements



GRID Modernization

Affordable

Safe

Accessible

Reliable

Clean

Secure

Resilient

Flexible

Federal Power Act
1930s

Blackouts
1960s

Oil Embargo,
Environmental concerns
1970s

9/11
Stuxnet
2000s

Hurricanes
Katrina, Sandy
Polar Vortex
2010s

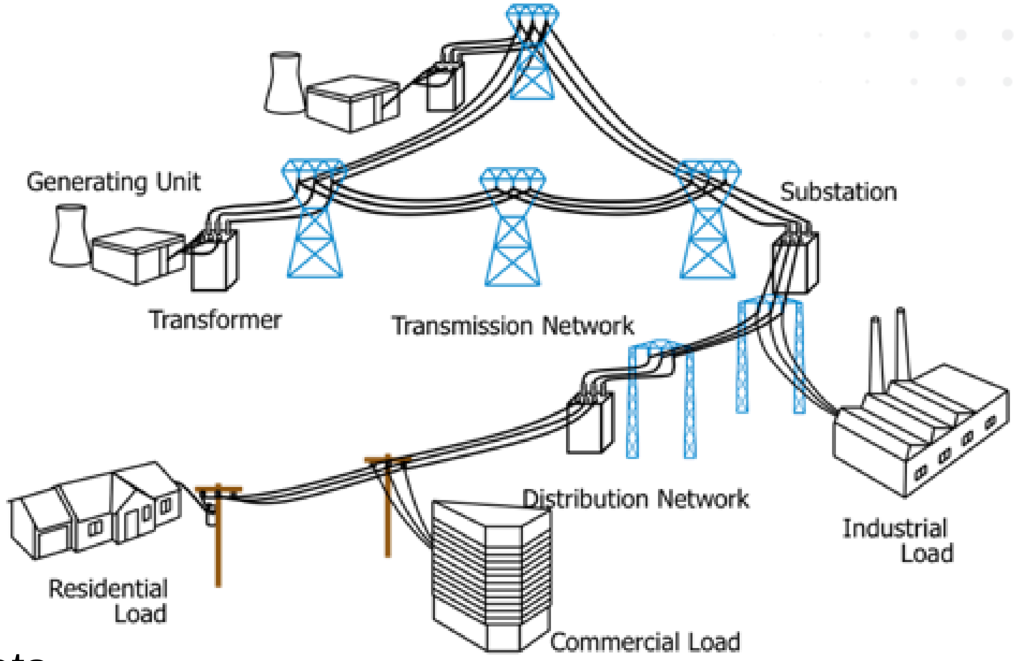
Increasing Dynamics
and Uncertainty
2020s

CHANGING WHAT'S POSSIBLE

Source: Adapted from DOE Grid Tech Team

New Potential Sources of Network Flexibility

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



Power Flow Controllers

- AC Power Flow Controllers
- High Voltage DC Systems

Transmission Topology Optimization

- Optimal line switching
- Corrective switching actions

Energy Storage Optimization

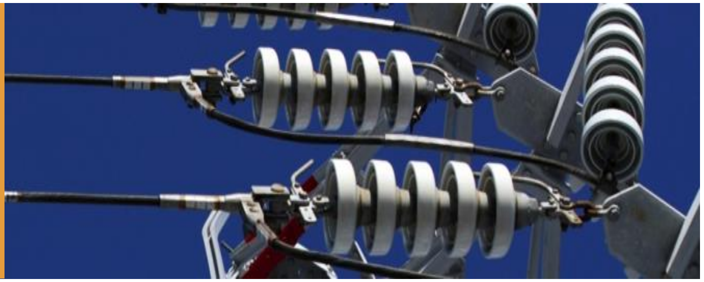
- Scheduling energy flows
- Coordination of diverse storage assets

Responsive Demands

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

GENI Program

Green Electricity Network Integration



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

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

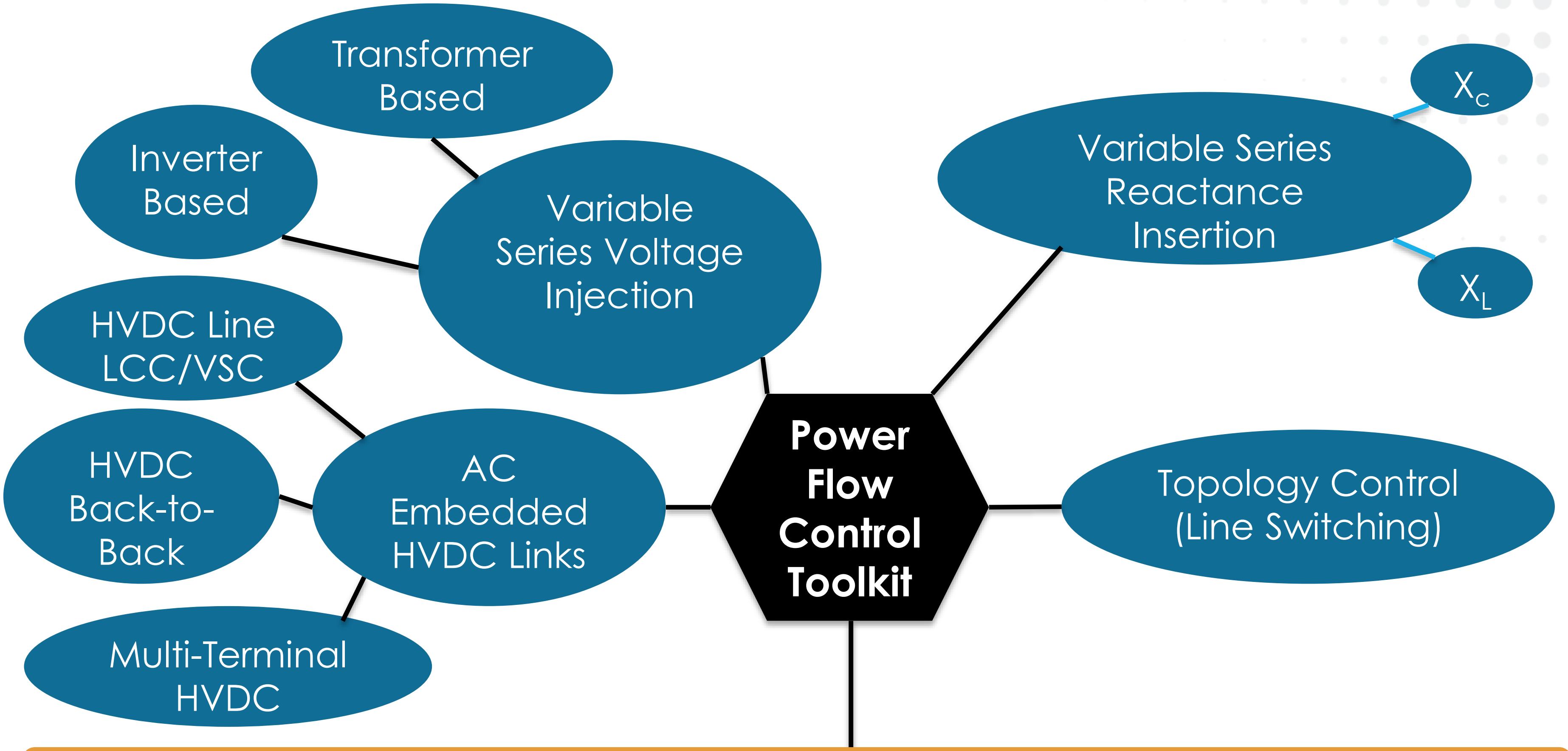
Project Categories

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

Power Flow Control White Space

- Historically, power flow control devices have typically been manually dispatched to correct local problems.
- High costs and reliability problems are often cited against the widespread installation and use of power flow control devices.
- ***New hardware*** innovations that can substantially reduce the cost of power flow control devices are needed
  - Fractionally rated converters (limited power device ratings).
  - Modular designs (increases manufacturability).
  - Series connected equipment with fail normal designs (gradual degradation).
- ***New software*** advances that exploit new developments in optimization and computational technologies are needed to enable the real time coordinated, optimized dispatch of many power flow control devices.

Power Flow Controllers



Power Flow Control Toolkit

Variable Series Voltage Injection

Transformer Based

Inverter Based

Variable Series Reactance Insertion

X_C

X_L

Topology Control (Line Switching)

AC Embedded HVDC Links

HVDC Line LCC/VSC

HVDC Back-to-Back

Multi-Terminal HVDC

Fast, Reliable, Ubiquitous Communications

Advances in Power Electronics (Components and Circuits)*

* ARPA-E's ADEPT, Solar ADEPT, and SWITCHES programs are funding some of these advances.

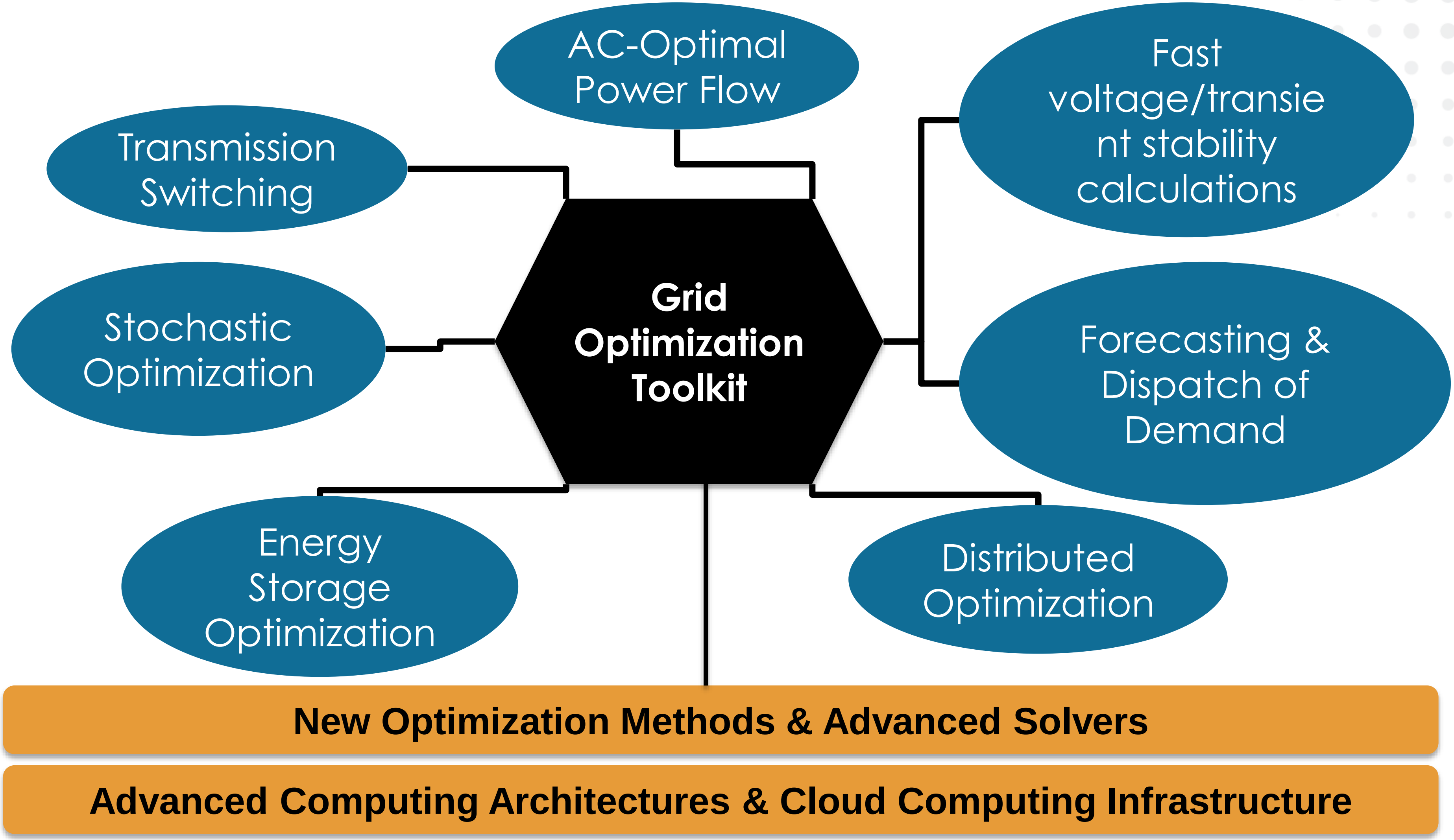
Grid Optimization Whitespace

- Existing grid optimization tools do not explicitly account for variability and uncertainty

- Emerging need/opportunity to coordinate larger numbers of distributed resources

- Recent advances enable more robust, reliable control of the electricity grid despite:
  - The limits of state estimation (finite numbers of sensors, limited models)
  - Incomplete and imperfect information flow (due to latency of communications)
  - Constrained computational resources for dynamic decision support (power flow optimization is mathematically (NP) hard)
  - Inherent uncertainties in price/market mediated transactions
  - Physical constraints to control (cost, performance, and reliability of power electronics).

Grid Optimization Opportunities



Grid Optimization Toolkit

AC-Optimal Power Flow

Transmission Switching

Fast voltage/transient stability calculations

Stochastic Optimization

Forecasting & Dispatch of Demand

Energy Storage Optimization

Distributed Optimization

New Optimization Methods & Advanced Solvers

Advanced Computing Architectures & Cloud Computing Infrastructure

GENI Portfolio

Power Flow Control Hardware

varentec
Compact Dynamic Phase Angle Regulator

Oak Ridge National Laboratory
Magnetic Amplifier

Michigan State University
Transformerless UPFC

Power flow control for the Grid
swg
Distributed Series Reactor

Cloud Computing & Big Data

Cornell University
Resilient Cloud / Data Replication

AutoGrid
Demand Response

HVDC Hardware

GE
HVDC EPR Cable

General Atomics
DC Breaker

GE
HVDC Multi-terminal Network Converters

Topology Control (Line Switching)

Boston University
Economic Optimization

TEES
Texas A&M Engineering Experiment Station
Contingency Management

Power System Optimization

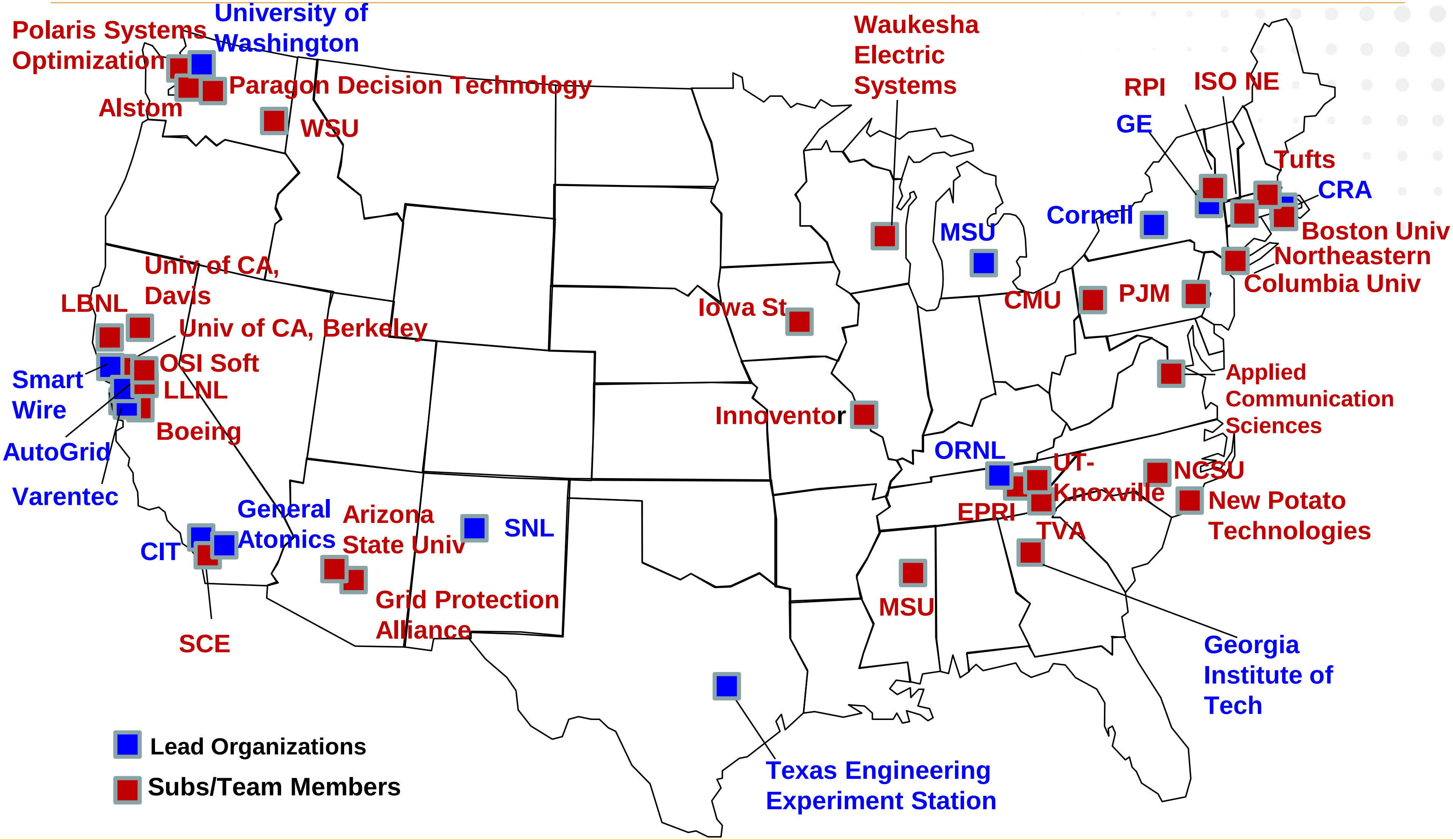
California Institute of Technology 1891
AC-OPF

Sandia National Laboratories
Stochastic Unit Commitment

W
University of Washington
Energy Storage Optimization

Georgia Tech
Distributed Grid Optimization (Prosumers)

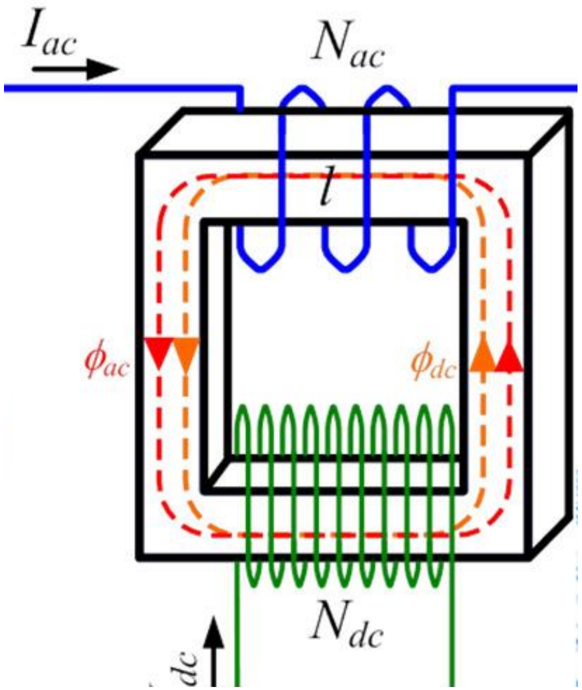
GENI Program Participants

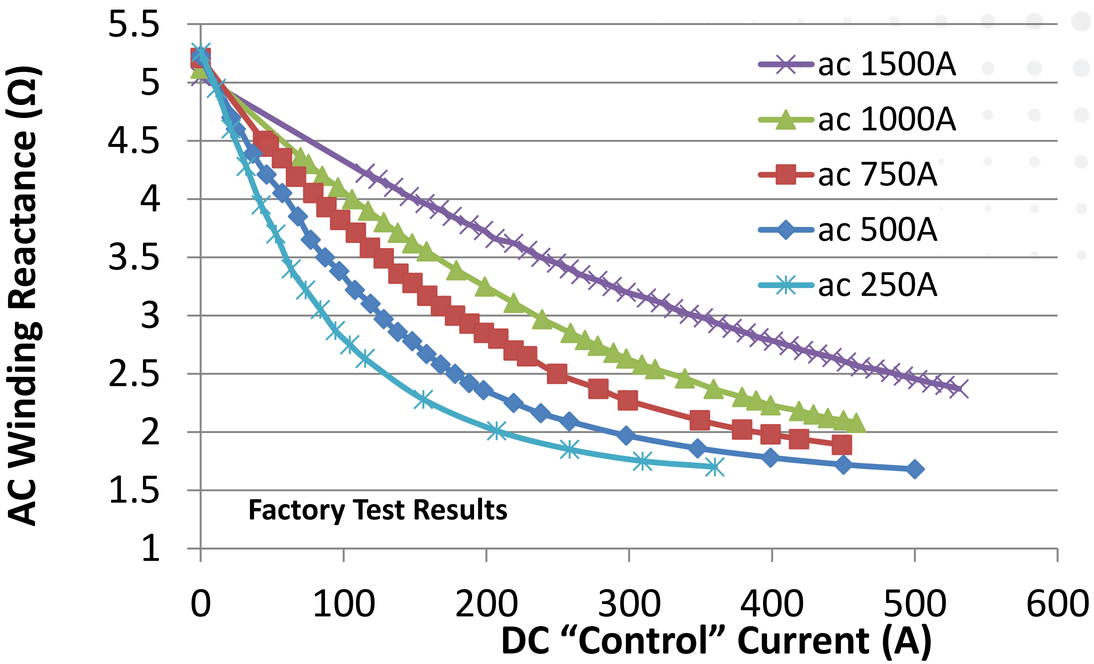


arpa·e
CHANGING WHAT'S POSSIBLE

GENI Project Examples

Magnetic Amplifier for Power Flow Control

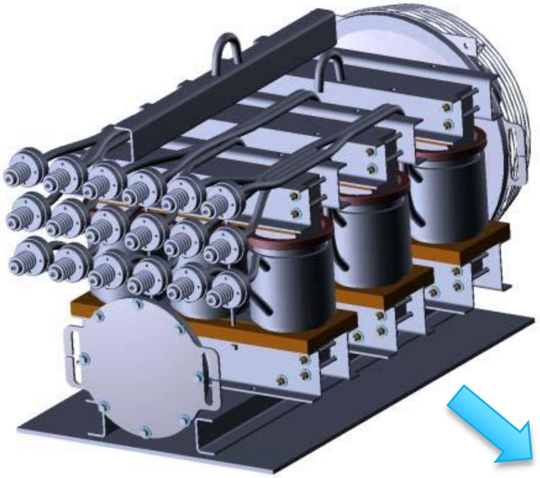




Factory Test Results

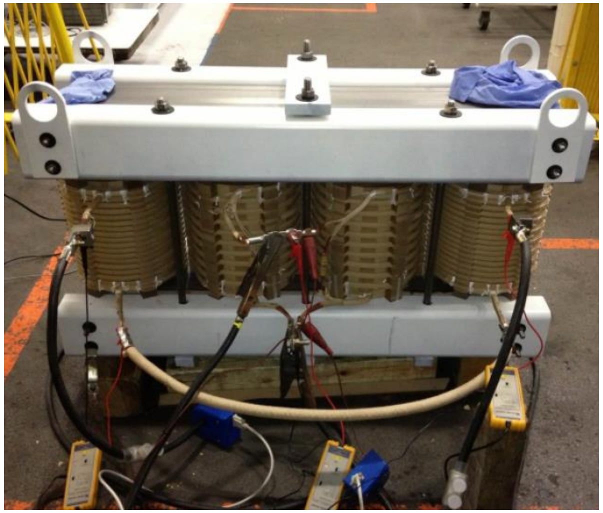
- Inserts a controlled variable inductance in the line
- Power electronics isolated from the HV line
- Low power dc source controls the high voltage ac inductance
- Smooth reactance regulation, acceptable harmonics
- Uses standard transformer manufacturing methods

Magnetic Amplifier Development Timeline



(2012)
480 V 200 A
3-phase Laboratory
Proof of Concept

(2013)
480 V Improved Design
With 4-Limb Core



(2015)
115 kV 1.5 kA
Field Test Prototype
(manufactured by SPX)

OAK RIDGE National Laboratory

SPX WAUKESHA

THE UNIVERSITY of TENNESSEE UT KNOXVILLE

arpa·e CHANGING WHAT'S POSSIBLE

Prototype (1-Phase) 7.5 MVA CVSR
Under Test at SPX

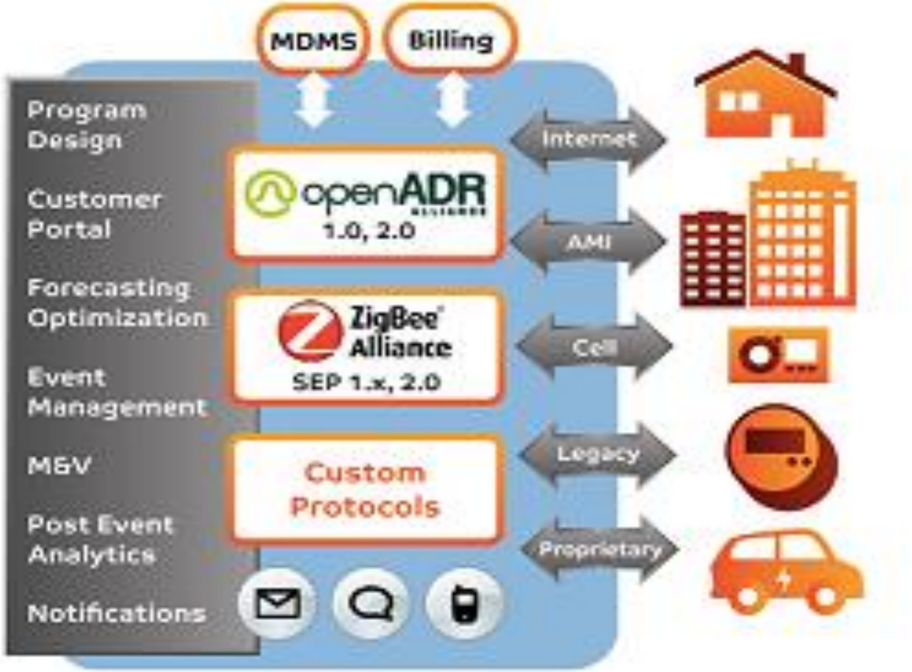
Demonstration:

115kV, 1500 A, 3-phase CVSR to be installed for field demonstration on the Bonneville Power Administration (BPA) transmission system at Sacajawea Substation, WA in 2015.

Highly Dispatchable, Distributed Demand Response

Objectives:

- Develop scalable SaaS platform (DROMS-RT) for optimization and management of Demand Response (DR) programs.
- Standard communications protocols for real-time DR signaling.
- Utilize machine learning to forecast and characterize customer response to DR signals.
- Optimization of economic dispatch with DR.



Potential Impact:

- Enable Real-Time predictive analytics on data from grid customers & sensors.
- Provide 90% reduction in the cost of operating DR programs by eliminating up-front IT infrastructure costs for utilities.
- Increase the overall efficiency of DR operations by 30-50%.

Project Accomplishments

- Developed scalable cloud-based platform for managing and analyzing big-data sets for energy applications.
- Demonstrated highly parallel machine learning engine capable of processing >1M forecasts on a rolling basis every 10 min.
- Deployed commercial DR programs up to 70K customers.

Post ARPA-E Goal: “Energy Data Platform”: 10X Reduction in the Cost and Time to Market of Developing New IT/OT Apps

Transmission Topology Control Algorithms (TCA)

Objectives:

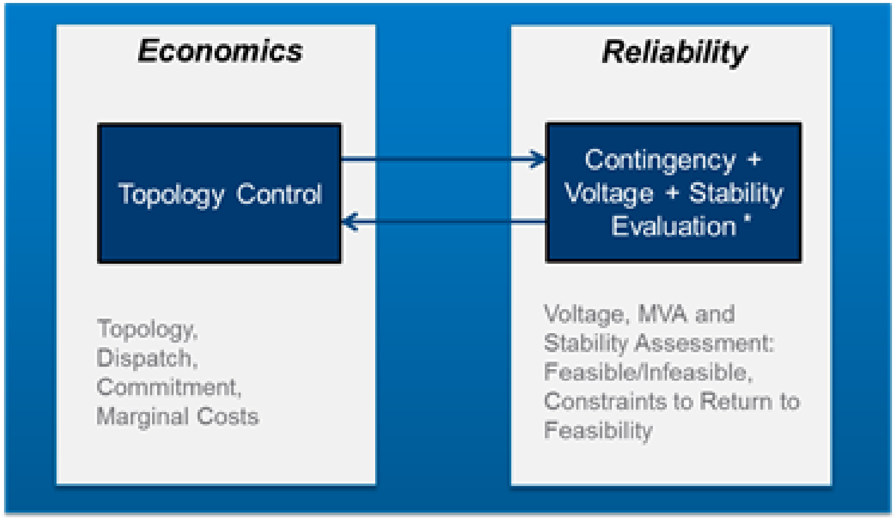
- Develop fast optimization, contingency analysis and stability evaluation algorithms to allow grid operators to optimize transmission topology (line switching) in real time.

Potential Impact:

- Significantly lower generation costs
- Provide additional controls to manage congestion.
- Enable higher levels of renewable generation.

Accomplishments:

- Developed detailed model of PJM historical operating hours (data supplied by PJM)
- Developed tractable topology control algorithms using sensitivity-based heuristics and a reduced MIP formulation of the TC problem. Practical solution times reached (below 5 minutes in PJM).
- Developed fast state estimation and transient stability algorithms to support the TC decisions



Economics

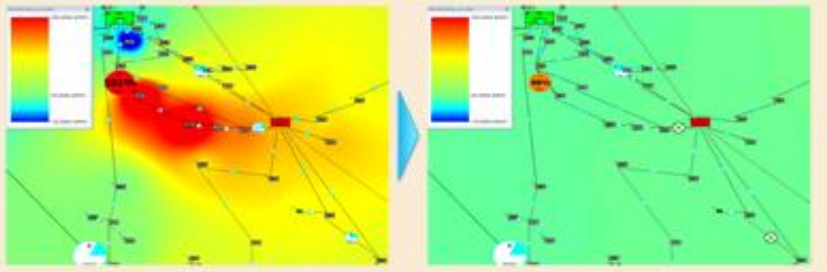
Topology Control

Topology, Dispatch, Commitment, Marginal Costs

Reliability

Contingency + Voltage + Stability Evaluation *

Voltage, MVA and Stability Assessment: Feasible/Infeasible, Constraints to Return to Feasibility



Before

Contingency constraint on 138kV line was mildly overloaded, causing price separation in the region.

After

Constraint was relieved by opening two nearby 138kV lines, diverting flow away from the overloaded line.

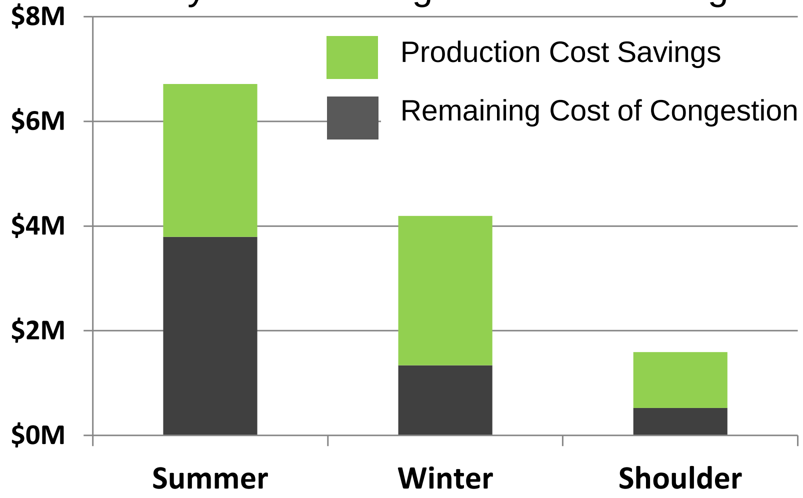
Estimated TCA Benefits

- Production cost savings in PJM RT markets under 2010 conditions were estimated to be **> $100 million/year**
- **Savings of over 50% of Cost of Congestion**

(Based on simulation results for three historical weeks)

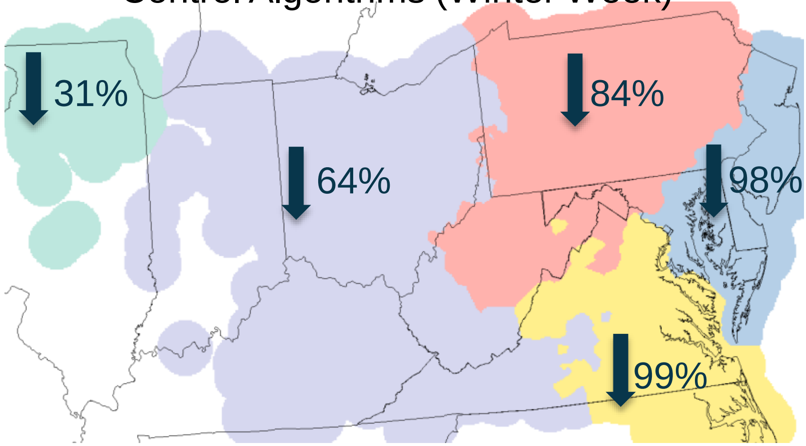
Production Cost Savings = production cost without TCA (full topology)
– production costs with TCA
Cost of Congestion = production cost with transmission constraints
– production costs without transmission constraints

Weekly Cost of Congestion and Savings



- Hybrid historical-high renewables simulation cases for PJM
  - One power flow snapshot per hour for three representative historical weeks in 2010 (one per season)
  - Renewables data from PJM Renewable Integration Study: 30% Low Off-shore Best sites On-shore Scenario
- **Renewable curtailments were reduced on average by 40%**

Renewable curtailment reductions with Topology Control Algorithms (Winter Week)



NODES

Network Optimized Distributed Energy Systems

Mission

Reliably manage dynamic changes in the grid by leveraging flexible load and Distributed Energy Resources’ (DERs) capability to provide ancillary services to the electric grid at different time scales.

Program Director	Dr. Sonja Glavaski
Year	2015
Projects	TBD
Anticipated Investment	$30 Million

Goals

- Enable renewables penetration at > 50%
- Improve the overall efficiency and reliability of the grid
- Reduce CO_2 emissions (renewables↑, reserves↓)
- Increase penetration of Distributed Generation (DG)

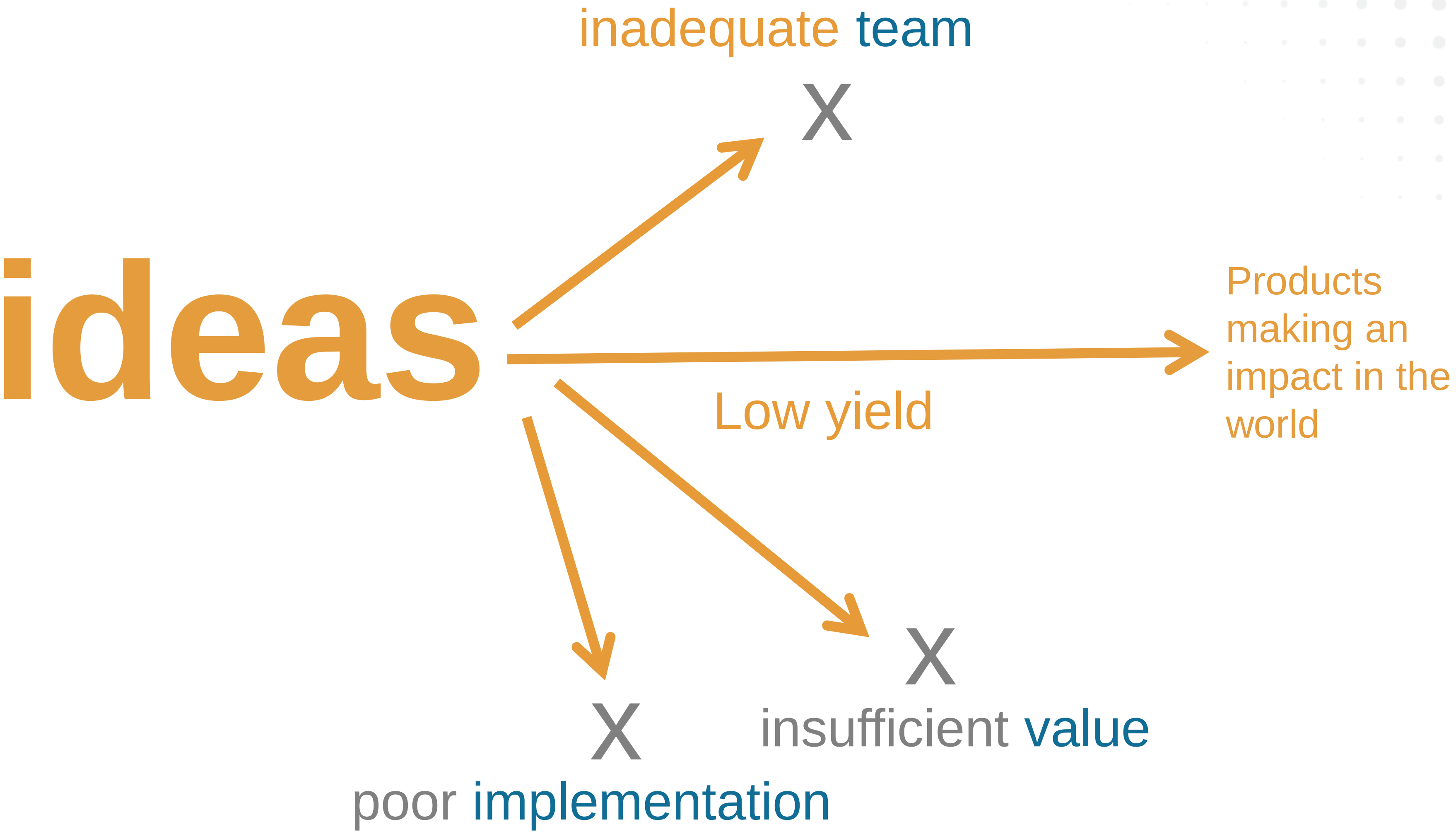
Technical Challenges

- Dispatching both bulk and distributed generation
- Proactively shaping load over different time scales
- Coordinating consumers and generation operation
- Distributed management of heterogeneous resources
- Guaranteeing customers’ QoS

Project Categories	Response Time	Ramp Time	Duration
Synthetic Frequency Response Reserves	**< 2 sec**	**< 8 sec**	**> 30 sec**
Synthetic Regulating Reserves	**< 5 sec**	**< 5 min**	**> 30 min**
Synthetic Ramping Reserves	**< 10 min**	**< 30 min**	**> 3 hr**

What happens after ARPA-E?

Ideas alone are often not enough



inadequate team

X

ideas

Products
making an
impact in the
world

Low yield

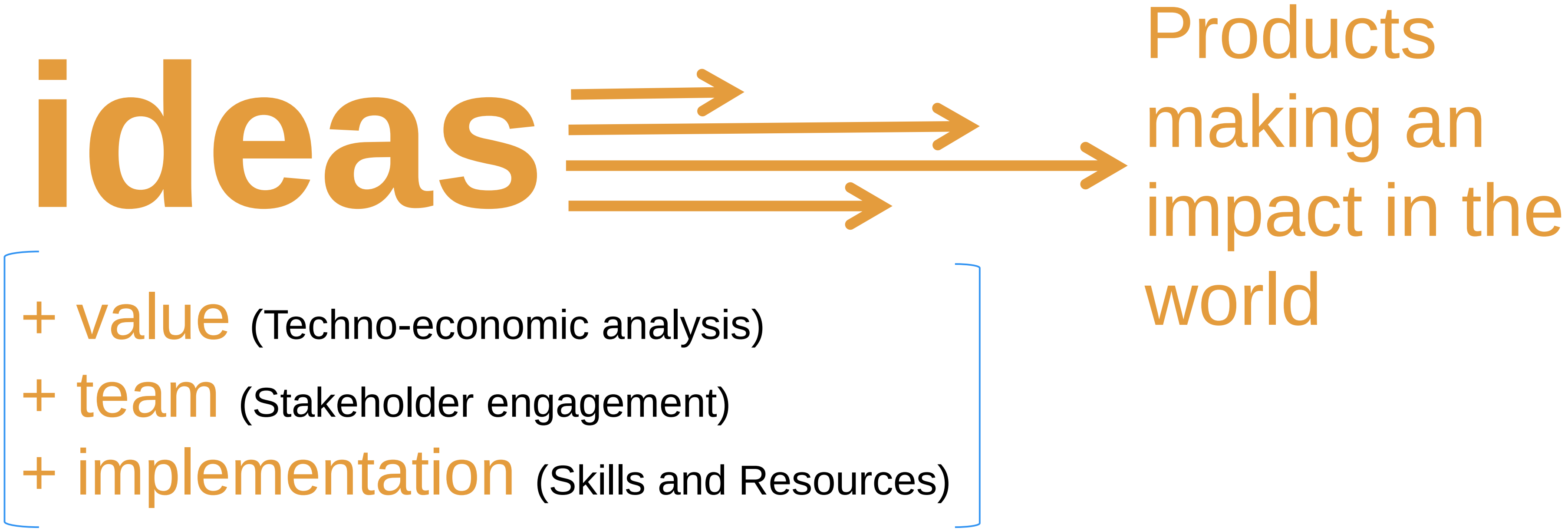
X

insufficient value

X

poor implementation

ARPA-E Tech-to-Market tries to improve yield

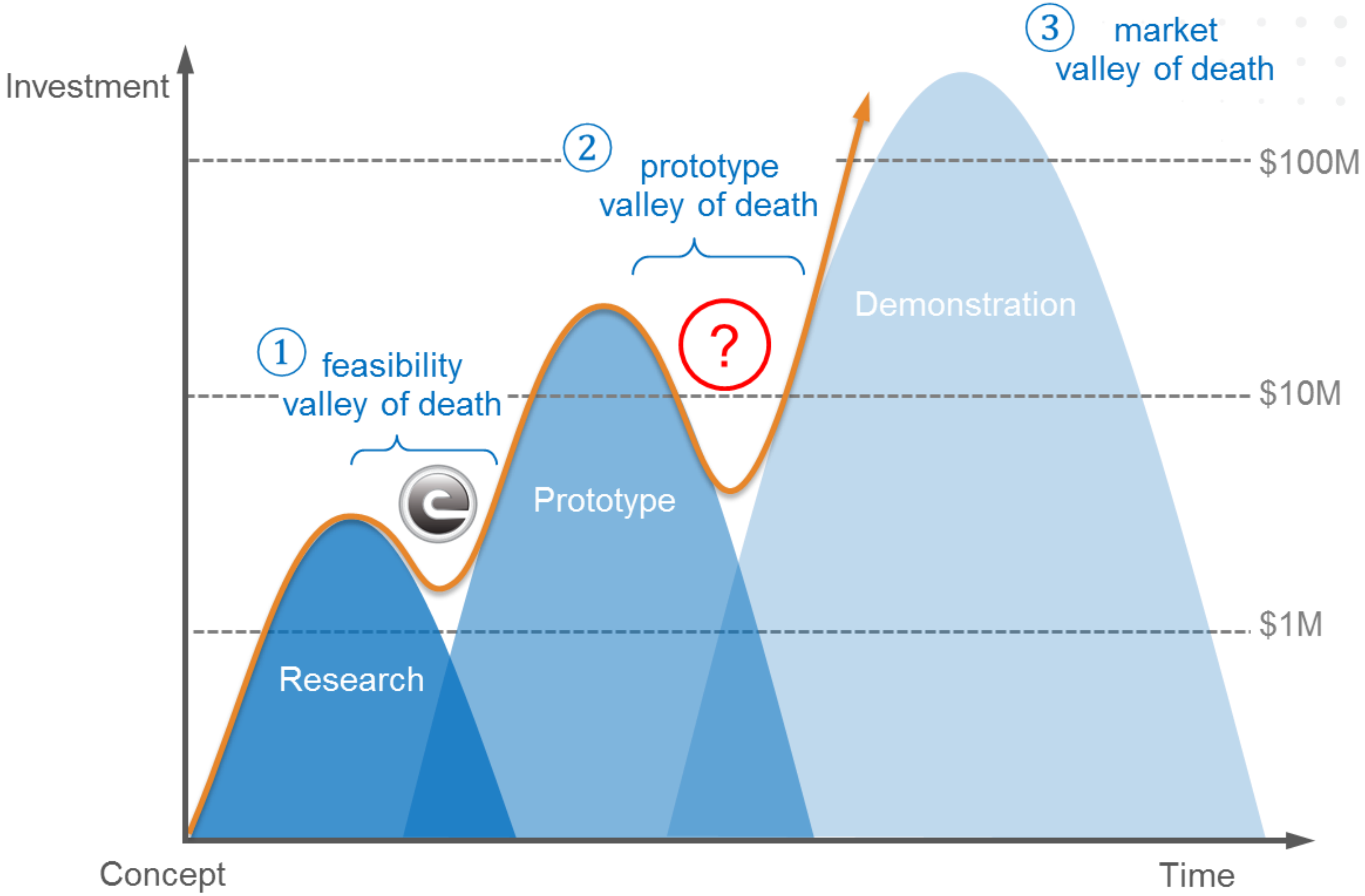


ideas

+ value (Techno-economic analysis)
+ team (Stakeholder engagement)
+ implementation (Skills and Resources)

Products making an impact in the world

Energy Technology “Valleys of Death”



arpa·e

U.S. DEPARTMENT OF
ENERGY

www.arpa-e.energy.gov