Advanced Power System Research at Argonne National Laboratory

Jianhui Wang Ph.D.

Center for Energy, Environmental, and Economic Systems Analysis
Decision and Information Sciences Division (DIS)
ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, IL 60439
Jianhui.wang@anl.gov +1-630-252-1474
http://www.dis.anl.gov/groups/ceeesa.html
https://sites.google.com/site/eejhwang/

University of NSW
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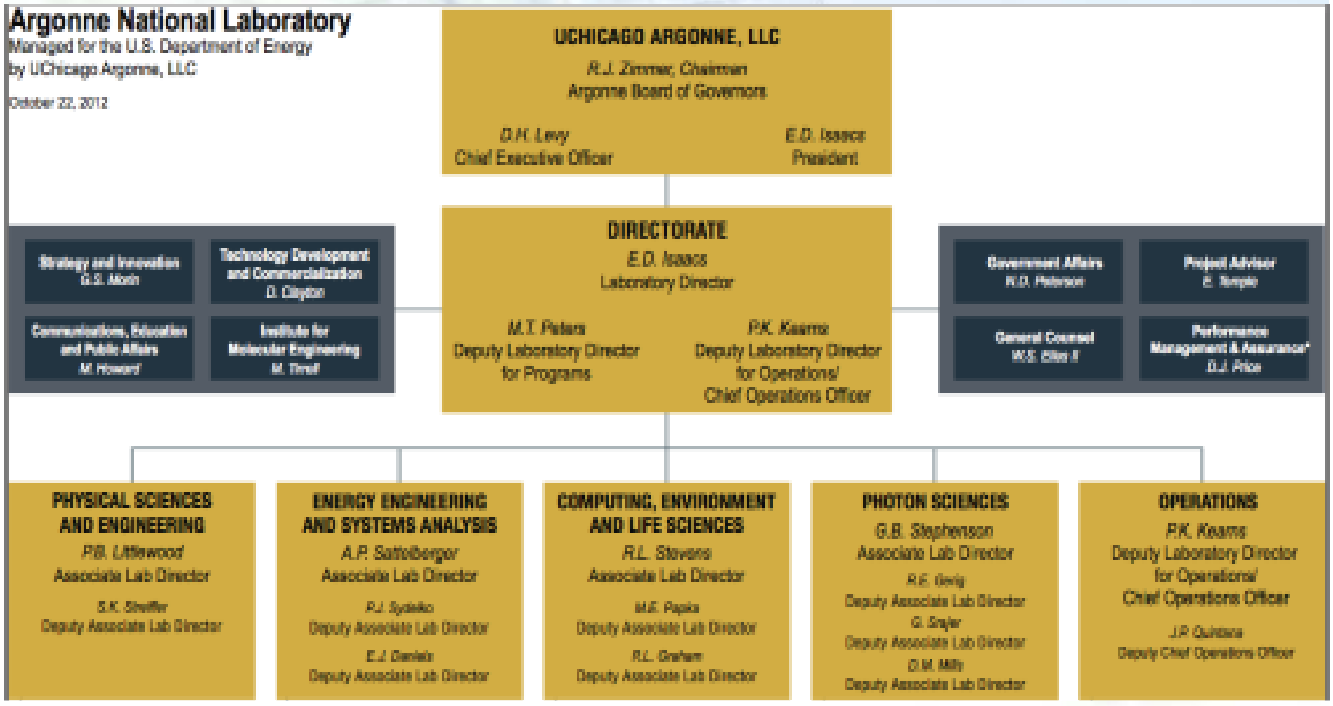
About the speaker

- Ph.D. Illinois Institute of Technology, 2007
- Computational Engineer – Energy Systems, Argonne National Laboratory (2008-)
- Affiliate Professor, Auburn University (2011-)
- Adjunct Professor, University of Notre Dame (2014-)
- Editor, *IEEE Transactions on Power Systems, IEEE Transactions on Smart Grid, IEEE PES Letters, Applied Energy, Journal of Energy Engineering, Artech House Publishers Power Engineering Book Series, IEEE CTN News*
- Authored/co-authored close to 100 journal articles and 50 conference publications
- Chair of the IEEE Power & Energy Society (PES) Power System Operation Methods Subcommittee and co-chair of an IEEE task force on integrating wind and solar power into power system operations
- Technical program chair of the IEEE Innovative Smart Grid Technologies conference 2012. Winner of the *Applied Energy* Editor's 2011 Best Reviewers Award and the recipient of the IEEE Chicago Section 2012 Outstanding Young Engineer Award

Argonne is America's First National Laboratory and one of the World's Premier Research Centers

- Founded in 1943, designated a national laboratory in 1946
- Part of the U.S. Department of Energy (DOE) laboratory complex
  - 17 DOE National Laboratories
- Managed by UChicago Argonne, LLC
  - About 3,400 full-time employees
  - 5,000+ facility users
  - About $800M budget
  - Main site: 1500-acre site in Illinois, southwest of Chicago
- Broad research and development portfolio
- Numerous sponsors in government and private sector

Argonne Organization



The Energy, Environment, and Economic Systems Analysis Group Offers a Diverse Set of Skills

- 16 staff, 4 postdocs, 5 STAs, 3 PhD students
- 16 PhDs, 8 MSc/MBA, 1 BS
- Degrees in Industrial Engineering, Electrical Engineering, Economics, Operations Research, Computer Sciences, others
- UofC Booth School of Business, Georgia Tech, IIT, UPenn Wharton School of Business, Harvard, MIT, others

HARVARD UNIVERSITY

Massachusetts Institute of Technology

Wharton

Rensselaer why not change the world?

ILLINOIS INSTITUTE OF TECHNOLOGY

CHICAGO BOOTH

Our Group Conducts Research Across Multiple Domains to Transform our Energy System

- Variable solar and wind resource forecasting and integration
- Hydro power optimization
- Energy storage
- Building efficiency and building/grid interaction
- Electric vehicles and grid interaction
- Smart-grid, microgrids, and power markets
- Large-scale grid modeling using high-performance computing
- Critical materials supply chain analysis
- Energy security and energy futures analysis

Our Research Projects Are Often Complex and Multi-Faceted and Require Broad Knowledge Base and Skill Sets

From Atmospheric Sciences to Environmental Impacts/Risks

Atmospheric Sciences
Design/deploy instrumentation
Execute field campaigns (ARM)
Atmospheric modeling

Forecasting
Resource characterizations
Solar forecasting
Wind forecasting

Grid and Markets
Short and long-term power system studies
Power market analysis
Demand response
Transmission switching

Environment
Geospatial analysis
Environmental risk factors

From Development of Advanced Algorithms to Commercialization/Deployment of Models

Advanced Algorithms
Predictive modeling
Advanced math
Scalable solutions for optimization
Integrative Frameworks

Model Development
Resource optimization
Stochastic UC/operations
Power market tools
Large-scale grid tools

Model Applications
Integration studies
Power market design
EV-grid impacts
Demand response analysis

Deployment
GTMax
EMCAS
EISPC

Our Group Collaborates with Researchers Across the Lab, at Other National Laboratories, Universities, and Industry

- We team across laboratory divisions and ALDshi
  - Environmental Sciences Division
  - Math and Computing Sciences Division
  - Energy Sciences Division
  - Facility Management and Services Division
  - Joint Center for Energy Storage Research
  - Urban Center for Computation and Data
  - Physics Division
- We team with other national laboratories
  - Berkeley, NREL, Oak Ridge, Pacific Northwest, Sandia
- We team with domestic and international universities
  - IIT, Georgia Tech, Notre Dame, Tsinghua University, INESC-Porto, etc.
- We team with private sector partners
  - ComEd, Arizona Public Services,
  - Alstom, Siemens
  - Montgomery Watson Harza
  - EDP-Horizon, Invenergy
  - Etc.

JCESR JOINT CENTER FOR ENERGY STORAGE RESEARCH

URBAN CENTER FOR COMPUTATION AND DATA

BERKELEY LAB LAWRENCE BERKELEY NATIONAL LABORATORY

NREL NATIONAL RENEWABLE ENERGY LABORATORY

MWH BUILDING A BETTER WORLD

SIEMENS

ComEd An Exelon Company

Our Group Conducts Research for a Diverse Set of Customers

- DOE Office of Electricity Delivery and Energy Reliability
- DOE Wind Power Program
- DOE Water Power Program
- DOE Solar Energy Technologies Program
- DOE Building Technologies Office
- DOE Vehicle Technologies Program
- DOE Advanced Manufacturing Office
- DOE Energy Policy and Systems Analysis Office
- DOE Hydrogen and Fuel Cells Program
- Western Area Power Administration
- U.S. Agency for International Development
- U.S. Energy Association
- World Bank, International Atomic Energy Agency, United Nations
- Private sector
- University of Chicago Seed Grant
- Defense Logistics Agency

Various Educational Programs – www.dep.anl.gov

- **Undergraduate Programs**
- **Graduate Programs**: Research aide, guest graduate appointment, etc.
- **Postdoctoral Programs**: Argonne Named Postdoc Fellowships, Director's Postdoc Fellowships, Division Postdoc
- **Faculty Programs**: Faculty research participation, faculty research leave, guest faculty research program, visiting faculty program

DOE Energy Innovation Hub for Advanced Batteries and Energy Storage

U.S. DEPARTMENT OF ENERGY | Office of Science

JCESR (Joint Center for Energy Storage Research) is a DOE Energy Innovation Hub, funded through the Basic Energy Sciences office of DOE, and led by Argonne National Laboratory

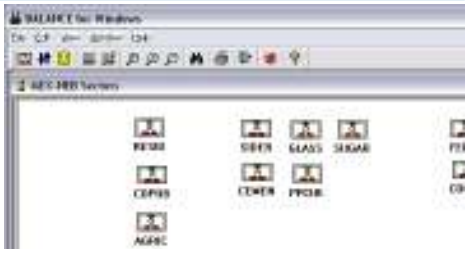
JCESR Goals: 5-5-5

Transformational technology goals:

- 5 times greater energy density → beyond Li-ion
- 1/5 cost
- within 5 years

Argonne's Energy and Power Systems Analysis Tools are Used Worldwide

- **Energy and Power Evaluation Program (*ENPEP-BALANCE*) simulates the entire energy system**
  - Our workhorse for over 20 years
  - Distributed to over 50 countries

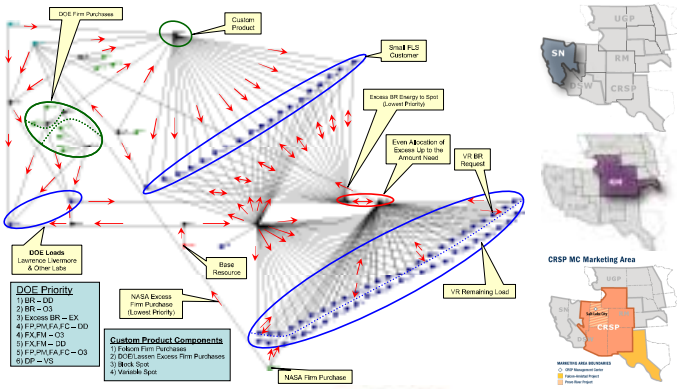


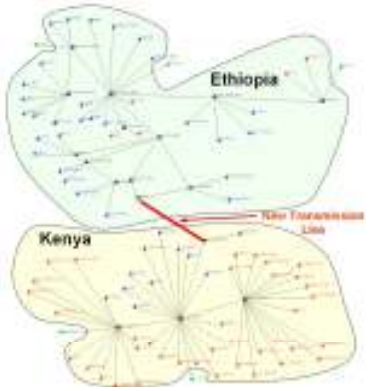
- **Generation and Transmission Maximization (*GTMax*) optimizes the operation of the generation and transmission system and analyzes regional interconnections**
  - Short-term model with hydro focus
  - Used extensively in the Western U.S.

- **Electricity Market Complex Adaptive Systems (*EMCAS*) simulates the behavior of restructured power market participants using an agent-based complex adaptive systems approach**
  - Our latest and most advanced power market model
  - Used both domestically and internationally

GTMax is Used in the U.S. and Around the World to Analyze Benefits of Regional Interconnections and Value of Power Resources in Regional Markets

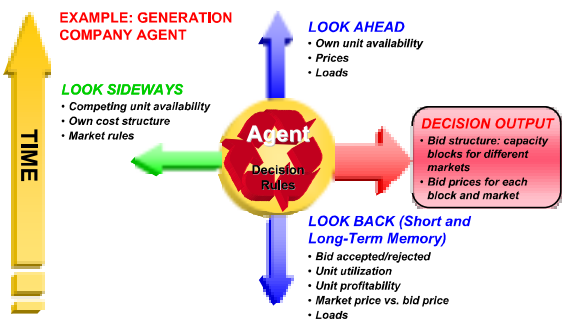
- For a variety of offices of the Western Area Power Administration and the Bureau of Reclamation
  - Optimize hydropower operations
  - Simulate operations of a complex cascade of reservoirs and power plants
  - Firm power purchasing programs
  - Determines optimal hourly power plant operations
  - Power Marketing EIS
- Most recently, in collaboration with a German consulting company (Fichtner Engineering), analyzed the benefits of a new interconnection between Kenya and Ethiopia

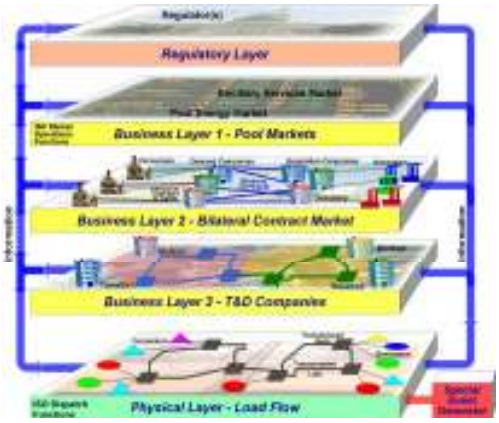




EMCAS is Argonne's Premier Analysis Tool to Study Restructured Power Markets

- Uses an agent-based modeling approach to represent multiple market participants (agents) with decentralized decision-making under uncertainty
- Alternative company strategies can be simulated
- Incorporates learning and adaptation
- Allows testing of market rules
- Allows market monitoring for price manipulation



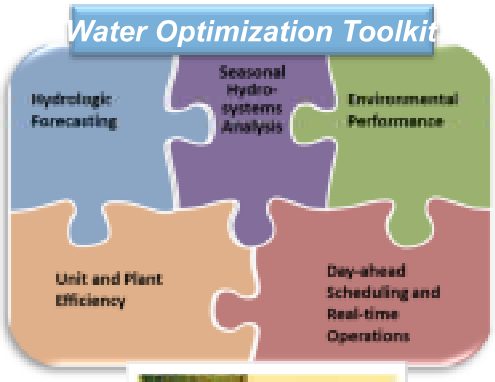


Argonne Has over 20 years of Domestic and International Hydropower Analysis Experience

- Western Area Power Administration (Western) and the Bureau of Reclamation (Reclamation)
- Environmental Impact Statements (EIS)
- Beach/habitat building flows
- SLCA/IP monthly analyses
- California Central Valley Project (CVP)
- Colorado River Storage Project (CRSP)
- Glen Canyon cost reallocation
- Economic analysis of operating rules
- Relicensing of existing dams
- Investment decision in new hydro facilities in Africa, Asia, Europe, South America

Argonne is Supporting DOE's Hydro Power Program in Developing New Methods/Tools for Optimization and Valuation of Hydropower Resources

- Leverages 20+ years of Argonne experience in hydropower modeling
- Innovation: Develop a suite of integrated modeling approaches for optimization of operations and environmental performance; demonstrate improved capability to manage risk of hydrological uncertainty
- Collaboration: Partnering with other national labs (Oak Ridge, Pacific Northwest, and Sandia)
- Impact: Support the goal of increasing power generation at existing hydropower facilities
- Argonne is leading the development of the Conventional Hydro-Electric and Environmental Resource Systems (CHEERS)
  - Simultaneously solves energy and environmental objectives



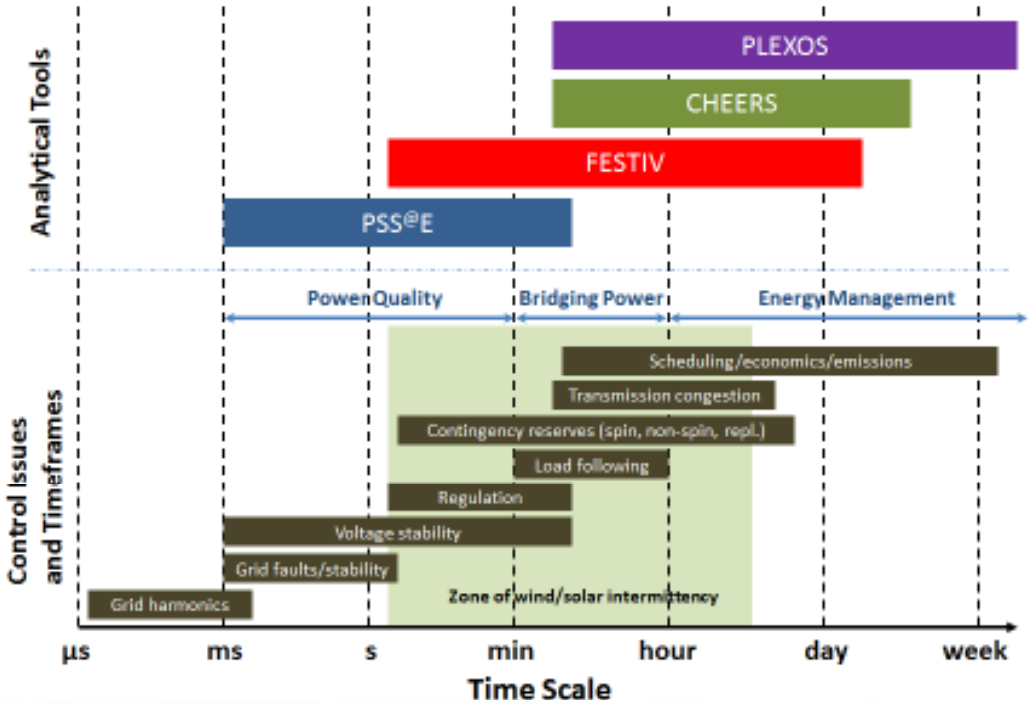
Argonne is DOE's Lead Lab for the Analysis of Pumped Hydropower Storage

- Argonne leads a team of industry and national laboratory partners
- Objective is to improve modeling representation of advanced pumped storage hydropower as well as conventional hydro plants in power system and energy market and reliability simulation models
- Improved models will capture the full range of technical capabilities and benefits/ revenues these facilities can provide
- New model(s) will be tested in the Western United States at test sites
  - Colorado River
  - California Department of Water Resources
  - East Coast system

ALSTOM MWH NREL SIEMENS

Pumped Storage Hydro Modeling and Simulation Will Address Wide Range of Control Issues and Timeframes

- The analysis aims to capture PSH operational characteristics and dynamic responses across different timescales, from a fraction of a second to days/weeks.



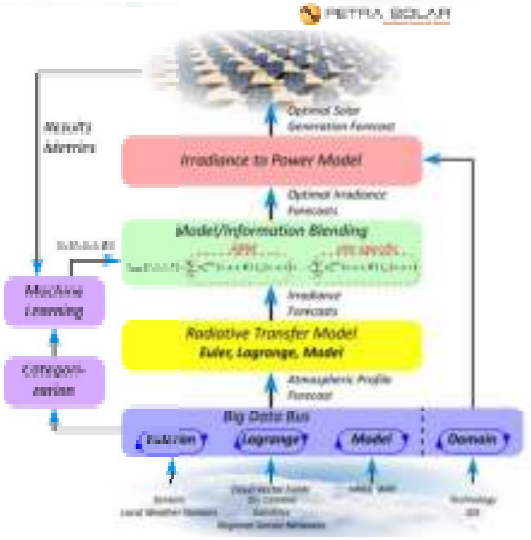
Argonne Supports the DOE-Solar Office on Solar Power Forecasting (with IBM - from Watson to Watt-SUN)

Energy Department Announces New SunShot Investment in Solar Energy Grid Solutions

December 07, 2012

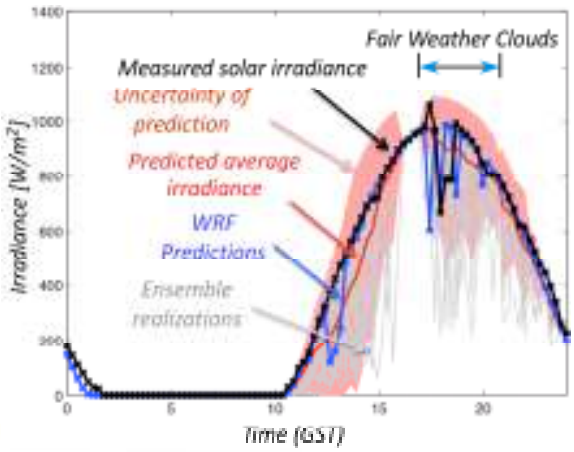
As part of the Energy Department's SunShot initiative, which is working to make solar energy competitive with other forms of energy without subsidy by the end of the decade, the Energy Department today announced a $20 million investment in four projects that will help advance affordable, reliable, clean energy for U.S. families and businesses. These projects are aimed at improving grid connection and reducing installation costs through innovative plug-and-play technologies and reliable solar power forecasts.

Watt-sun: A Multi-scale, Multi-Model, Machine-Learning Solar Forecasting Technology



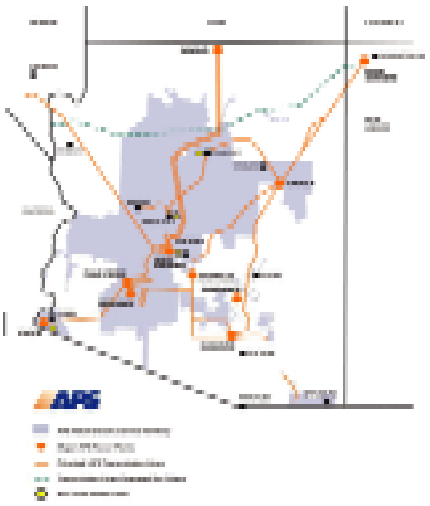
Radiative Transfer Modeling

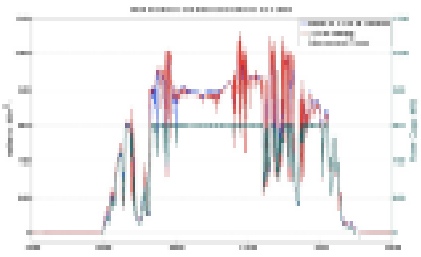
- **Monte Carlo Aerosol Radiation Model**
  - Inputs: Cloud profiles, optical depth and water vapor density, aerosols' properties, surface data (vegetation) etc
  - Accounts for multiple scattering, absorption and includes 25 frequency bands with 50 layers
  - MCAR model has several advantages:
    - Extensively validated in literature
    - Typical more accurate than radiative transfer models included in weather codes
    - Computational very efficient
    - Argonne team has hands-on experience with this model

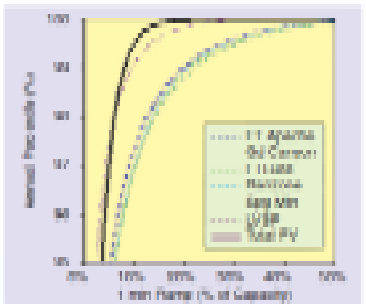


Argonne is Supporting DOE's Solar Energy Technologies Program in Studying Solar Integration Issues

- For the DOE Solar Energy Technology Program
- In collaboration with NREL and Berkeley
- Industrial partner: Arizona Public Service (APS)
  - Will provide data under non-disclosure agreement
  - Model will be implemented for APS footprint
- Goals: Develop detailed understanding of the operational integration issues of solar PV energy on an individual utility system and enhance the state-of-the-art in analytical methodologies/ tools used to analyze solar PV integration
- How much balancing reserve should a utility schedule in order to maintain compliance with NERC control performance standards with increased PV?
- How much does it cost to schedule additional balancing reserves?
- How should unit commitment decisions differ with increased forecast uncertainty?



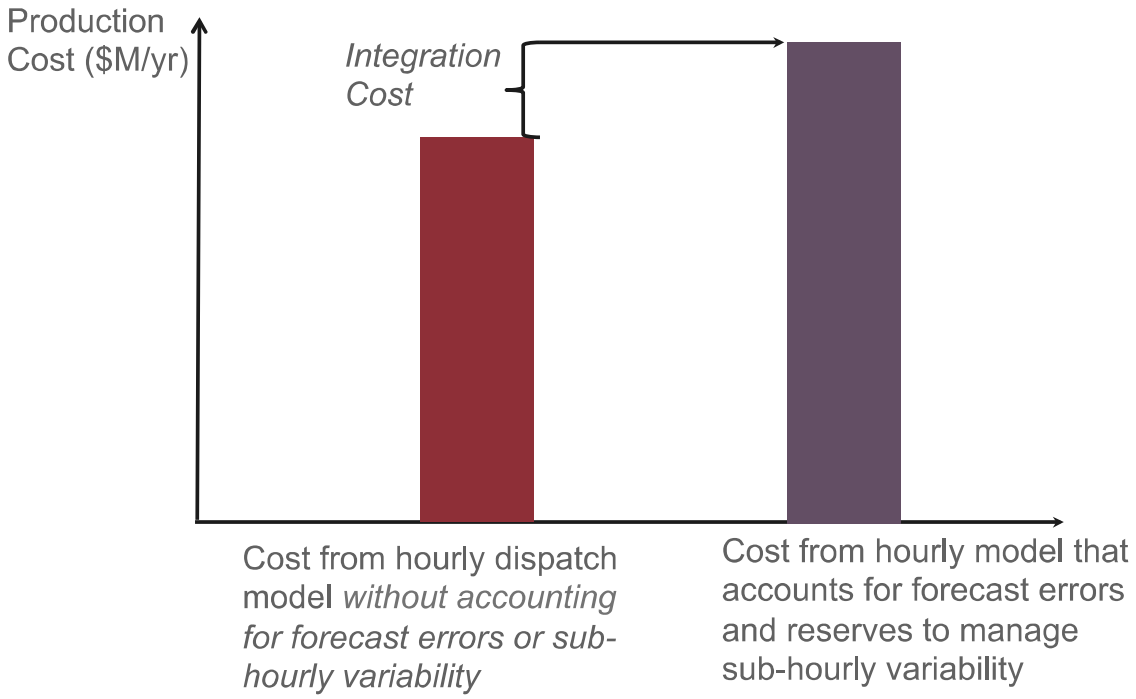




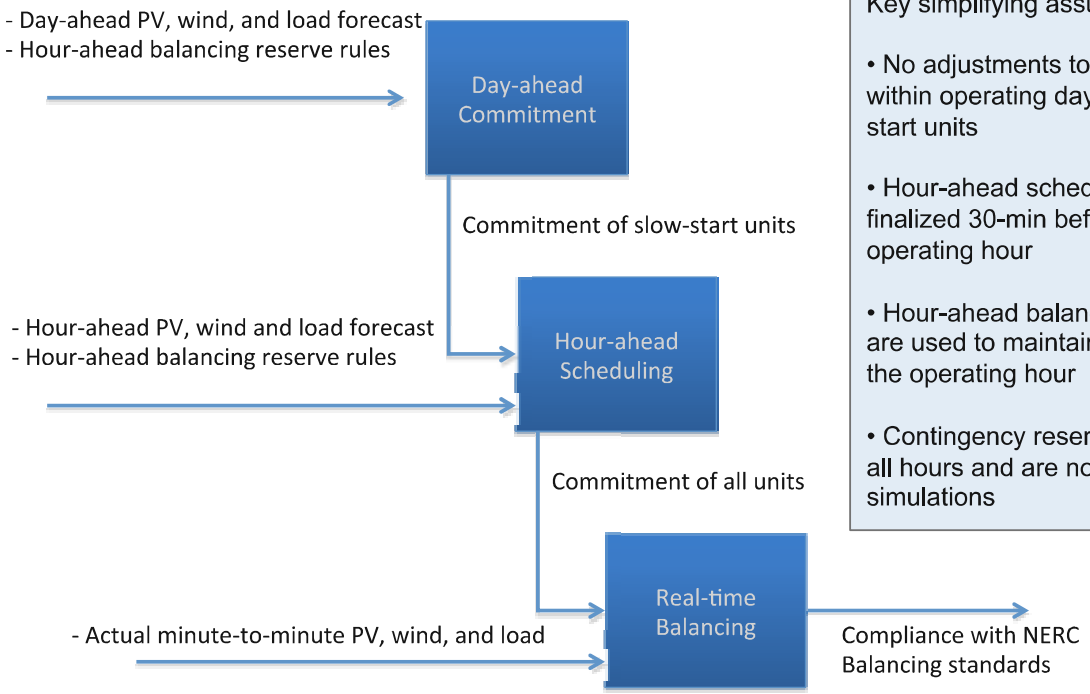
Integrating Solar PV in Utility System Operations

- Project objectives
  - Improve understanding of operational challenges from large-scale expansion of PV with focus on intra-hour variability and operating reserve requirements
  - Improve state-of-the-art in tools and methodologies used to analyze power system operations with PV
  - Conduct a detailed case study of Arizona Public Service Company (APS)
- Key questions
  - How much additional operating reserves are needed to maintain reliability?
  - How does operations change?
  - What is the additional cost?
  - What are cost effective solutions?
- Lab collaborators
  - LBNL, NREL

Defining Integration Costs



Simulation Framework



Key simplifying assumptions:

- No adjustments to commitments within operating day, except fast-start units
- Hour-ahead schedules are finalized 30-min before the operating hour
- Hour-ahead balancing reserves are used to maintain balance within the operating hour
- Contingency reserves are held in all hours and are not deployed in simulations

Integration costs with Base Assumptions (Low and High PV)

Table ES-1. Impact of PV in 2027 Using Base Assumptions

	Load-Wind	Net Load		
	No PV	Low PV	High PV (Const. Nucl.)	High PV (Flex. Nucl.)
PV nameplate capacity (MW-ac)	0	1,674	2,974	2,974
Energy from PV (% annual demand)	0%	8.8%	14.3%	16.8%
Renewable curtailment (% renewable energy)	0%	2.9%	17.8%	3.4%
Maximum balancing reserve up (MW)	187	278	556	556
Average balancing reserve up (MW)	132	171	241	241
CPS2 score (must be >90)	96.1	95.8	92.6	92.6
Integration Cost				
Balancing reserve cost ($/MWh-PV)	N/A	1.61	3.56	1.11
DA forecast error cost ($/MWh-PV)	N/A	0.27	0.21	0.63
Total PV integration cost ($/MWh-PV)	N/A	1.88	3.77	1.74

Minimum net-load periods in the spring require large downward flexibility

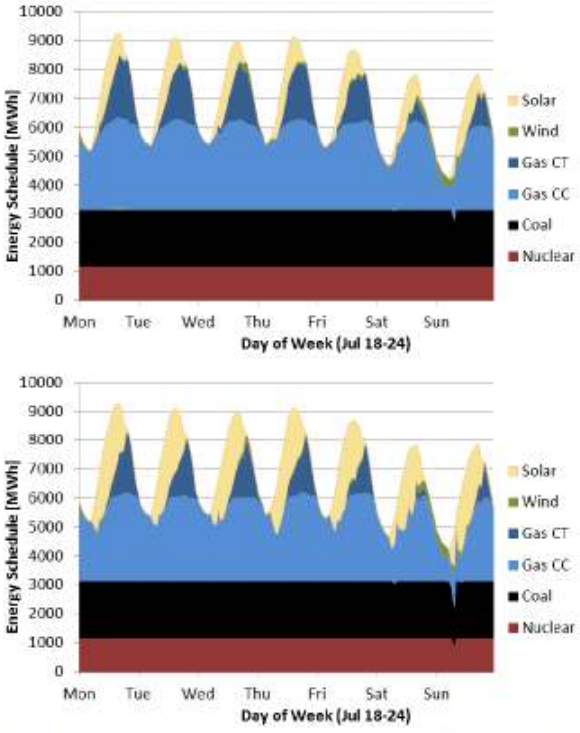


Figure 10. HA Energy Schedule in Peak-Load Week, July 18–24, under the Low-PV (top) and High-PV (Flex. Nucl.) (bottom) Scenarios

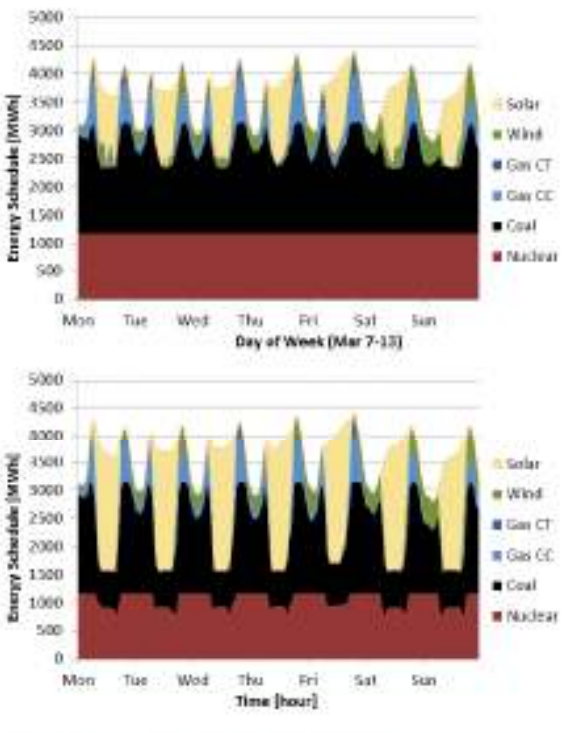
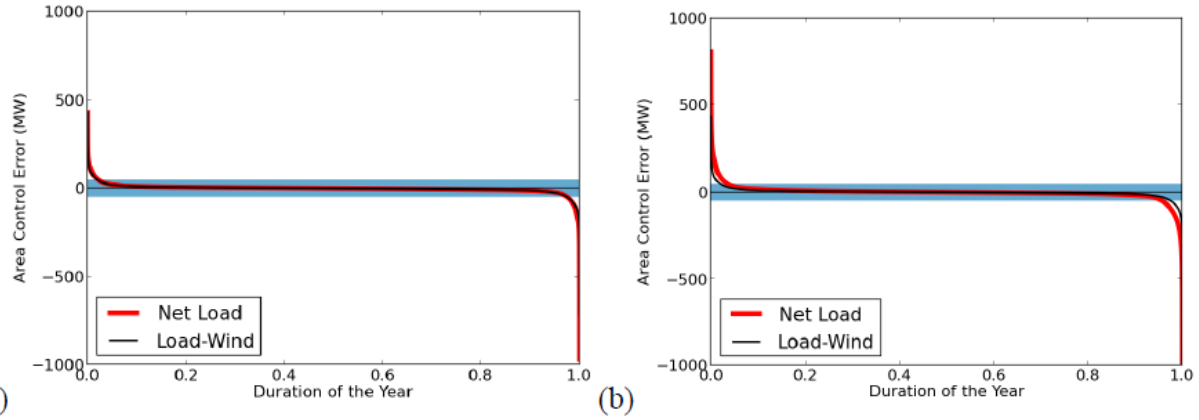


Figure 11. HA Energy Schedule in Minimum-Load Week, March 7–13, under the Low-PV (top) and High-PV (Flex. Nucl.) (bottom) Scenarios

NERC reliability compliance is achieved, though performance degrades with high PV



Note: Blue bar represents the L_{10} parameter for APS, which is assumed to be 46 MW

Figure 13. ACE Resulting from a Mismatch between Deviations from the HA Schedule and Deployment of Balancing Reserves in RT in the Low-PV Scenario (a) and the High-PV Scenario (b)

Scenario	CPS 2 (must be >90%)		Approximate CPS1 (must be >100	
	Load-Wind	Net Load	Load-Wind	Net Load
Low-PV	96.1%	95.8%	184	182
High-PV	96.1%	92.6%	184	169

Reliability performance (CSP2) can be improved, but it comes with increased integration costs

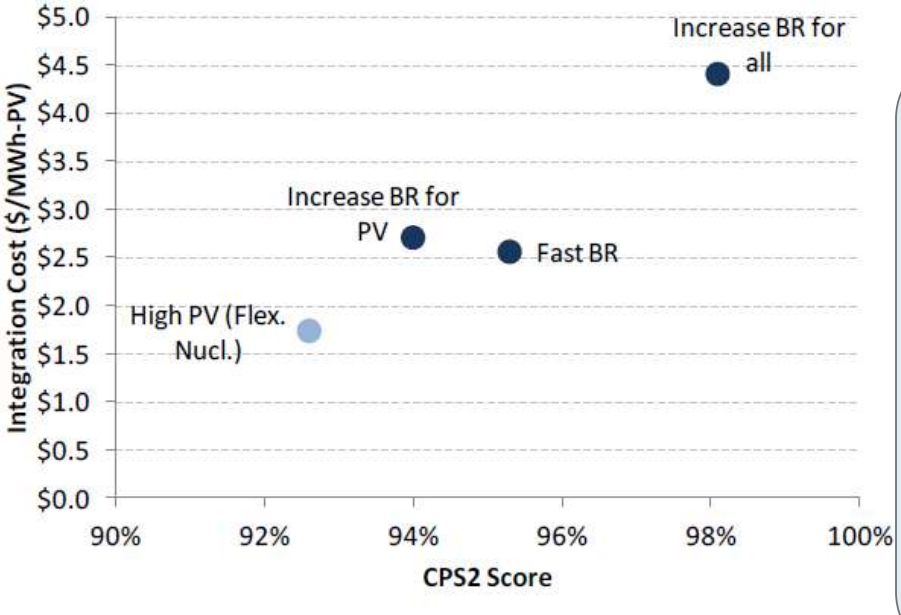


Figure 15. Tradeoff Between Balancing Performance (CPS2 Score for Net Load) and Integration Cost of PV

- **Increase BR for PV:**
  - Increase balancing reserves to cover 98% of PV deviations from schedule
- **Fast BR:**
  - Require balancing reserves to be fully deployed in 5-min (rather than 10-min)
- **Increase BR for all:**
  - Increase balancing reserves to cover 99.8% of load, wind, and PV deviations

Sensitivity Analysis (high PV w/flex nuclear): Integration Costs

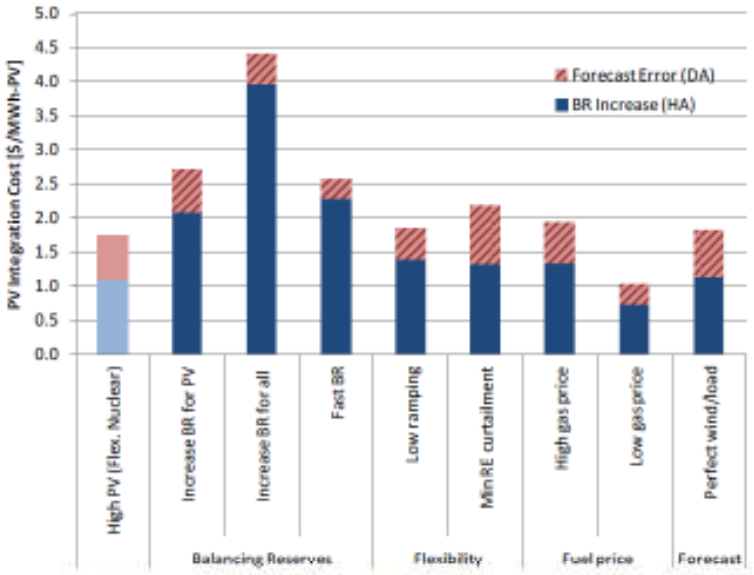


Figure 17. PV Integration Cost Estimates for High-PV (2027) Sensitivity Cases

- **Low ramping:**
  - Use lower ramp rate estimate for thermal generation
- **Min RE curtailment:**
  - Add significant penalty for curtailing renewable resources
- **High gas price:**
  - Increase gas price by 25% (from $5.85 to 7.31/MMBtu)
- **Low gas price:**
  - Decrease gas price to $4.00/ MMBtu and increase coal price from $1.96 to $3.00 / MMBtu
- **Perfect wind/load:**
  - Assume perfect load and wind forecasts in DA and HA

Sensitivity Analysis (high PV w/flex nuclear): Curtailment of Renewable Energy

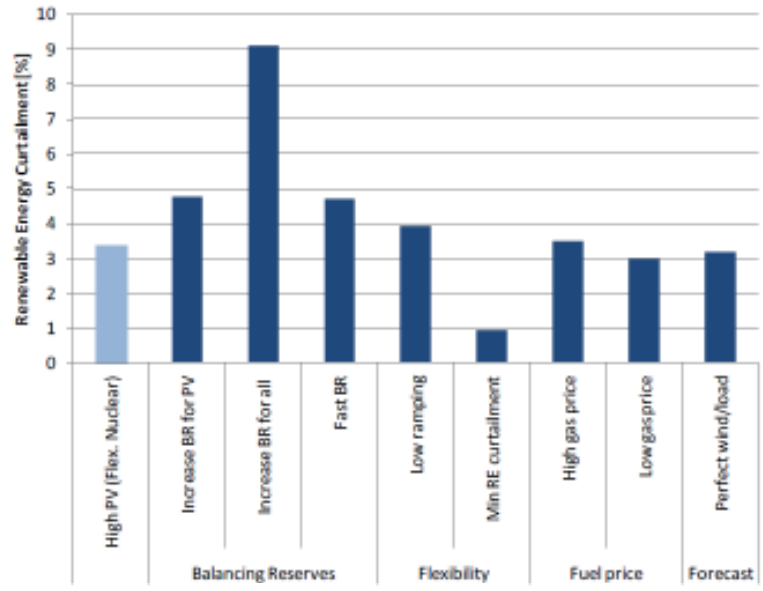


Figure 16. Renewable Energy Curtailment as a Percentage of Total Available Resources for High-PV (2027) Sensitivity Cases

- **Low ramping:**
  - Use lower ramp rate estimate for thermal generation
- **Min RE curtailment:**
  - Add significant penalty for curtailing renewable resources
- **High gas price:**
  - Increase gas price by 25% (from $5.85 to 7.31/MMBtu)
- **Low gas price:**
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- **Perfect wind/load:**
  - Assume perfect load and wind forecasts in DA and HA

Recommendations and Areas for Future Work

- Flexibility in the downward direction may be a major challenge with high PV:
  - Identify potential buyers of power in spring season
  - Evaluate downward balancing reserves from renewables, particularly during times when curtailment would otherwise be needed
  - Consider bulk power storage or load shifting with high PV
- Increased sub-hourly variability may be managed through alternatives to holding more balancing reserves:
  - Energy imbalance market can increase access to balancing resources
  - New NERC balancing standard may be less stringent than CPS2
- Utilize probabilistic forecasts to reduce reserves on clear days
- Account for forecast errors in day-ahead commitment, consider stochastic UC
- Consider alternative providers of reserves (demand response, renewables)

- Project report for more details:

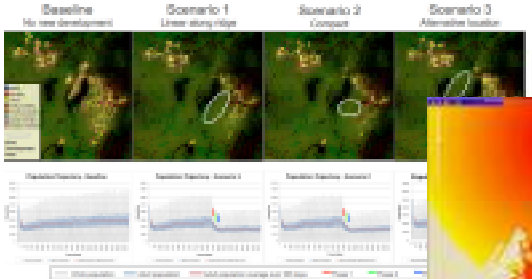
A. Mills, A. Botterud, J. Wu, Z. Zhou, B-M. Hodge, M. Heaney, "Integrating Solar PV in Utility System Operations, Report ANL/DIS-13/18, Argonne National Laboratory, Oct. 2013.

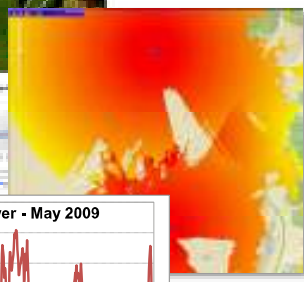
Online: http://www.osti.gov/scitech/biblio/1107495

Argonne's Wind Power Research is Currently Focused on Four Main Areas

- Advanced drive train development
  - Superconducting direct drive train
  - New award with industrial partners under recent off-shore solicitation

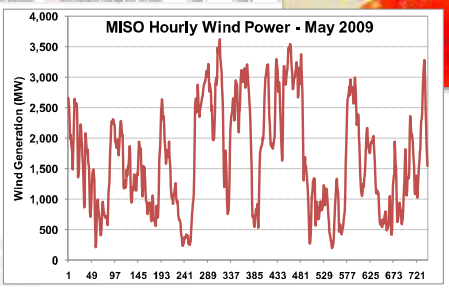
- Wind turbine reliability
  - Improved coatings and lubricants
  - Better gear box reliability





- Environmental Impacts of wind power
  - Impact on critical wildlife habitats
  - Visual impact analysis (on-, off-shore)

- Wind Power Forecasting and Electricity Markets
  - Improved statistical forecasting models
  - Use of forecasting in operational decisions
  - Wind power bidding
  - Investment analysis



Wind Power Forecasts are the Result of Combination of a Diverse set of Models and Input Data

NWP Output Data

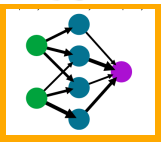
Weather Data

Off-site Met Data

Site Power Gen & Met Data

Physical Models

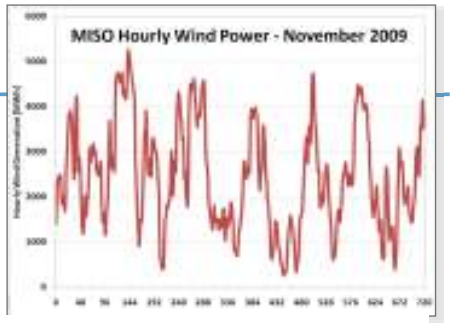
$$X_t = c + \sum_{i=1}^{p} \varphi_i X_{t-i} + \varepsilon_t,$$



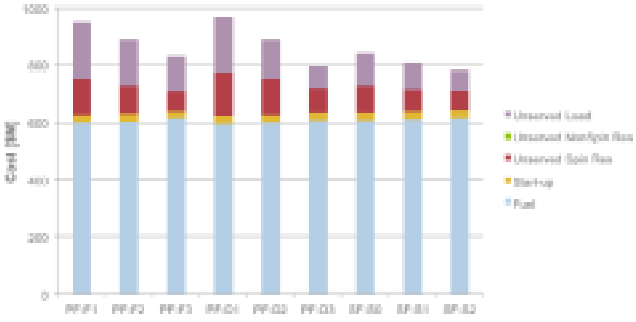
Statistical Models

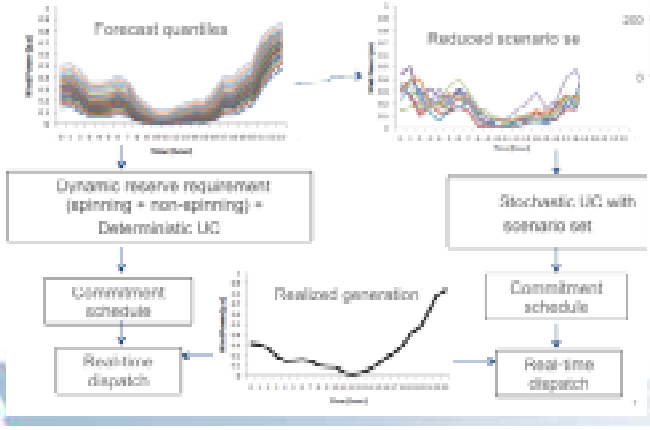
Forecast Results

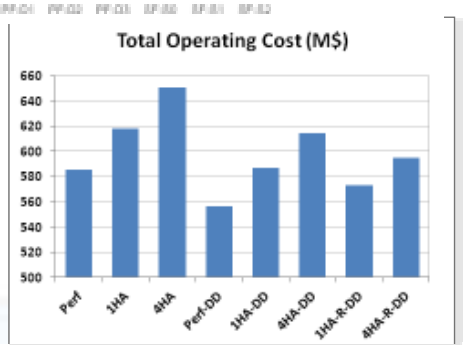
Grid Integration of Wind Power



- Argonne developed new stochastic planning model to evaluate different operational practices and market policies to reduce the cost of wind integration
- Model is tested in case studies for Illinois (20% Wind)
  - More reserves gives lower total cost (less curtailment)
  - Dynamic reserves tend to perform better than fixed reserves
  - Stochastic UC performs slightly better than dynamic reserves

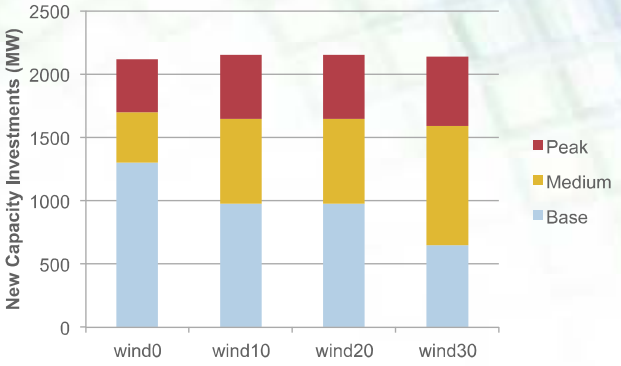


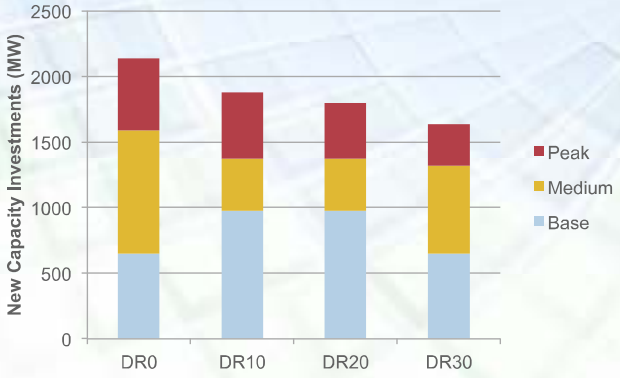




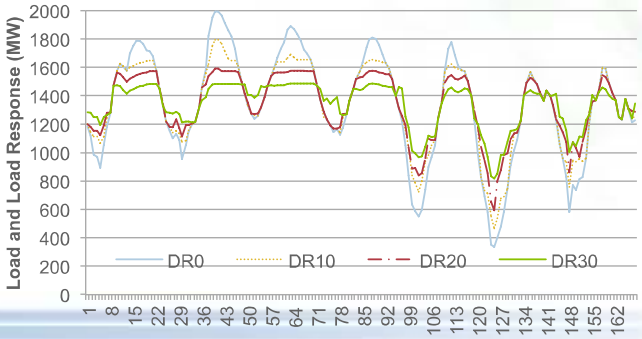
Analyzing Smart Grid Issues: Flexible Load Can Help Integrate Variable Resources

New Generating Capacity Needs Without and With DR

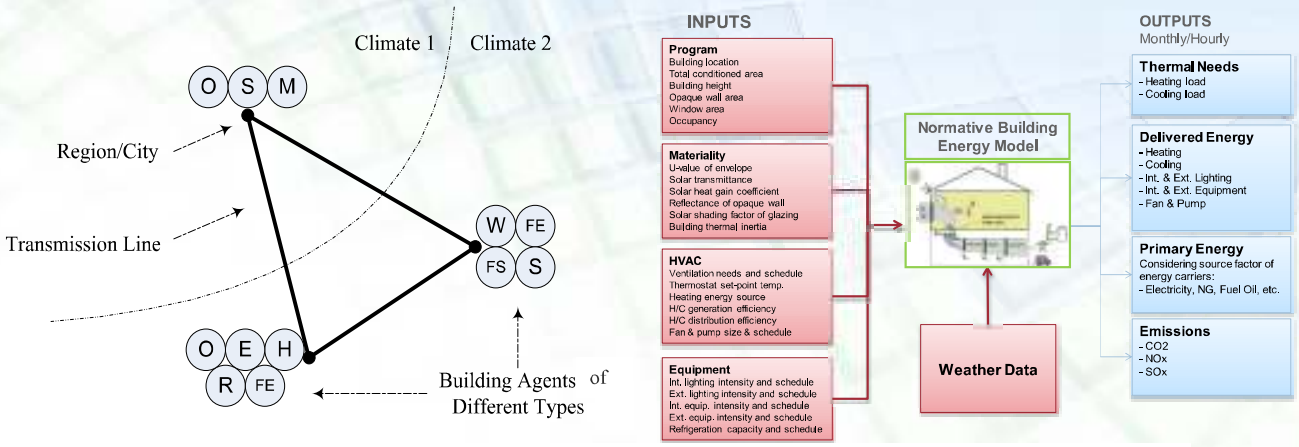


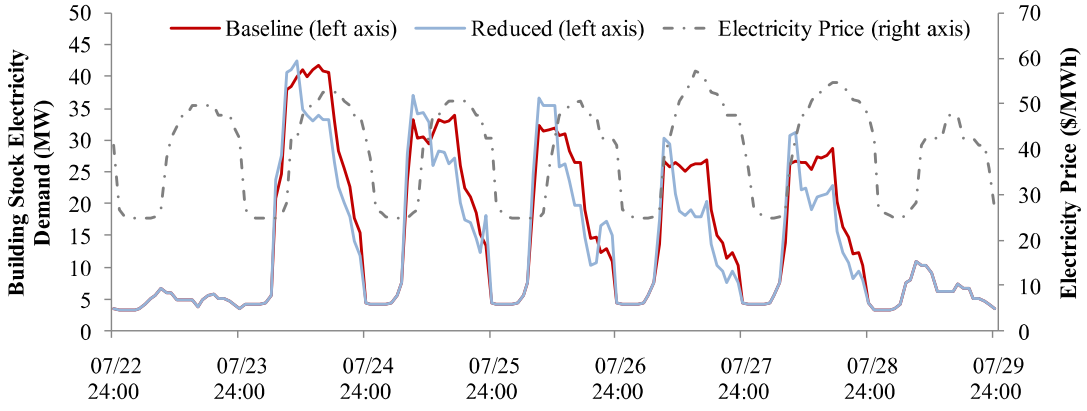


Load Shape at Different Levels of DR



Argonne Analyzes Smart Buildings and Energy Storage in Commercial Buildings and Interactions with the Power Grid





Argonne is Developing a New Online Tool to Identify Clean Energy Zones in Eastern Interconnection

- Technical Support for Interconnection-Level Electric Infrastructure Planning
  - Support the Eastern Interconnection States' Planning Council (EISPC) Energy Zones Study
  - Lead by Argonne, support by NREL and ORNL
- Builds on Argonne's extensive GIS analysis capabilities

EZ Study Analyzes 30 Clean Energy Technologies

Biomass
- ☐ Forest biomass and wood waste
- ☐ Agricultural biomass and waste resources
- ☐ Dedicated energy crops
- ☑ Methane from landfills
- ☑ Methane from wastewater treatment
- ☑ Methane from animal manure processing

Clean Coal
- ☑ New clean pulverized coal technology
- ☑ New integrated gasification combined cycle
- ☑ New coal fluidized bed
- ☑ Retrofitted pulverized coal

Geothermal
- ☑ Enhanced geothermal systems
- ☑ Geopressured geothermal

Natural Gas
- ☐ Combined cycle
- ☐ Underground natural gas storage
- ☐ Above-ground natural gas storage

Nuclear
- ☑ Large light-water reactor
- ☑ Small modular reactor, integral pressurized-water reactor
- ☑ High-temperature gas cooled reactor/ Very high temperature gas-cooled reactor

Solar
- ☑ Concentrating solar power
- ☑ Utility-scale photovoltaic
- ☐ Rooftop photovoltaic solar

Storage
- ☑ Hydroelectric pumped storage
- ☐ Compressed air energy storage

Water
- ☑ Added output from existing hydropower dams
- ☑ New output from existing non-powered dams
- ☐ In-stream hydrokinetic energy
- ☐ Tidal hydrokinetic energy
- ☑ Wave energy

Wind
- ☑ Onshore wind turbines
- ☑ Offshore wind turbines

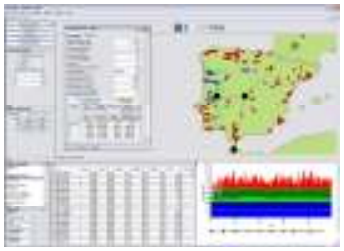
Planned suitability models

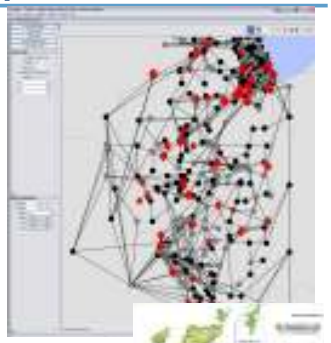
Planned reports based on inventory, or basic resource

☑ **Completed suitability models and reports - available on web site**

Argonne Works with Private Sector and Regulatory Agencies on Electricity Market Analysis (Some Examples)

- Illinois Power Agency
  - Support of annual procurement process





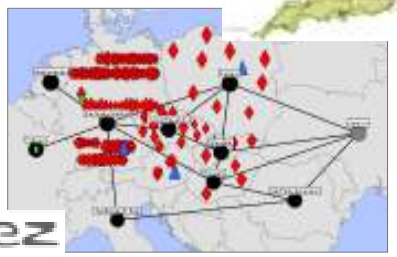
- Deloitte Eastern Europe and Czech Regulator
  - Analysis for Central Europe with detailed representation of the Czech Republic

- Portuguese Power Company (EDP), Transmission Company (REN), and Energy Regulatory Office (DGGE)

- EDF: Joint activity by Argonne and EDF Research Department
  - Phase 1 (short-term issues)
  - Phase 2 (long-term investment issues)

EDF
CHANGER L'ÉNERGIE ENSEMBLE

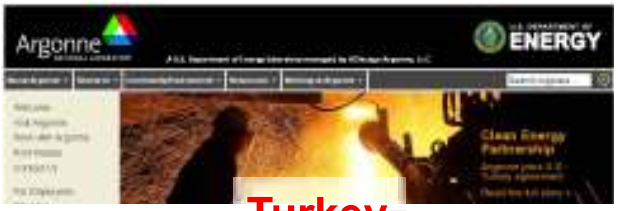
- Recent engagement with GDF
  - Purchased EMCAS, received training in 2011
  - Model implementation initiated in 2012



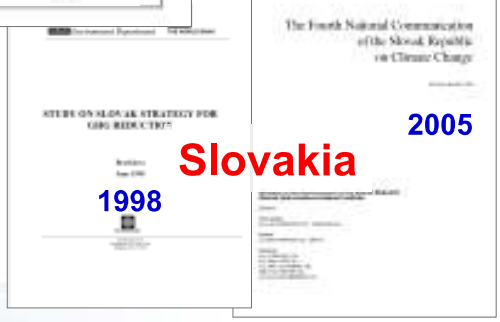
GDF SUEZ
BY PEOPLE FOR PEOPLE

Argonne Model Training and Transfer has Made a Worldwide Impact

- Analysts around the world use our models to conduct energy and climate policy studies
  - Funded by the World Bank, USAID, UNDP, IAEA, etc.
- Recent and ongoing model implementations for energy forecasting, UNFCCC reporting requirements, CO2 national allocation plans
  - Albania, Belarus, Bulgaria, Croatia, Czech Republic, Greece, Hungary, Latvia, Lithuania, Moldova, Poland, Portugal, Romania, Slovakia, Turkey, Ukraine

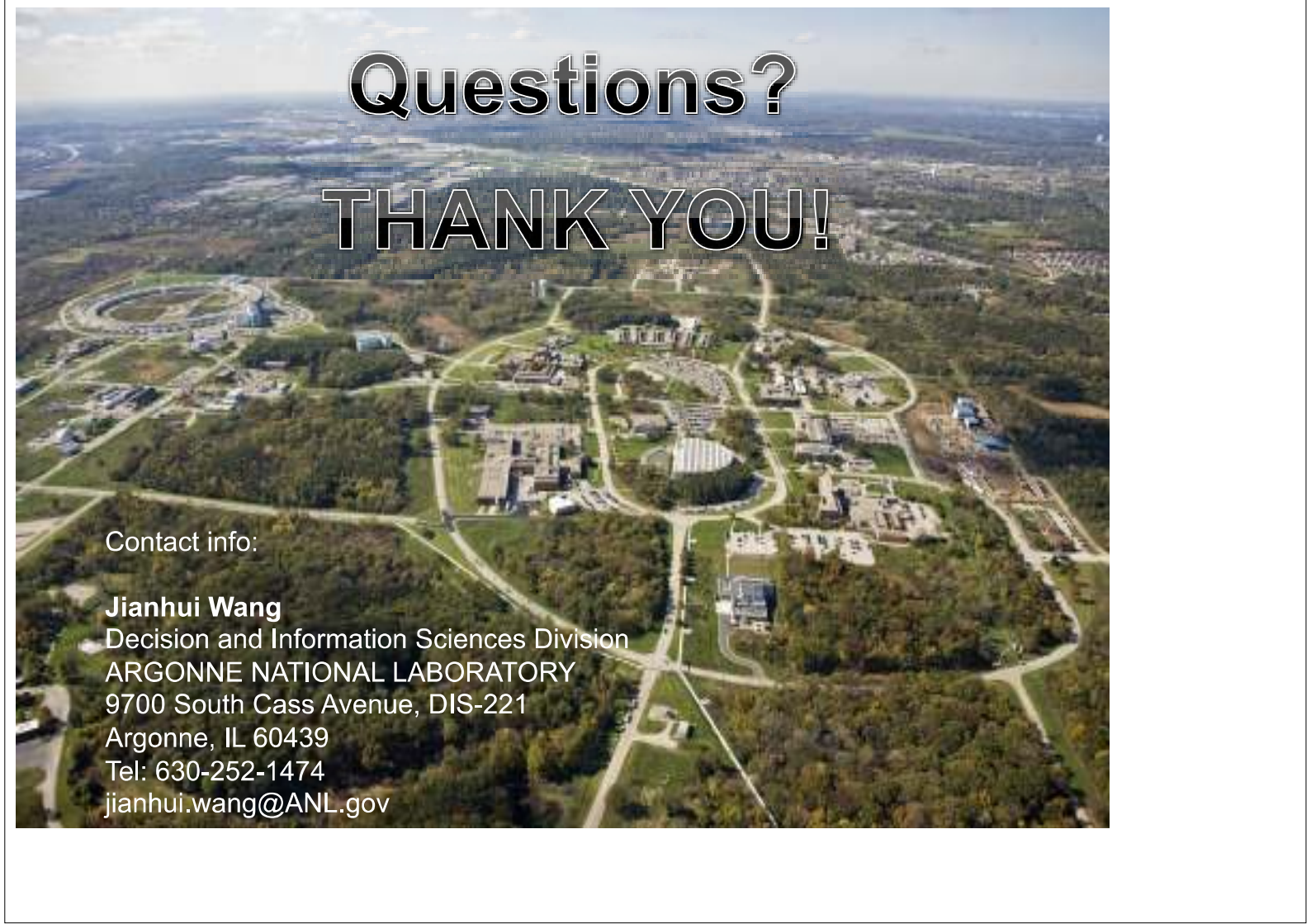


Turkey



Conclusion

- We have extensive technology and analysis capabilities in the energy and power domain
- We are a recognized center for training and technical support for energy and power market analysis
- We have extensive experience in partnering and working with federal, private sector, and academic partners



Contact info:

Jianhui Wang
Decision and Information Sciences Division
ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue, DIS-221
Argonne, IL 60439
Tel: 630-252-1474
jianhui.wang@ANL.gov