Energy Assurance with Renewable Generation

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Outline

- A quick introduction
- Renewable energy outlook
- Variable generation and associated challenges
  - Ramping rates and ranges
  - Variability and mitigation
  - Impact on system stability
- Impact and sizing of storage
- ERiSe research on renewable integration
- Concluding remarks

Introduction

- Director, ERiSe (**E**nergy **R**el**i**ability & **Se**curity) Laboratory at MSU
- Experience: ~19 years academic; 5 years industry and consulting
- Known for my contributions to reliability and reliability-based planning
  - Co-authored a text book on grid reliability and an IEEE Standard on reliability reporting
  - Elected IEEE Fellow for contributions to the development of power system reliability methods

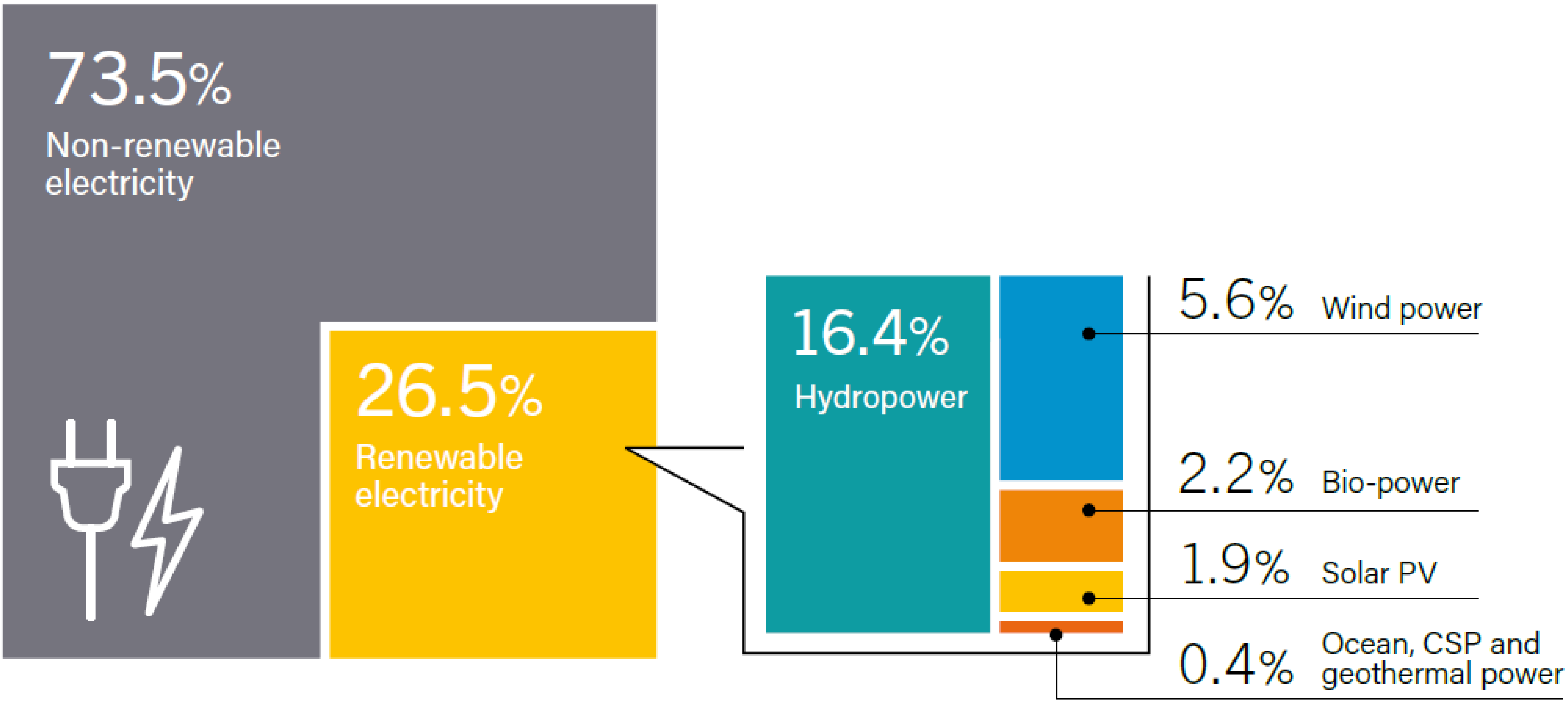
ERiSe Research

- Research Mission:
  Energy assurance. We develop innovative systemic approaches to facilitating secure and reliable energy delivery solutions.
- Research Sponsors:
  DOE, ARPA-E, NSF, National labs, Utilities
- Where our Ph.D. alumni go:
  - 4 in U.S. academia, 2 in National Labs, 1 in Schweitzer Engineering Labs, 1 in GE Grid Solutions
- Recent and ongoing work:
  - Energy assurance with renewable generation
  - Assistance from grid-scale storage
  - Microgrid architecture

Students Who Have Contributed to this Body of Work

- Prior:
  - Dr. Mallikarjuna Vallem, PNNL
  - Prof. Mohammed Benidris, U of Nevada – Reno
  - Prof. Nga Nguyen, U of Wyoming, Laramie
  - Prof. Salem Elsaiah, SUNY Bronx
  - Prof. Samer Sulaeman, Tenn State U, Nashville
  - Dr. Yuting Tian, Argonne National Lab
- Present:
  - Saleh Almasabi
  - Atri Bera

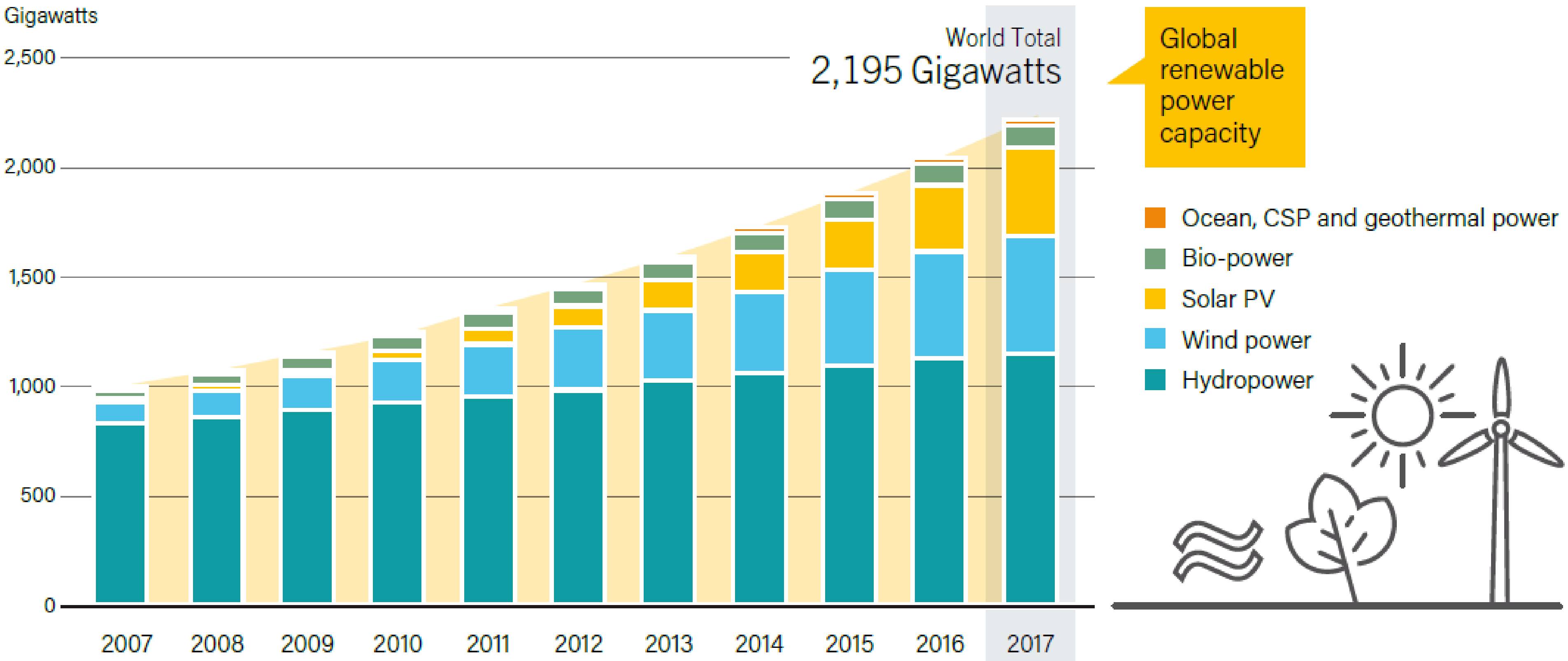
Renewables in Worldwide Energy Use



Based on installed capacity of renewable energy sources at the end of 2017.

Source: *Ren 21: Renewables 2018 Global Status Report.*

Growth of Renewables Over Last Decade



Source: *Ren 21: Renewables 2018 Global Status Report.*

Social and Political Factors Affecting the Energy Outlook

- Two phenomena that have been influenced by politics and health concerns:
  - Increasing pressure to reduce coal generation, and
  - Fear of nuclear generation following the Fukushima event.
- The design and operation of electricity markets, with their focus on economic and financial instruments, have undermined operational efficiency from an engineering perspective.
- Discovery of shale gas in America has strongly influenced the resource mix and redistributed the global “petroleum economy”.

Operational Challenges in RE Integration

- Resource variability (intermittency)
  - Increased uncertainty (uncertainty of wind + uncertainty of load)
  - Increased need for ramp rate
  - Increase in overall ramp range
- Reduction of regulation capability and increased need for frequency regulation
- Decrease of base load and impact on base-load generators

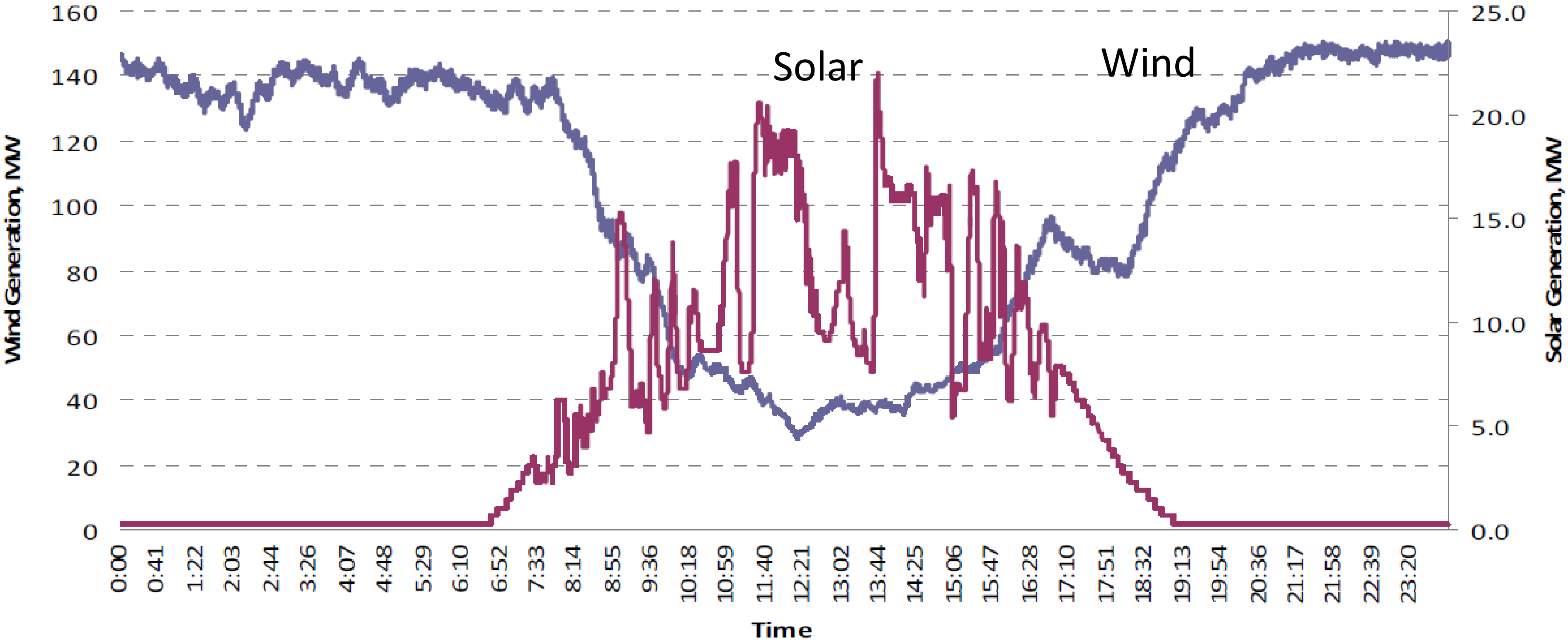
Variability of Wind and Solar Power

- Wind and solar are both considered variable (or non-

Capacity value of a resource is the amount of load it can reliably support. Different ways of understanding it:

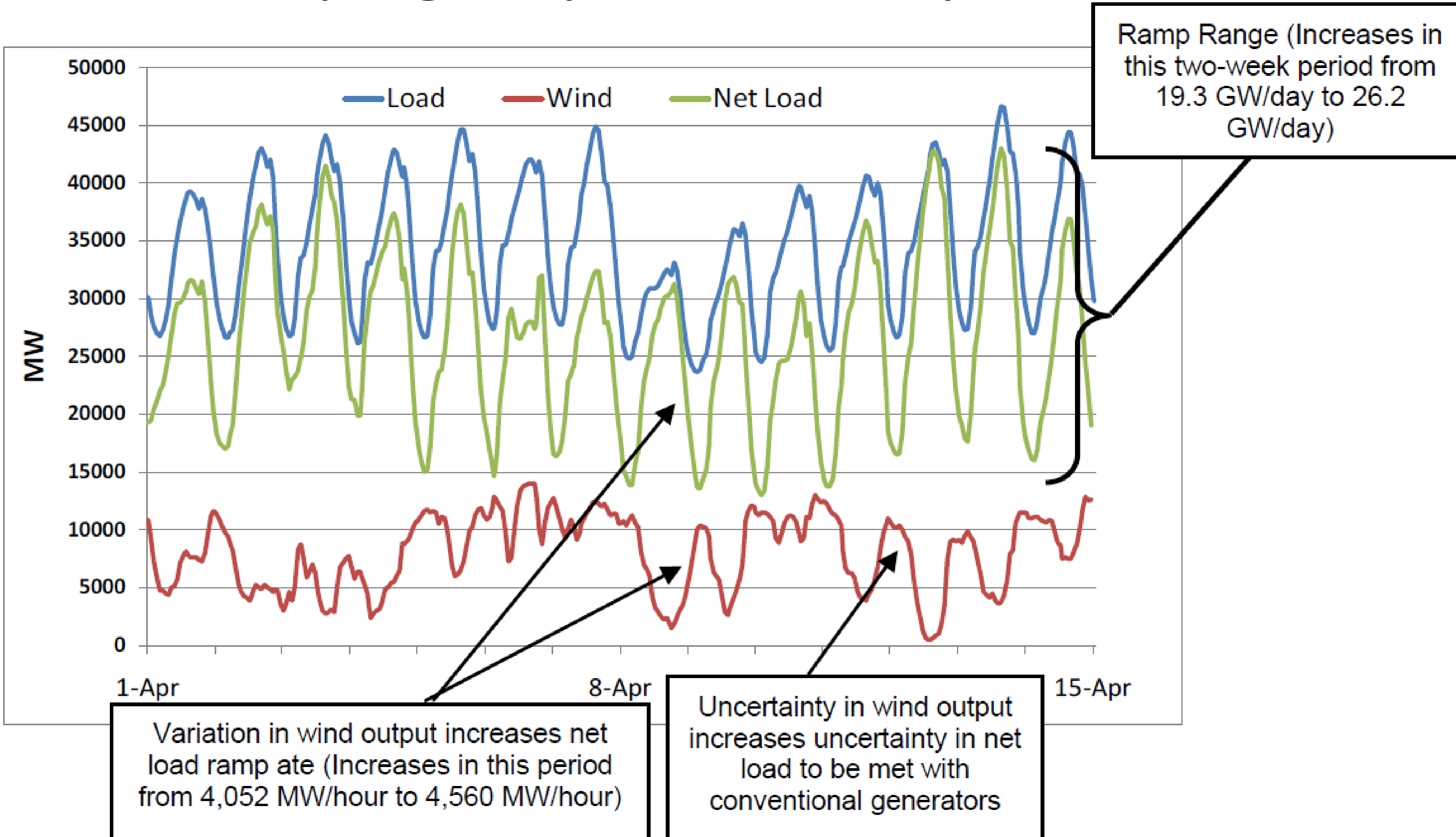
1. What is the size of a dispatchable resource that would replace the wind farm and provide the same level of system reliability?
2. How much additional load can the system with the wind farm support at the same level of reliability it had without the wind farm (and additional load)? (ELCC)

Variability – An Illustration



Wind and Solar generation over a 24-hour period from a 150 MW Wind Farm and a 24 MW Solar PV Farm in California. GE Report to California ISO, *Integration of Renewable Resources at 20% RPS*.

Ramping Requirement Explained



NREL, *The Role of Energy Storage with Renewable Electricity Generation*

Means of Variability Mitigation

- Options for variability mitigation
  - Temporal diversity — storage
  - Geospatial diversity — aggregation
  - Flexible loads — generation following
- Technology and cost
  - Storage is expensive
  - Aggregation requires significant (and costly) transmission upgrades
  - Need “smart grid technologies” to monitor and control

Challenges and Opportunities Using Storage

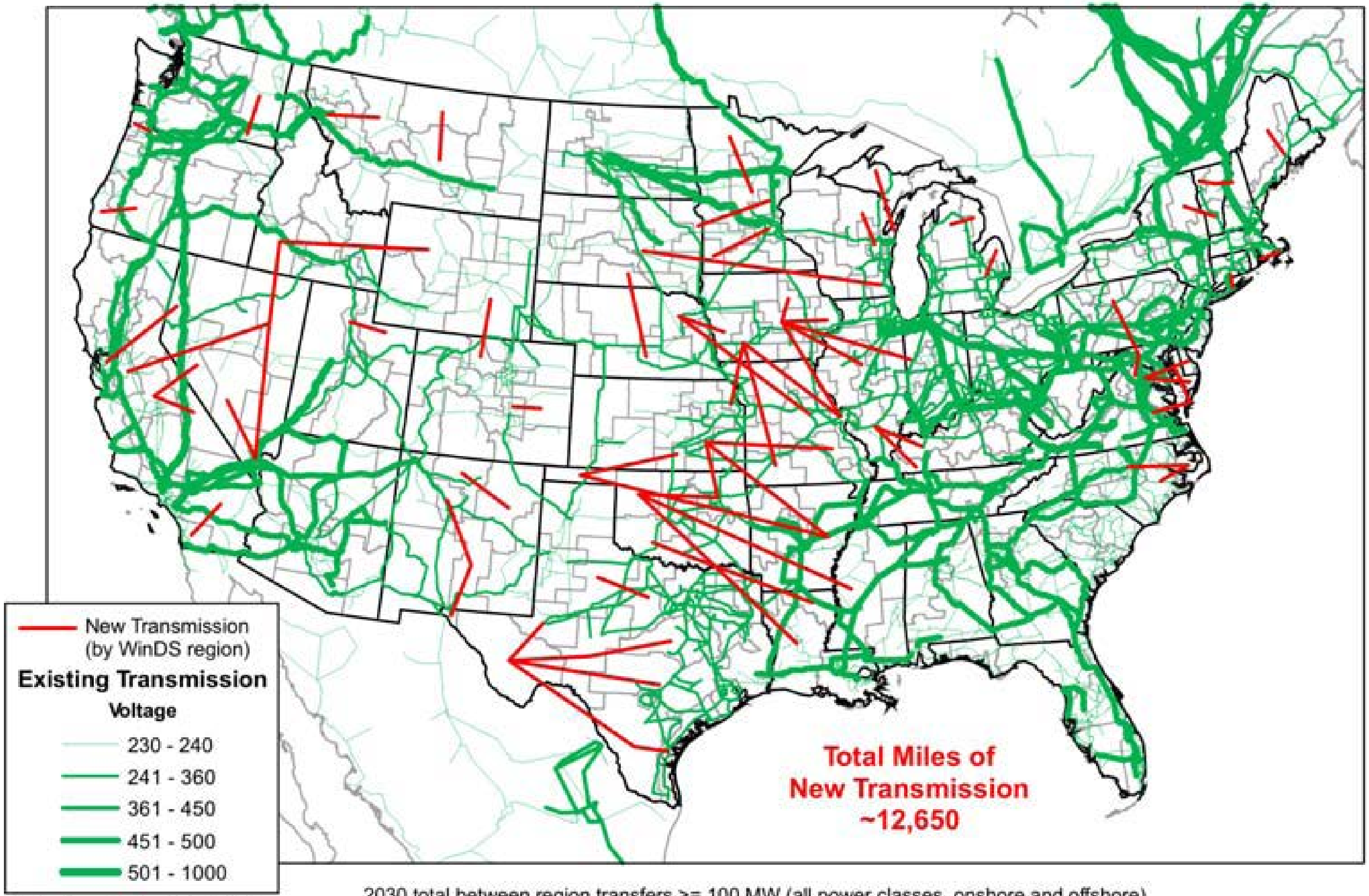
- The only economical grid-scale storage technology available today is pumped hydro.
- There is little opportunity for new pumped hydro facilities; some existing installations are being decommissioned.
- Pumped hydro is not always convenient for use with variable resources due to differences in scale.
- Recent times have seen enormous investment in grid-scale storage technologies.

Comparison of Energy Storage Systems

Systems	Maturity	Unit Costs	Efficiency (charging/ discharging)	Typical Nominal power	Discharging at Nominal Power
CAES	Mature	700 $/kW	60%-70%	0.1-400 MW	hours
Flywheel	Mature and commercial products	1300 $/kW	90%	0.01-2 MW	secs-mins
SMES	Prototype units	700 $/kW- 4000$/kW	90-95%	10-100 MW	secs-mins
Battery	Mature and commercial products	1100 $/kW- 3100 $/kW	70-90%	0.001-10 MW	mins-hours
Supercapacitor	Prototypes	$30 (per cell)	80-95%	0.01-1 MW	secs-mins
Pumped Hydroelectric	Mature	2300 $/kW	80%	0.1-1 GW	hrs-days

Transmission Expansion

2030 - New Transmission Lines - WinDS Region Level - Simplified Corridors >= 100 MW



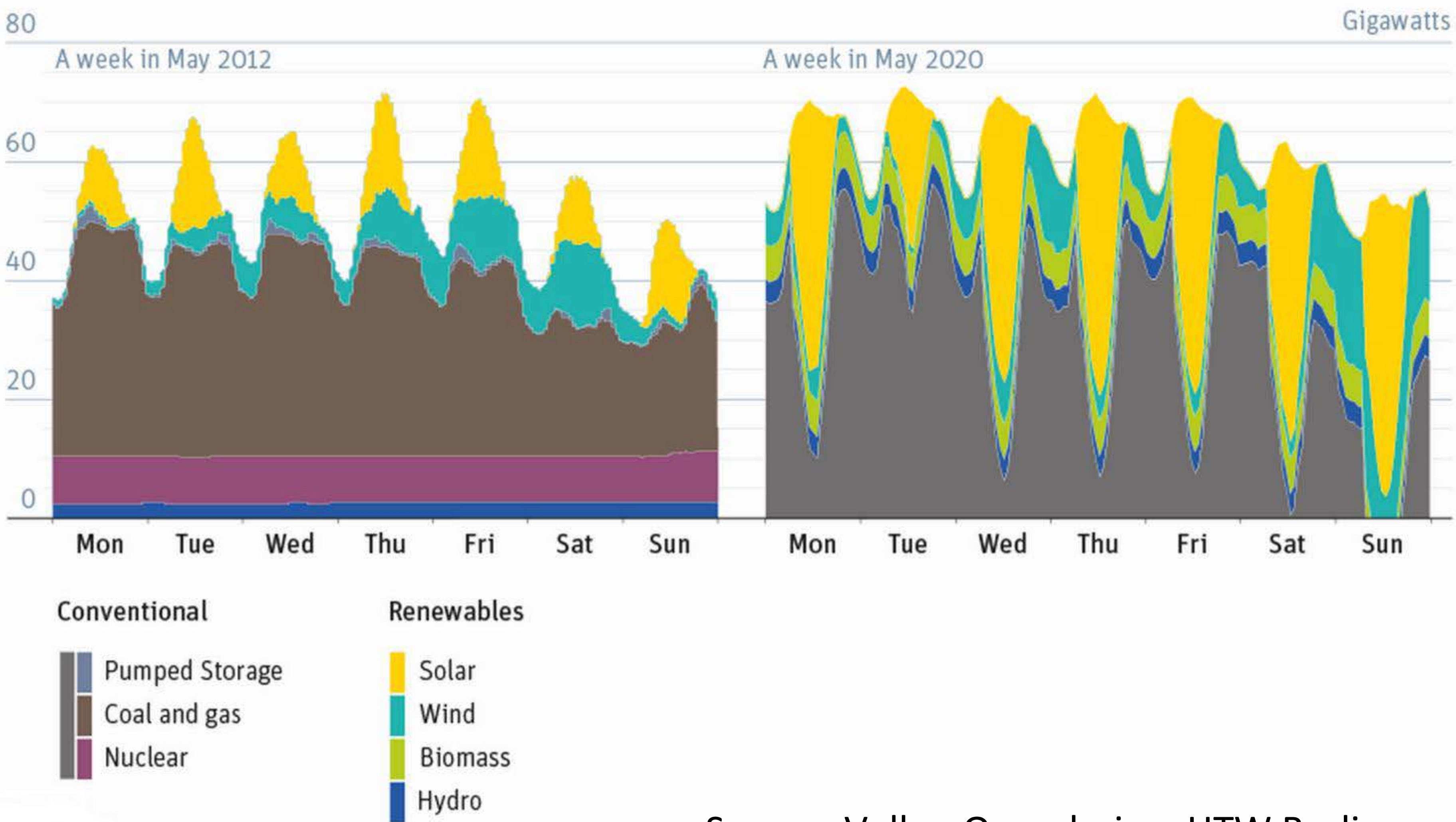
Existing Transmission Data: POWERmap, powermap.platts.com ©2007 Platts, A Division of The McGraw-Hill Companies

2030 total between region transfers >= 100 MW (all power classes, onshore and offshore), visually simplified to minimal paths. Arrows originate and terminate at the centroid of the region for visualization purposes; they do not represent physical locations of transmission lines.

20% Wind 06-19-2007

Over 12,000 miles of new transmission, costing about $20 Billion, is expected to be needed to meet the target of 20% wind by 2030. (DOE, *20% Wind by 2030*)

Generation Following



Source: Volker Quaschning, HTW Berlin

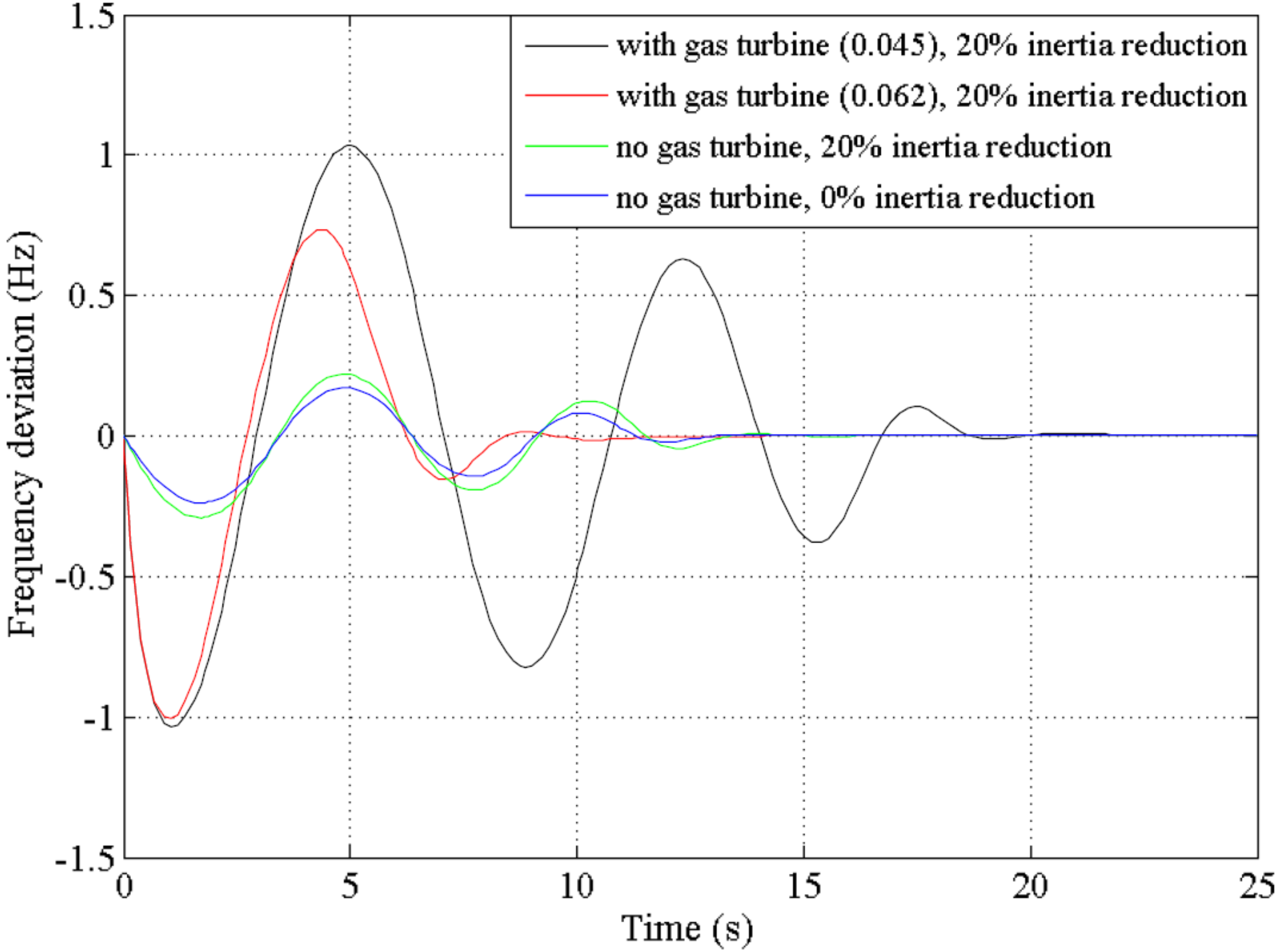
Other Issues in Integration of Variable Generation

- Land use and quality of life
- Collection
- Reactive power issues
- Power quality issues
- Low voltage ride through (LVRT) issues
- Stability concerns
- Turbine reliability (one study reports ~6 outages per year with downtime of ~60 hours)

Frequency Regulation Issues

- Stable and secure operation of the grid relies considerably on the rotational inertia and governor characteristics of conventional turbine generators.
- Variable sources contribute very little to inertia.
- The short-term variation in variable generation often increases the regulation burden borne by conventional generators like gas turbines.
- There is an opportunity for using fast-acting power electronic controls at the point of interface of variable resources to contribute to dynamic stability.

Frequency Regulation with Reduced Inertia



Frequency Regulation with Reduced Inertia

Observations:

- With inertia reduction:
  - Frequency excursion is larger
  - Recovery time is longer
- Gas turbines, which are being increasingly deployed to help with ramping capability, exacerbate the frequency excursion.

For more such case studies please see N. Nguyen and J. Mitra, “An Analysis of the Effects and Dependency of Wind Power Penetration on System Frequency Regulation,” *IEEE Trans. Sustain. Energy*, 7(1): 354–363, Jan 2016.

Sizing Storage for Reliability

Problem:

- Can we determine the amount of storage required to meet a specified level of reliability?
  - Power capacity
  - Energy capacity
- Can we determine how much storage we need to mitigate variability?

Three Scenarios

- We shall systematically develop the solution by going through three scenarios:
  - Isolated system
  - Island-capable system
  - Grid-connected system

Scenario 1: Isolated System

- Consider a system with availability A_0 for wh lity to A
- The of sto reli

Availability is defined as the *probability* that a component or system is performing its *designated functions* at a *given point in time* under the conditions in which it was *designed to operate*.

J. Mitra, "Reliability-based Sizing of Backup Storage," *IEEE Trans. Power Syst.*, 25(2): 1198–1199; 2010.

Storage Sizing Approach

- Define the unavailability reduction ratio

$$\alpha = \frac{1 - A_1}{1 - A_0}$$

- Denote:

S_F eve ... e failed

L eve ... es failure of ...

Example:

If A_0 = 0.999 and A_1 = 0.9999, then $\alpha = 0.1$

t_A length of time for which the additional storage can support the load in the event of failure of the existing resources

R random variable representing the down time (outage duration) of the existing system

$f_R(r)$ probability density function of R

Storage Sizing (continued)

L occurs when down time with existing resources exceeds t_A

The probability of L is given by

$$P\{L\} = P\left[\{R > t_A\} \cap S_F\right]$$

$$= P\{R > t_A\} P\{S_F\}$$

$$= \left(\int_{t_A}^{\infty} f_R(r)\,dr \right) P\{S_F\}$$

$1 - A_1$

$1 - A_0$

Storage Sizing (continued)

- But $P\{L\} = 1 - A_1$ and $P\{S_F\} = 1 - A_0$
- Hence

$$\int_{t_A}^{\infty} f_R(r)dr = \alpha \qquad (1)$$

- The solution to this equation yields the *energy capacity* of the additional storage required
- The *power capacity* is given by the size of the load—P_L

Exponentially Distributed Down Time

$$f_R(r) = \frac{1}{\bar{r}} \exp\left(-\frac{r}{\bar{r}}\right), \quad r \geq 0$$

$$\text{then } t_A = -\bar{r} \ln \alpha$$

Example:

If $\alpha = 0.1$ and $\bar{r} = 4$ h,

then $t_A = 9.21$ h

Weibull Distributed Down Time

$$f_R(r) = \frac{\beta r^{\beta-1}}{r'} \exp\left[\left(\frac{r}{r'}\right)^{\beta}\right], \quad r \geq 0$$

where $\quad r' = \dfrac{\bar{r}}{\Gamma(1+1/\beta)}$

then $\quad t_A = r'(-\ln\alpha)^{1/\beta}$

Lognormal Distributed Down Time

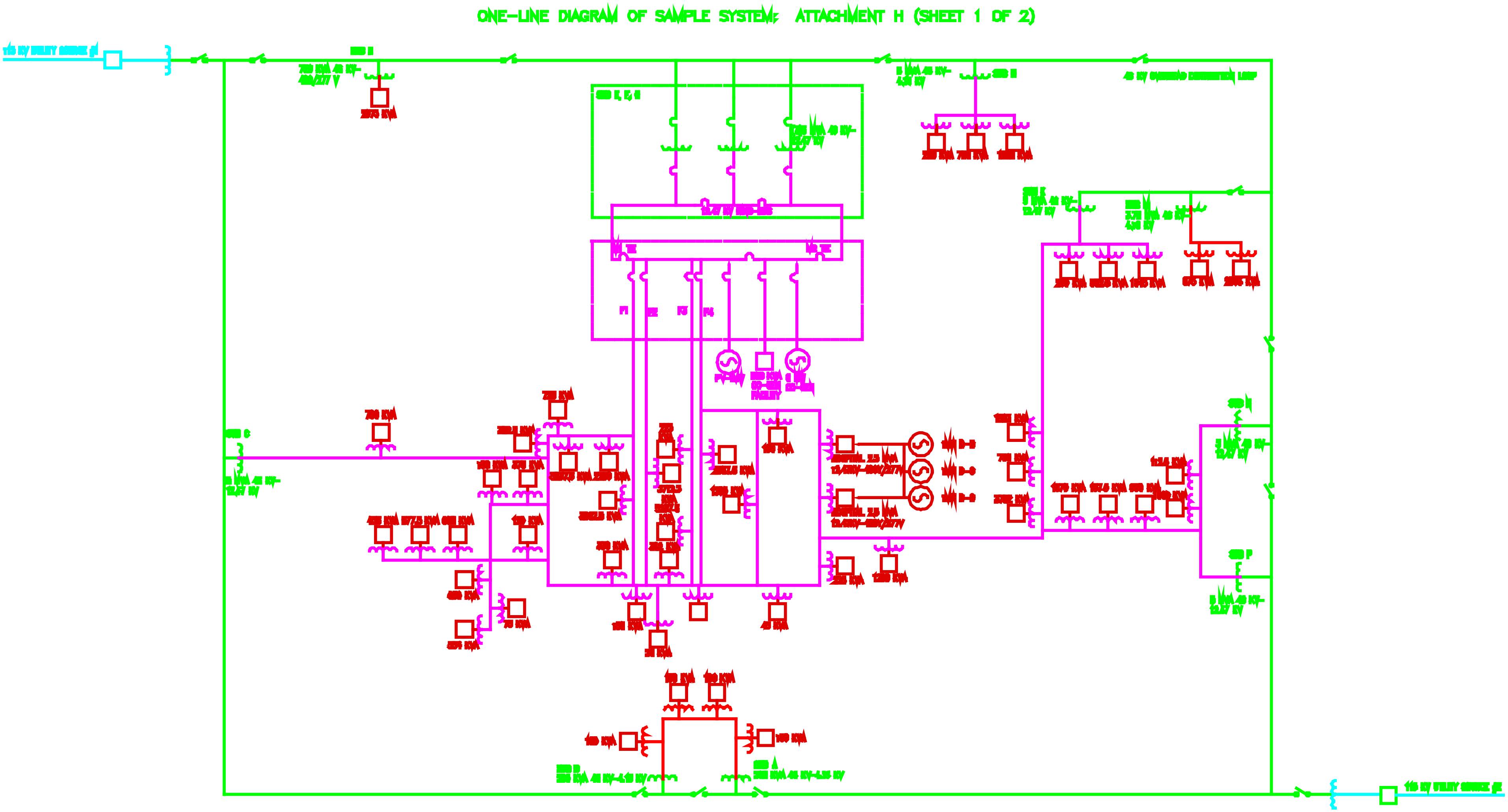
$$f_R(r) = \frac{1}{\sqrt{2\pi}\beta r}\exp\left[-\frac{1}{2\beta^2}\left(\frac{\beta^2}{2}+\ln\frac{r}{\bar{r}}\right)^2\right], \quad r \geq 0$$

then $$t_A = \bar{r}\exp\left(\beta z - \frac{\beta^2}{2}\right)$$

where $$\Phi(z) = 1-\alpha = \int_{-\infty}^{z}\frac{1}{\sqrt{2\pi}}\exp\left(-t^2/2\right)dt$$

J. Mitra, "Reliability-based Sizing of Backup Storage," *IEEE Trans. Power Syst.*, 25(2): 1198–1199; 2010.

Scenario 2: Island-capable System



System Characteristics

- On-site resources include PV and standby generators
- Target reliability can be defined based on system need; example: determine the storage required at different parts of system to increase availability by an additional ‘9’

J. Mitra and M. R. Vallem, “Determination of Storage Required to Meet Reliability Guarantees on Island-Capable Microgrids with Intermittent Sources,” *IEEE Trans. Power Syst.*, 27(4): 2360–2367; 2012.

Solution Strategy

- Use sequential Monte Carlo Simulation to determine distribution of down time
- Use

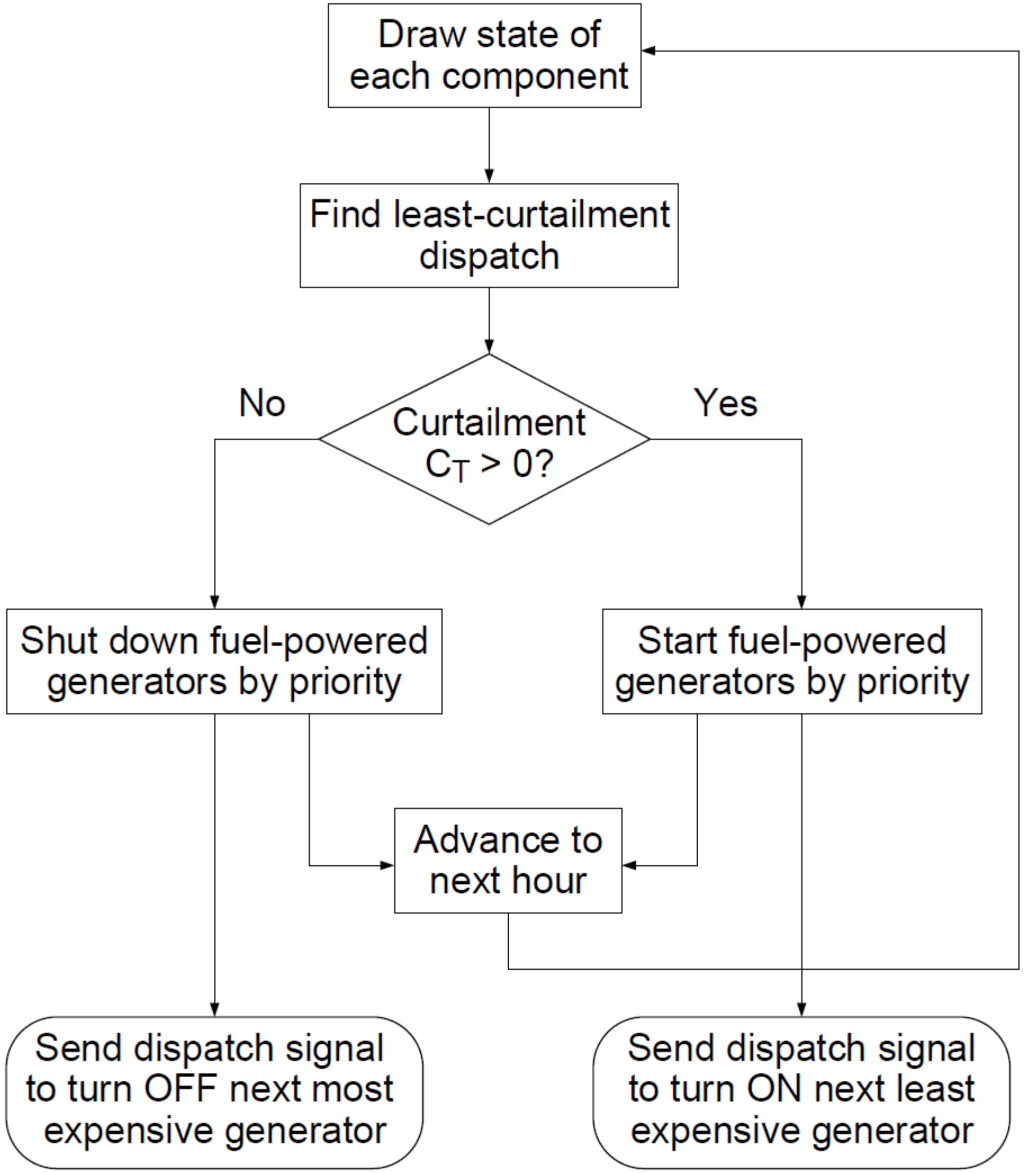
$$\int_0^{t_A} r f_R(r)\,dr = (1-\alpha)\bar{r} \qquad (2)$$

  to determine t_A at every node. This can be shown to be approximately equivalent to (1) [see Mitra & Vallem, 2012]
- Assign storage based on loads and t_A values

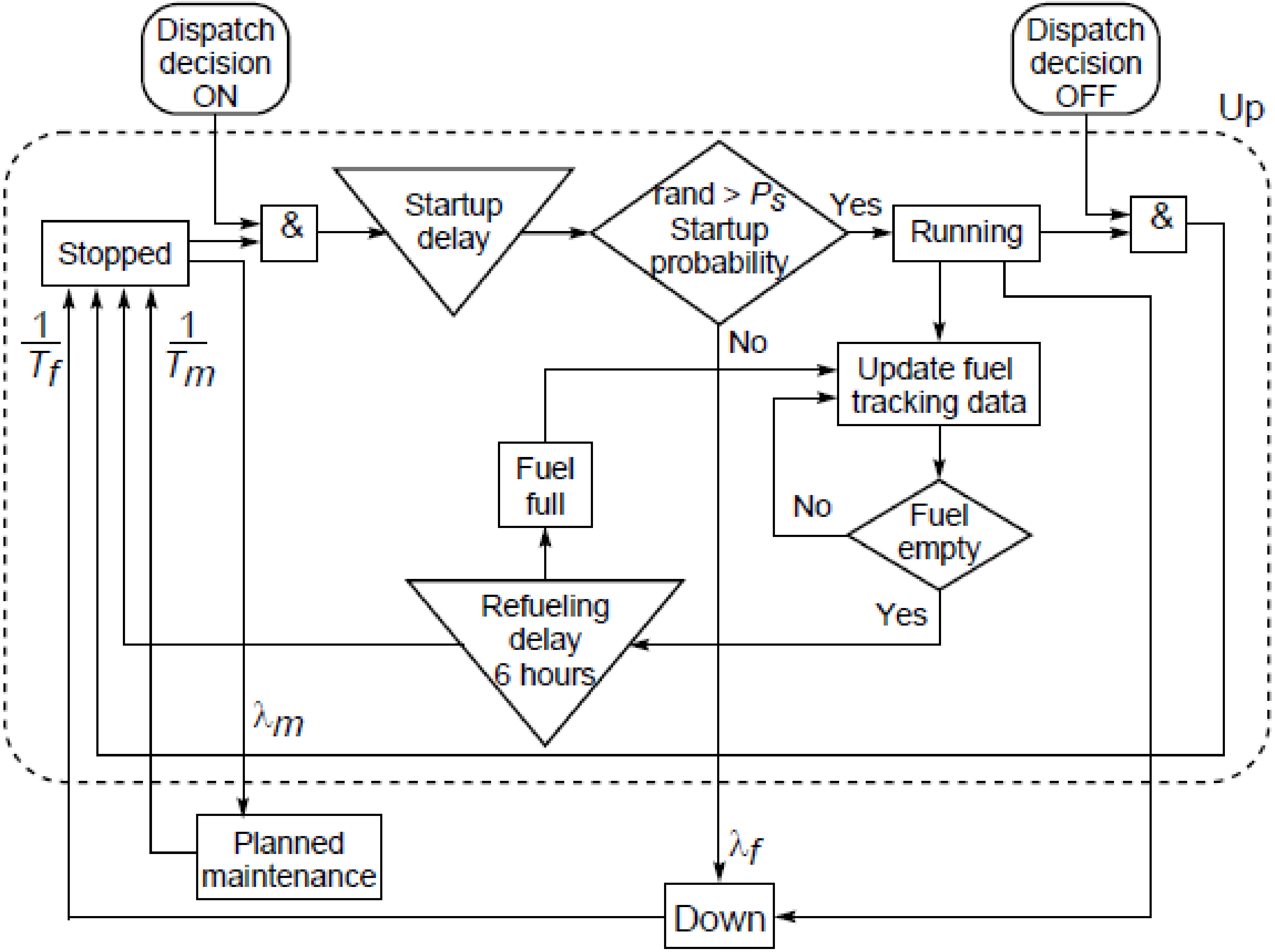
System Modeling

- Consider islanded operation
- (Grid ties can be modeled as generators with same availability as supply reliability)
- All components considered two-state
- Transportation model assumed for network flows
- Use hourly load curve and insolation curve
- PV panels generate whenever available, following insolation curve
- On-site backup generators follow prescribed dispatch and operation logic

Generator Dispatch Logic



Generator Operation Logic



Reliability Improvement

Bus	LOLP without augmentation	t_A (hours)	Storage augmentation (MW)	LOLP with augmentation
3	0.000706	28.34	0.1885	0.0000868
4	0.000103	5.16	0.293	0.00000141
5	0.41681	16.95	4.323	0.0280723
6	0.323866	13.47	1.2	0.000998
8	0.000019	14.19	0.639	0
9	0.141279	7.32	2.062	0.022622
10	0.333059	14.53	1.588	0.0236499
11	0.3581850	13.38	2.466	0.0252796
12	0.0121722	9.78	0.228	0.0038562
22	0.330202	14.2	1.44	0.0236543
System	0.781381	11.71	14.428	0.075569

Scenario 3: Grid-connected System with Wind Farm

Problem

We want to use storage to “firm up” the wind generation.

– How do we quantify the notion of “firming up”?
– How do we apply the method developed?

Questions

- How do we specify the target availability?
- How do we determine *power capacity* (P_L)?
  – No longer equal to the size of the load!

Firming up Wind Generation

- By “firming up” a variable resource, we expect to neutralize its intermittency and variability, thereby causing it to behave like a *dispatchable* resource.
- The target reliability of the system should therefore be the reliability that the system would attain if the wind farm were replaced by a dispatchable generator *with the same nameplate capacity* (as the wind farm).

Approach to Firming Up

Questions

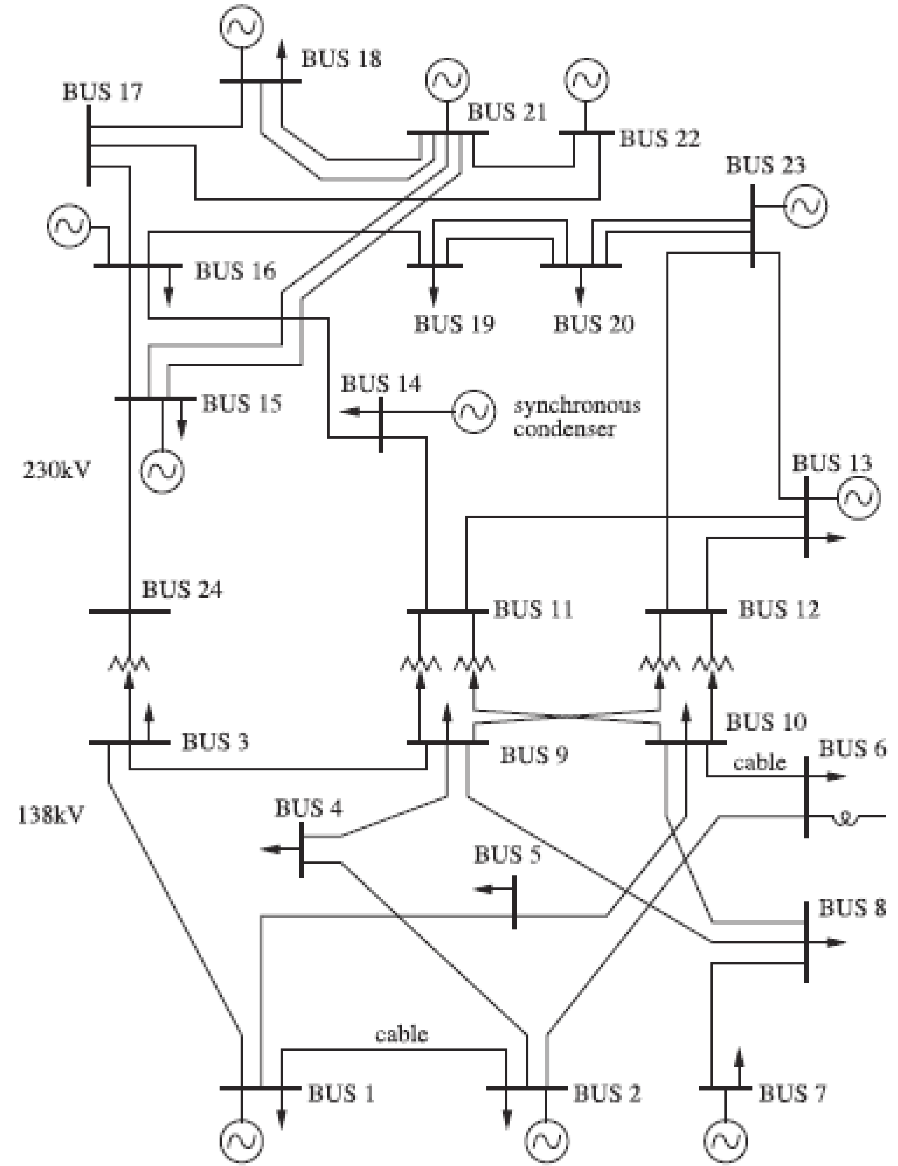
- How do we specify the target availability?
- How do we determine *power capacity* (P_L)?

Answers

- Calculate system reliability by using a dispatchable resource instead of the wind farm (this gives A_1)
- Calculate the capacity value of the wind farm and subtract it from the nameplate rating (the difference gives P_L)

Example

- IEEE Reliability Test System (RTS)
- Augmented with wind farm
  - 200 MW nameplate capacity
  - 100 Vesta V90 turbines, each 2 MW, MTTF 3600 h, MTTR 150 h
  - Correlation coefficient of –0.1059 between hourly wind variation and RTS load



Solution Strategy

- Determine the capacity value of the wind farm
  - From this the power capacity (storage) is found to be 157.5 MW
- For each candidate location, determine reliability by adding a 200 MW conventional generator at that location
  - This helps define the target availability A_1
- For each candidate location, determine system indices by adding the wind farm at that location (in place of the conventional unit)
  - The resulting availability A_0 allows calculation of the unavailability reduction ratio α
  - The sequential simulation data also allows determination of t_A

Results

Bus	Target LOLP (System)	Power Capacity (MW)	α	t_A (h)	LOLP with Storage
18	0.00036	157.5	0.34	8	0.000369
13	0.00039	157.5	0.36	6	0.000415
6	0.00044	157.5	0.40	6	0.000430
10	0.00053	157.5	0.46	5	0.000592
9	0.00057	157.5	0.49	4	0.000584

S. Sulaeman, M. Benidris, Y. Tian and J. Mitra, "Quantification of Storage Necessary to Firm Up Wind Generation," *IEEE Trans. Ind. Appl.*, 53(4): 3228–3236; Jul/Aug 2017.

Comments

- Target buses were identified in this by examining where the wind farm provided the most benefit
- Results were validated by applying Monte Carlo simulation again, with the storage added (and a reasonably detailed model for storage operation)
- Additional considerations may be applied to storage sizing, e.g., float charge levels

Other ERiSe Contributions in RE Integration: Methods

- Sizing of storage for frequency regulation

  N. Nguyen, A. Bera, J. Mitra, "Energy Storage to Improve Reliability of Wind Integrated Systems under Frequency Security Constraint," *IEEE Trans. Ind. Appl.*, 54(5): 4039–4047; Sep/Oct 2018.

- Development of operational constraint resulting from diminution of frequency regulation and inclusion in reliability analysis

  N. Nguyen and J. Mitra, "Reliability of Power System with High Wind Penetration under Frequency Stability Constraint," *IEEE Trans. Power Syst.*, 33(1): 985–994; Jan 2018.

- Development of frequency security constraint for optimal power flow

  N. Nguyen, S. Almasabi, A. Bera, J. Mitra, "Optimal Power Flow Considering Frequency Security Constraint," Proc. *IEEE PowerAfrica 2018*, Cape Town, South Africa, June 26–28, 2018.

Other ERiSe Contributions in RE Integration: Models

- Reliability model of wind farms considering wind variability, turbine failures, and turbine correlations

  S. Sulaeman, M. Benidris, J. Mitra, C. Singh, "A Wind Farm Reliability Model Considering Both Wind Variability and Turbine Forced Outages," *IEEE Trans. Sustainable Energy*, 8(2): 629–637; Apr 2017.

- Refining wind farm reliability model by including correlation between wind speed and turbine availability

  N. Nguyen, S. Almasabi, J. Mitra, "Impact of Correlation Between Wind Speed and Turbine Availability on Wind Farm Reliability," *IEEE Trans. Ind. Appl.*, 55(3); May/June 2019. (available on IEEExplore; doi: 10.1109/TIA.2019.2896152)

Ongoing and Recent Research Projects at ERiSe

- Models for Evaluation and Optimization of Grid-Scale Energy Storage (Sandia National Laboratories)
- Application of Utility-Scale Battery Storage in Power Distribution System (Consumers Energy Corporation)
- Impacts of Power Flow Control in Distribution Systems (Michigan Economic Development Corporation, 2017)
- A Lyapunov function based remedial action screening tool using real-time data (DOE, 2012–15)

  Partners: FSU, LANL, SCE, LCG
- Transformer-less UPFC for wind and solar power transmission (ARPA-E, 2012–15; PI: F. Z. Peng)
- Impact of Increased Renewable Generation Resources Across the MISO Zone 7 Footprint (Consumers Energy Corporation, 2014–15)

L-RAS Project at ERiSe

"A Lyapunov function based remedial action screening tool using real-time data"

- Uses direct (Lyapunov/energy function) method for rapid contingency screening
- Updates contingencies with real-time data
- Recommends stabilizing remedial actions
- Partners:
  - Florida State University
  - Los Alamos National Lab
  - Southern California Edison
  - LCG Consulting (software vendor)

Vision for Energy Assurance

- Over the last two decades I have conducted research on all aspects of energy assurance:
  - Strategic planning: resource adequacy, fault-tolerant sensing/monitoring, stable and secure architecture
  - Tactical responses: absorption, adaptation, restoration
- I am now working on extending this to a broader and more multi-disciplinary and multi-infrastructure framework encompassing energy, water, and transportation.

Concluding Reflections

- Renewable resources present complex challenges to energy assurance.
- Competitive markets and "smart grid" technologies are additional elements that push system operation closer to stability and reliability margins.
- Creative ideas are emerging but they will need support from regulating bodies.
- In the meantime, there is tremendous thrust in deployment of storage technologies and transmission upgrades (including flow control technologies).
- Aspects of energy assurance are intertwined with concerns related to natural resources, sustainability and the environment.

Thank You!