

**Building the Power Grid
of the Future:
Resource Adequacy
Issues**

Minnesota Clean Energy Advocates
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Themes
<ul style="list-style-type: none">• We have well-developed metrics for RA• However, the changing nature of electricity supply – and to some extent, demand – will challenge resource assessments• <i>At very high RE penetrations (~80%) long-term data and long-term weather/climate forecasts will be critical</i>• Transmission can avoid capacity builds• Emergency reserve in some form is likely needed – will DR be adequate?
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Two aspects of reliability

- 1. What/how much/what kind do I need to build to ensure the power system can be operated reliably and economically? (Planning, investment time frame)**
- 2. How do I operate the system that I've been given in a reliable and cost-effective manner, even when things go wrong? (Operational – Debbie has solved that one)**
- 3. Note that (1) is necessary, but not sufficient, for (2)**

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Why is reliability different than coffee?

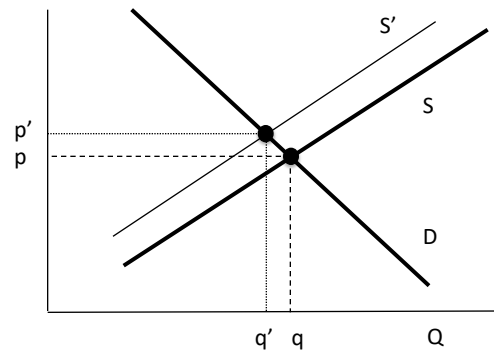
- **Coffee supply/demand, and thus price, fluctuates.**
 - Consumers may choose tea instead
- **Electricity is sold to consumers via a tariff, administered by PUC/PSC (in most cases)**
- **Price signals are therefore muted, and likely almost non-existent**
- **Obligation to serve**
- **Electricity as a “need” for heating, lights, well-being**
- **“Outage for one is outage for all”**
- **Currently we can’t sell 2 different levels of reliability to customers on the same feeder**
- **Electricity is regulated, need of society**
- **Electricity has a long investment cycle (but getting shorter)**

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What about coffee?

- **Shortage caused by reduction in supply causes price increase, reduction in quantity demanded (voluntary)**

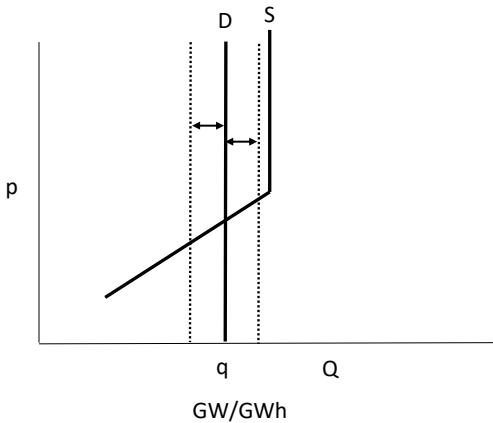


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Variations in Demand

- Retail price usually fixed by tariff

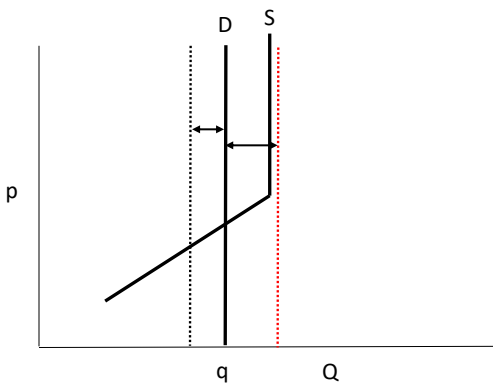


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Shortage: Loss of load

- No equilibrium price exists – so establish LOL criterion



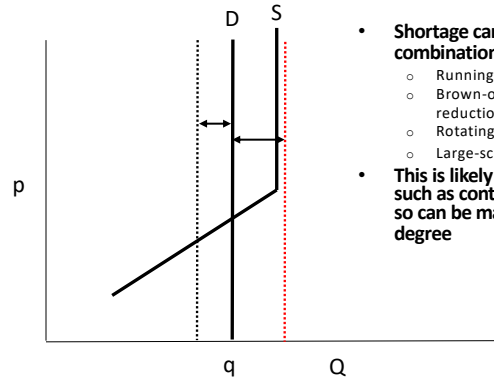
Loss of load probability (LOLP) is predicated upon this gap between supply and demand. In principle, this could be fixed by fully price-responsive demand, but various complications prevent this

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Shortage: Loss of load

- No equilibrium price exists – so establish LOL criterion



- Shortage can consist of combination of
 - Running with low/no reserves
 - Brown-out (voltage reduction)
 - Rotating black-out
 - Large-scale blackout
- This is likely not a fast event such as contingency reserve, so can be managed to some degree

Loss of load probability (LOLP) is predicated upon this gap between supply and demand. In principle, this could be fixed by fully price-responsive demand, but various complications prevent this

For a somewhat deeper dive into market-related issues see Milligan, M.; Frew, B.; Clark, K; Bloom, A. (2017). Marginal Cost Pricing in a World without Perfect Competition: Implications for Electricity Markets with High Shares of Low Marginal Cost Resources. NREL Technical Report NREL/TP-6A20-69076 . December. Available at <https://www.nrel.gov/docs/fy18osti/69076.pdf>

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Traditional Approach to RA

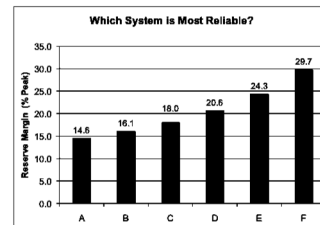
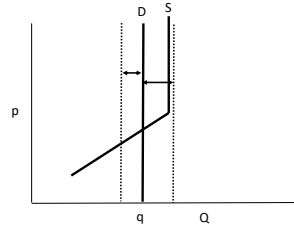
- Often measured based on installed capacity, peak load, and a planning reserve
- A fixed planning reserve margin (PRM), often in a range of 12-15% above forecasted peak demand, was common
- However this isn't a true reliability measure:
 - How often does it fail?
 - How long are failures?
 - Or...how successful are we in keeping the lights on?



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Resource Adequacy: From PRM to LOLP

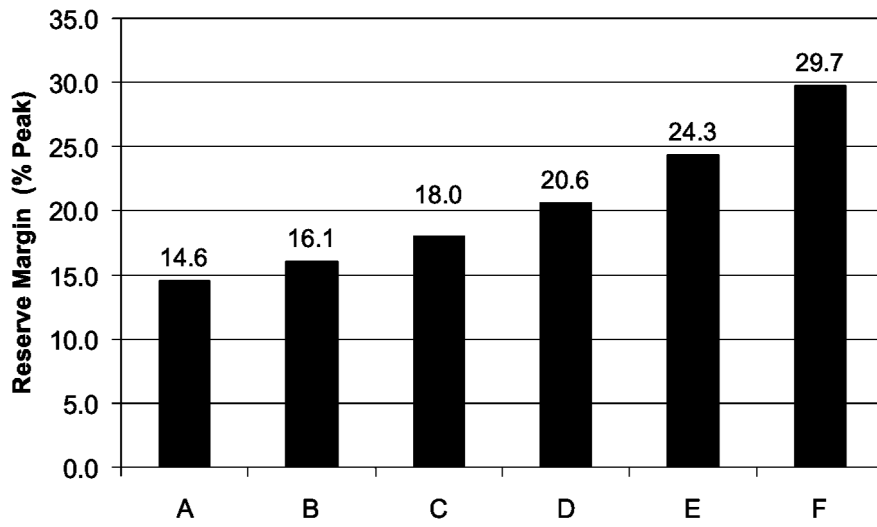
- *How adequate is adequate enough?*
- Quantify the number of times system will be inadequate – often measured as hours/year or days/year (1d/10y \approx 99.97%)
- Probability that demand will exceed supply: Loss of load probability (LOLP)



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Which System is Most Reliable?



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Loss of load probability (LOLP)

- Reliability metric, first used in 1940's
- LOLP in a resource adequacy context = probability that demand will exceed supply
- Based on risk calculations that account for failure rates of all resources, compiled into a "capacity outage probability table" COPT

Determination of Reserve Capacity by the Probability Method
 G. Calabrese
 Transactions of the American Institute of Electrical Engineers
 Year: 1950 | Volume: 69, Issue: 2 | Journal Article | Publisher: IEEE
 Cited by: Papers (22)
 ▶ Abstract  (1917 Kb) 

Determination of Reserve Capacity by the Probability Method Effect of Interconnections
 G. Calabrese
 Transactions of the American Institute of Electrical Engineers
 Year: 1951 | Volume: 70, Issue: 1 | Journal Article | Publisher: IEEE
 Cited by: Papers (7)
 ▶ Abstract  (479 Kb) 

Generating Reserve Capacity Determined by the Probability Method
 Giuseppe Calabrese
 Transactions of the American Institute of Electrical Engineers
 Year: 1947 | Volume: 66, Issue: 1 | Journal Article | Publisher: IEEE
 Cited by: Papers (54)
 ▶ Abstract  (2547 Kb) 

Probability method of finding reserve capacity-effect of interconnection
 Giuseppe Calabrese
 Electrical Engineering
 Year: 1951 | Volume: 70, Issue: 10 | Journal Article | Publisher: IEEE
 ▶ Abstract  (874 Kb) 

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How is this probability calculated?

- We use forced outage rates (EFORd) – the probability that a resource will fail – and combine into a loss of load probability (LOLP) for the system at each hour
- The "capacity outage probability table" (COPT) is developed to calculate the LOLP

Assume 6-50 MW units, each with FOR=.08

	MW-Out	MW-In	Probability	LOLP
0	0.0000	300.0000	0.60635500	1.00000000
1	50.0000	250.0000	0.31635913	0.39364500
2	100.0000	200.0000	0.06877372	0.07728587
3	150.0000	150.0000	0.00797377	0.00851214
4	200.0000	100.0000	0.00052003	0.00053838
5	250.0000	50.0000	0.00001809	0.00001835
6	300.0000	0.0000	0.00000026	0.00000026

Monte Carlo methods are also often used and are driven by similar data sets.

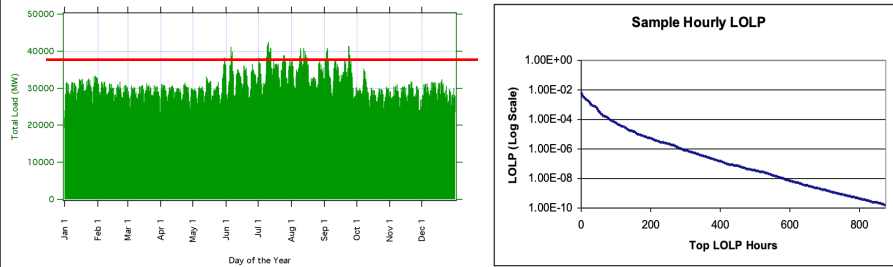
$$\text{EFORd} = \text{probability unit will fail completely when needed}$$

$$= (\text{FOH} * \text{ff} + \text{EFDH} * \text{fp}) / (\text{SH} + \text{FOH} * \text{ff})$$

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Peak periods are *generally* high LOLH periods



- **Most hours (days) have LOLP of zero**

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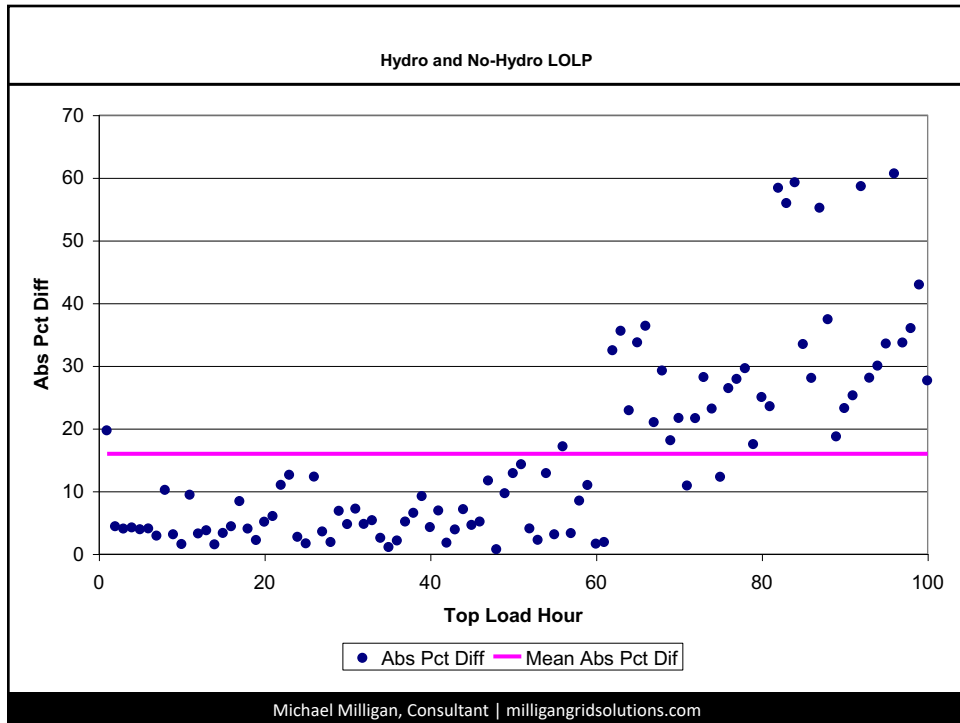
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Relationship of risk to peak demand

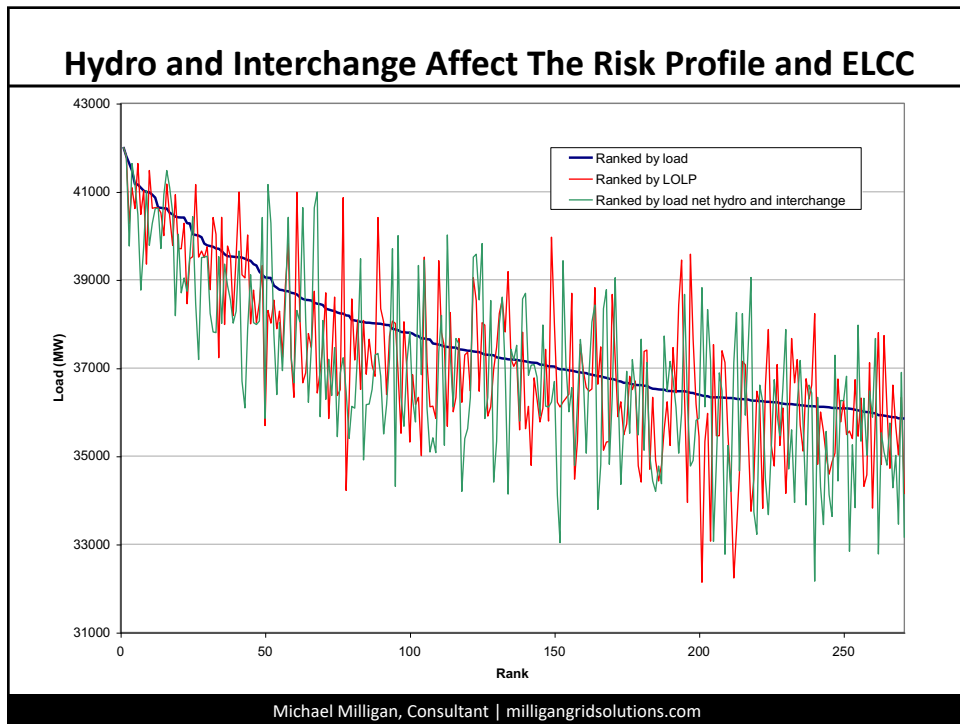
- **Risk may not be perfectly correlated with load**
 - Scheduled maintenance during shoulder months may increase risk relative to peak
 - Dispatchable hydro can lower on-peak risk, increase near-peak risk
 - Other on-peak transactions that aren't available during near-peak hours
 - Other factors that shift risk profile
 - Renewables will change this
 - Following examples are from California Renewables Portfolio Standard analysis by Kirby, Milligan, Jackson, Shiu, Hawkins, Makarov circa 2005.

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Where did 1 day/10 years LOLE come from?

- Nobody knows, but Marsh's paper is a good possibility
- On the other hand, Calabrese used 1d/50y, and 1d/10y seems like a nice round number
- Corresponding LOLP = $1/3650 = 0.0002734$
- But what does 1d/10y really mean?

POWER GENERATION REPORT NO. 125
 Title: Measures of Generating System Reliability
 Date: October 4, 1972
 Author: W.D. Marsh

Introduction

In contrast to the aerospace industry, the electric utility industry does not have a precise definition for the term reliability which can be used for quantitative measurement. The term is completely general; other terms have been adopted for specific measurement of reliability of various parts of the utility system. In generation systems, the most frequently used measure is "Loss of Load Probability" (LOLP), which, it has been pointed out, (1) is not really a probability at all, but is an expected value. To say this, however, does not illumine the subject for many people in the industry who are not specifically schooled in the fields of statistics and reliability engineering. Accordingly, this report will attempt to by-pass this deficiency by an analogy, and by the introduction of a new measure of generation system reliability which is a probability, the presumption being that most people understand a probability to be a measure of "chance" or "odds" as in a horse race or a poker game.

The Rainfall Analogy

Once upon a time, a man named George Flol conceived an idea for a new breakfast cereal which he felt had advantages that would obsolete all other cereals. The production process was unique: it required the exposure of the grain to strong sunlight on a daily cycle for a continuous period of one year. This, he calculated, would polyunsaturate the fats, convert the sugar, and multiply the vitamins. The process, however, was extremely sensitive to moisture; in fact, just a few drops of rain on one day during the year's exposure would completely destroy the batch of cereal.

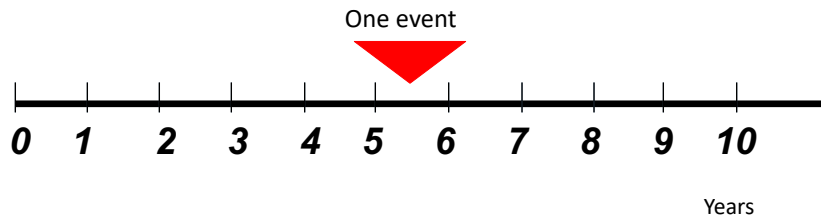
LOLP: probability, $0 \leq \text{LOLP} \leq 1$
 LOLE: expected value = $P \times \text{Time}$
 LOLH: hours of LOL events
 LOLEv: # of events of LOLE
 EUE: Expected unserved energy

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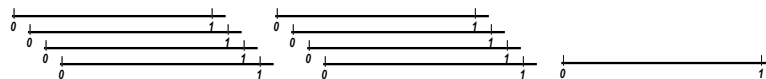
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Data and Measurement Issues: Loss of load event

- What is 1d/10y?



- 9 years have no recordable events

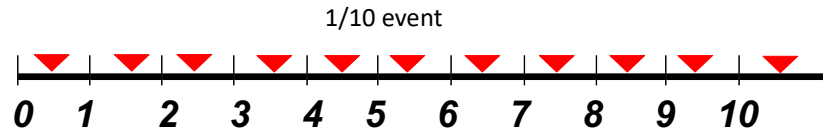


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1d/10y is not the same as 0.1d/y

- What is 0.1d/y?

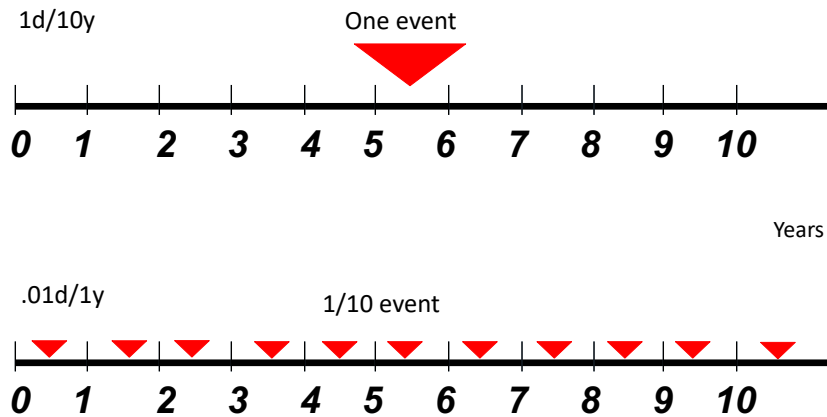


- All 10 years have an event, albeit smaller than the 1d/10y event

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Comparing 1d/10y to 0.1d/10y

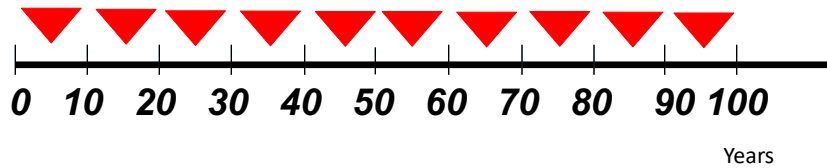


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Longer time horizons

- With 1d/10y event we would expect ~10 of them in a century

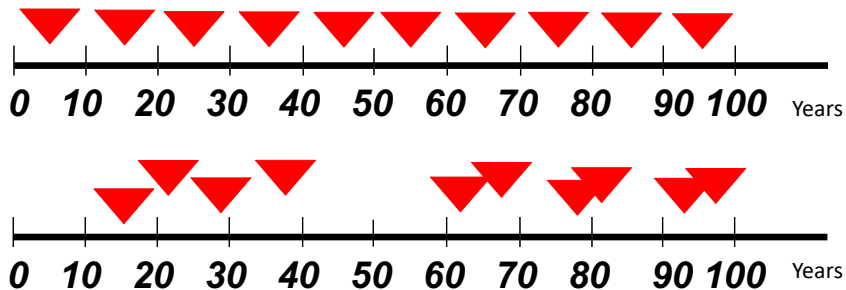


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Longer time horizons

- With 1d/10y event we would expect ~10 of them in a century...but not necessarily each 10-year period

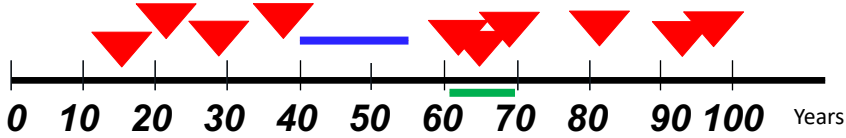


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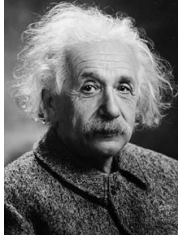
A Theory of Special Relativity for Power System Modelers

- A modeler in year 55 with 15 years of data would conclude 0d/15y reliability —



The diagram shows a horizontal timeline from 0 to 100 years. Red triangles representing data points are located at approximately 15, 25, 35, 45, 65, 75, 85, and 95 years. A blue horizontal bar representing a 15-year observation period is shown from year 40 to year 55. A green horizontal bar representing a 10-year observation period is shown from year 60 to year 70.

- A modeler in year 70 with 10 years of data would conclude 3d/10y —



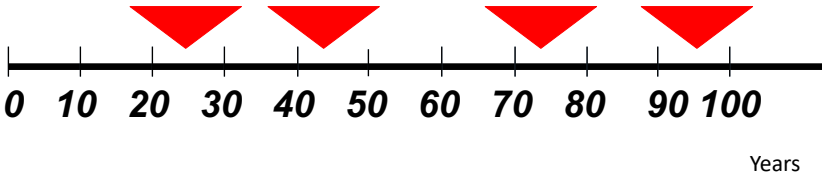
A black and white portrait of Albert Einstein is positioned to the right of the second bullet point.

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Infrequent events

- What is the risk of
 - La Nina/El Nino events
 - Other jet stream anomalies
 - Climate change on wind speeds/solar insolation
- And how do collect good data sets?



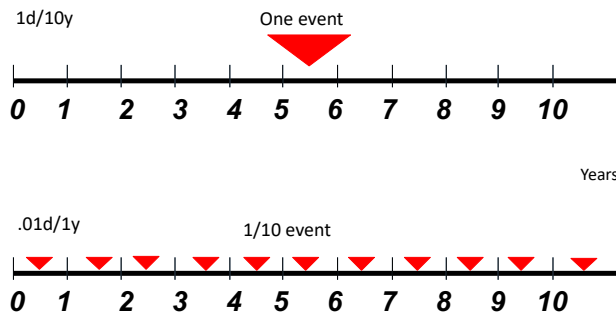
The diagram shows a horizontal timeline from 0 to 100 years. Red triangles representing infrequent events are located at approximately 25, 45, 75, and 95 years.

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Data limitations are common

- ...and thus some studies use 0.1d/y instead of 1d/10y.
- This is common convention but should really be changed



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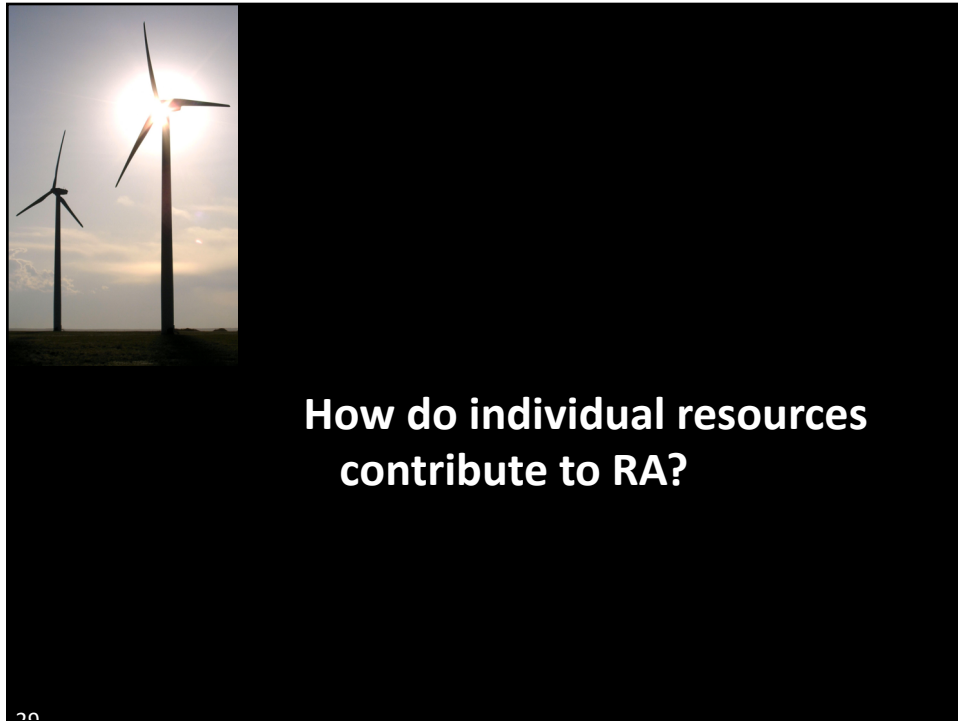
Alternative underlying metrics

- Daily LOLE – counts # of days of shortfalls
- LOLH (hourly) – counts # of hours of shortfall
- EUE (expected unserved energy) – measures energy shortfall
- Choice of metric will influence result
- However, metrics will “find” similar/same times of shortfalls



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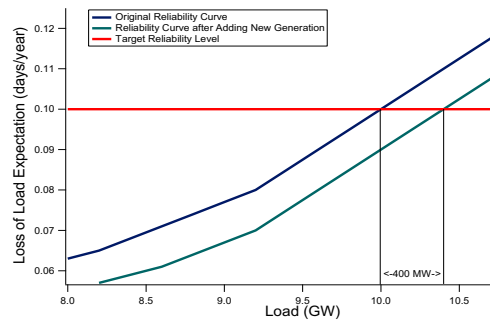


How do individual resources contribute to RA?

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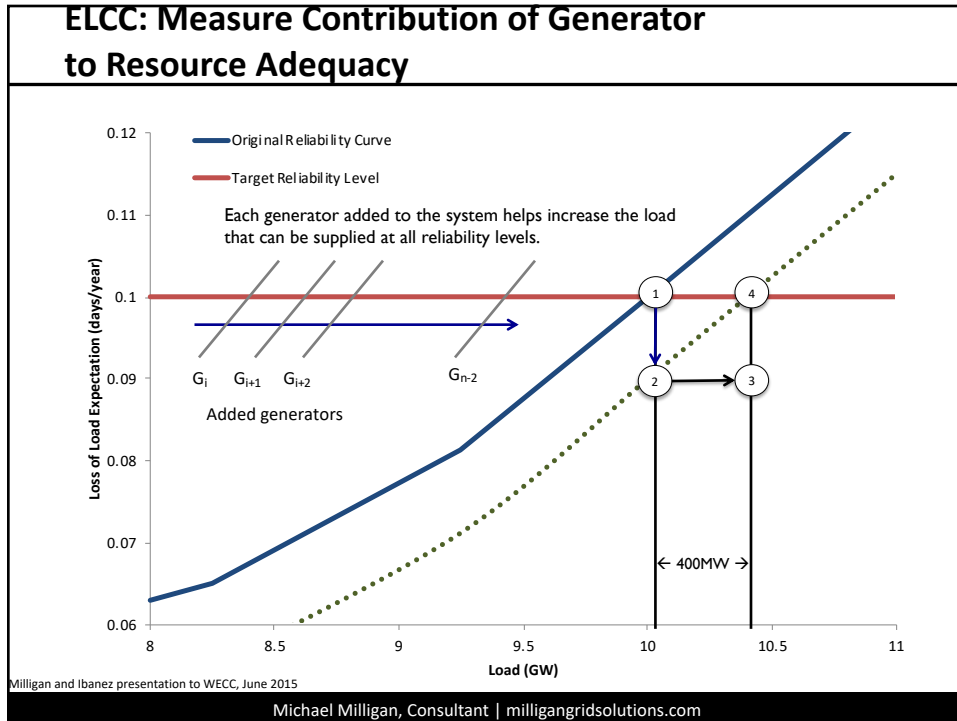
Individual Generators' Contribution to Adequacy can be Measured

- Effective load carrying capability (ELCC)
- Applies to all generators
- De-composes each individual generator's contribution to system adequacy



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How Does ELCC Work?

- **Holds the system at constant annual risk level with/without the generator of interest (wind, solar)**
- **Utilizes reliability/production simulation model**
 - Hourly (or daily) loads
 - Generator characteristics
 - Calculates hourly LOLP (loss of load probability)
- **The hourly LOLP calculation finds high-risk hours: risk can be caused by**
 - Peak loads
 - Unit unavailability (such as planned maintenance)
 - Interchange and hydro schedules/availability
 - High/low levels of wind/solar energy

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EFORd depends on other factors

- Cycling
- Ambient temperature
- Long peak period when unit is pushed to limit
- Fuel quality
- Regular maintenance
- Plant vintage
- Plant design (base-load, cycling)
- Operational practice

High Mix (16.5% solar, 16.5% wind)

NREL's Western Wind and Solar Integration Study Phase 2
<https://www.nrel.gov/grid/wwsis.html>

IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 27, NO. 6, NOVEMBER 2012

Unit Commitment With Dynamic Cycling Costs

Niamh Troy, Member, IEEE, Damian Flynn, Senior Member, IEEE, Michael Milligan, Senior Member, IEEE, and Mark O'Malley, Fellow, IEEE

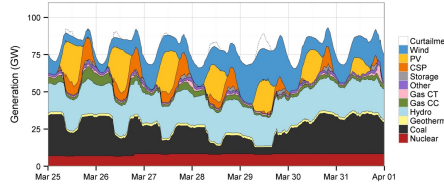
Abstract—Increased competition in the electricity sector and the integration of variable renewable energy sources is resulting in more frequent cycling of thermal plants. This, in turn, has led to increased wear-and-tear to generator components and the related costs are a growing concern for plant owners and system operators alike. This paper presents a formulation that can be implemented in a MIP dispatch model to dynamically model cycling costs based on unit operation. When implemented for a test system, the results show that dynamically modeling cycling costs reduces cycling operations and leads to change the merit order over time. This leads to the burden of cycling operations being more evenly distributed over the plant portfolio and reduces the total system costs relative to the case when cycling costs are not modeled.

Index Terms—Power system modeling, thermal power generation.

NOVENCLATURE

Indices/Sets
 t, T Time step, set of time steps.
 g, G Units, set of units.
 i, I Interval of cycling cost function, set of intervals of cycling cost function.
 j, J Level of ramp, set of all ramp levels.
 l, L Segment of the piecewise linearization of the variable cost function, set of all segments of the piecewise linearization of the variable cost function.

$cost_g^c$ Cycling cost increment incurred by unit g for each additional start-up.
 $TH_g^c(i)$ i th threshold corresponding to cumulative start-ups by unit g .
 $cost_g^r(i)$ Cycling cost increment incurred by unit g for each additional start-up until cumulative start-ups $\{N_g^c(t, i)\}$ reach a given threshold $\{TH_g^c(i+1)\}$.
 R_g Production change (MW) over time period l deemed damaging for unit g .
 $R_{g,l}$ l th production change (MW) over time period l deemed damaging for unit g .
 $cost_g^d$ Cycling cost increment incurred by unit g for each additional ramp $> R_{g,l}$.
 $TH_g^d(i)$ i th threshold corresponding to cumulative ramps for unit g .
 $cost_g^r(i)$ Cycling cost increment incurred by unit g for each additional ramp, until cumulative ramps $\{N_g^r(t, i)\}$ reach a given threshold $\{TH_g^d(i+1)\}$.
 I_g Total number of intervals in cycling cost function for unit g .
 J_g Number of ramp levels defined for unit g .
 P_g Maximum capacity of unit g .
 $P_{g,l}$ Maximum capacity of unit g .
 A_g Fixed cost for unit g (\$/hr).



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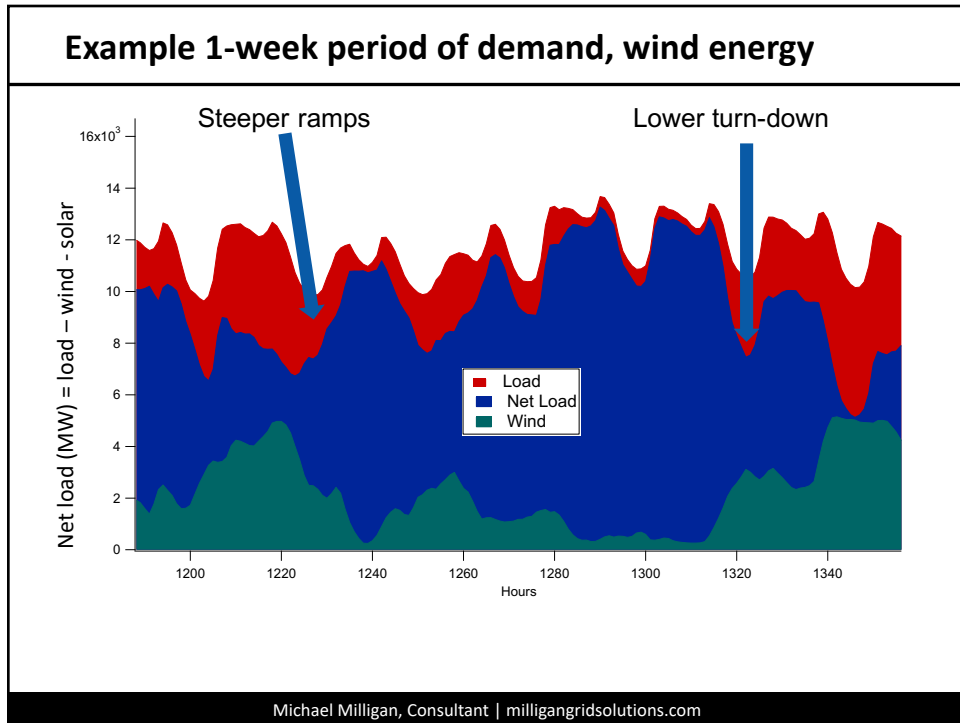
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Relevant characteristics of VG

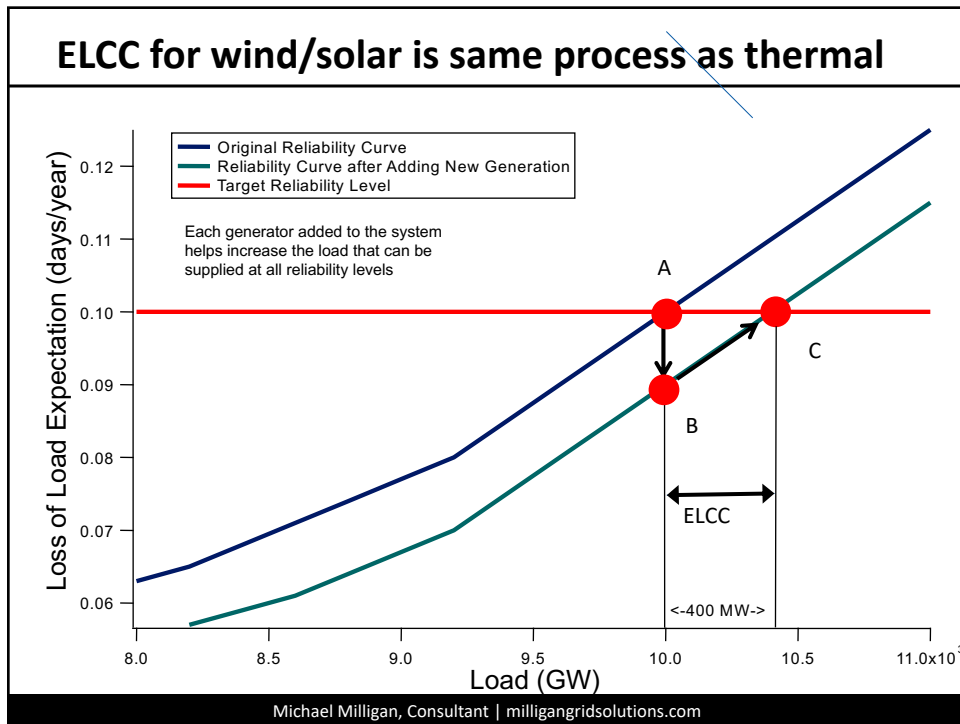
- Variable
- Predictable (up to a point)
- Marginal cost = 0, therefore comes in at the bottom of the dispatch stack
- Modern wind/solar plants can be dispatched up or down (if pre-curtailed; usually an economic decision)
- Increases the flexibility requirement from the remaining power system
- Has some ELCC but generally low relative to its nameplate capacity

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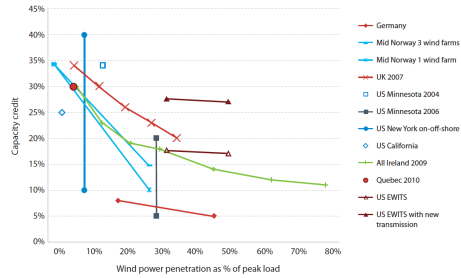
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VG Capacity Credit (ELCC) Properties

- Use same approach as conventional units
- VG capacity credit depends on output profile (hourly for *multiple years*):
 - Low when VG contributes small amount to reliability
 - High when VG contributes large amount to reliability
 - Depends on system and VG characteristics

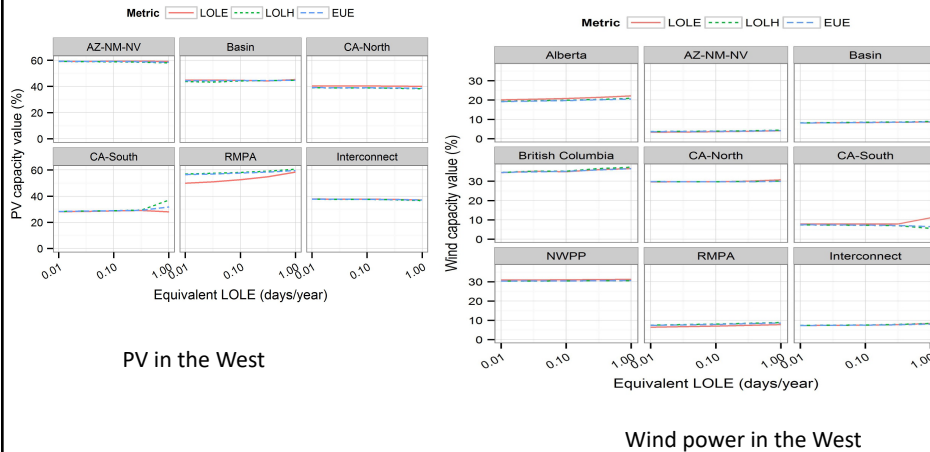


- Values can range from approximately 10%-40% for wind, 30-82% (WECC analysis) for solar
- Capacity credit outside this range are possible
- Use multiple years of data if available

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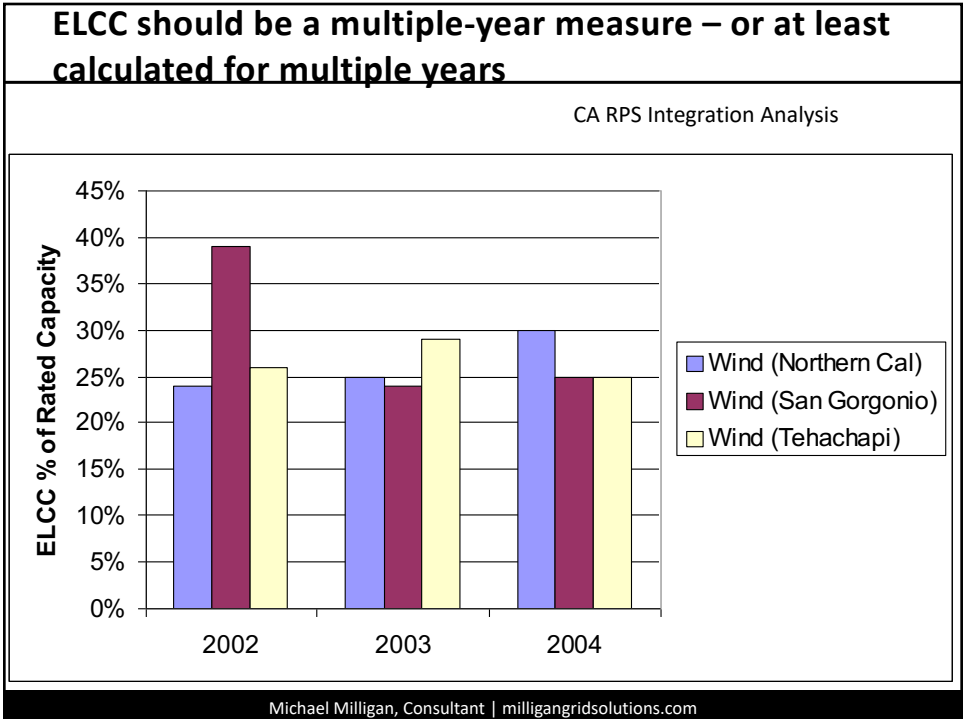
Example: alternative metrics, targets



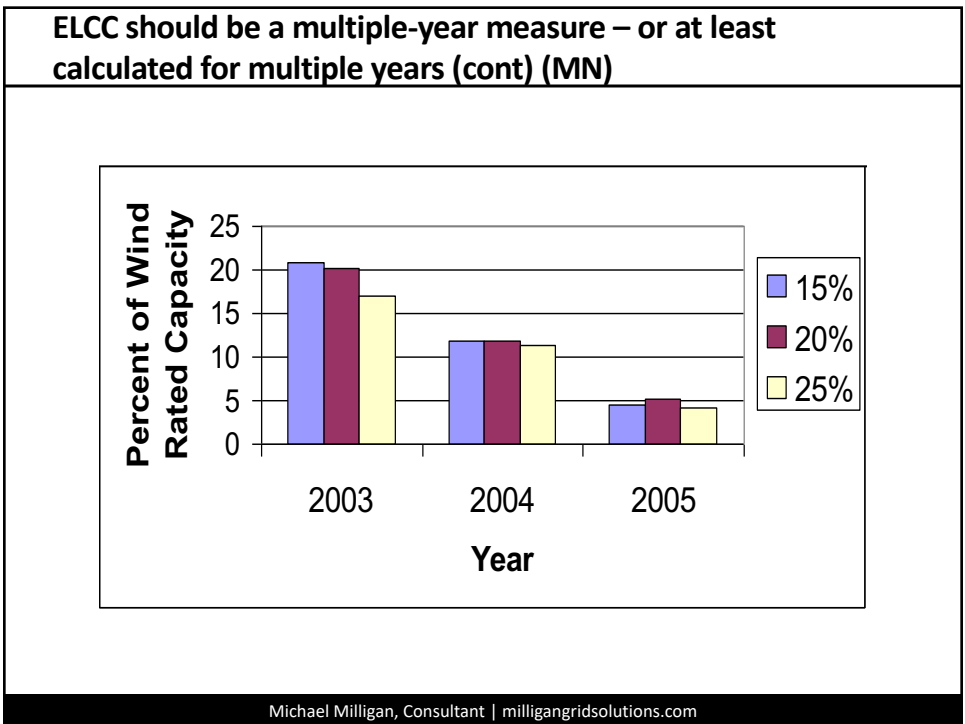
Milligan, Michael; Bethany Frew; Ibanez, Eduardo; Kiviluoma, Juha; Holttinen, Hannele; Söder, Lennart, [Capacity Value Assessments for Wind Power: An IEA Task 25 Collaboration](#). Wiley Wires. 2016

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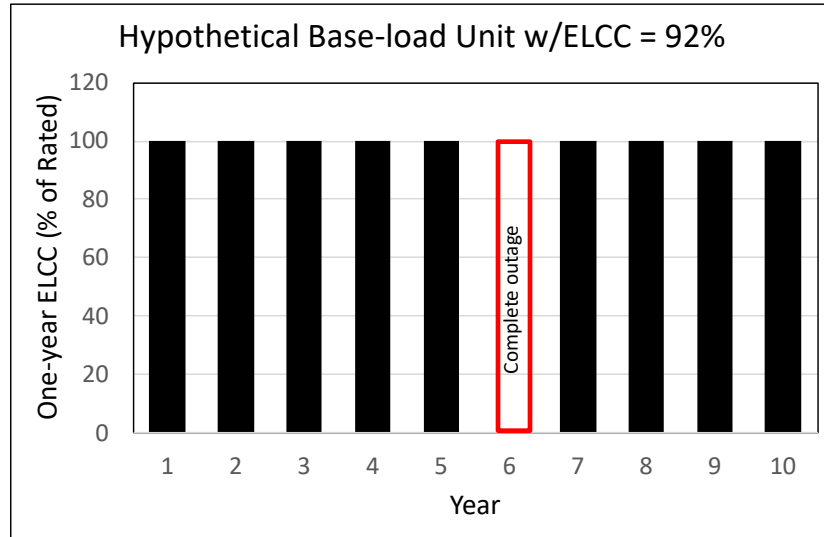


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Multi-year Base-load ELCC Example



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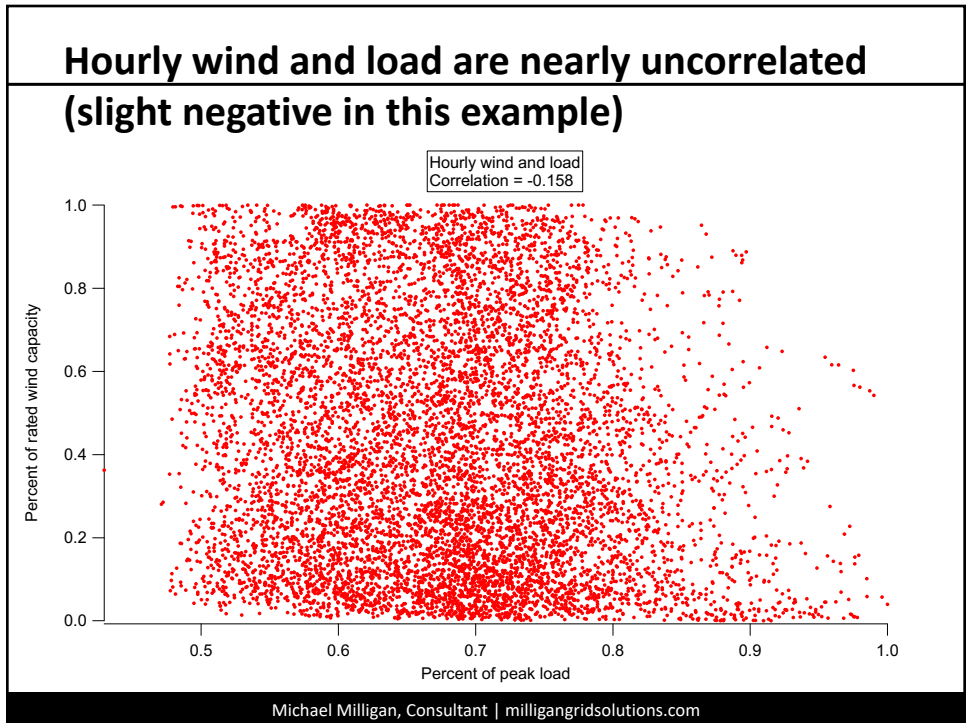
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Data Requirements: Wind, Solar, and Load

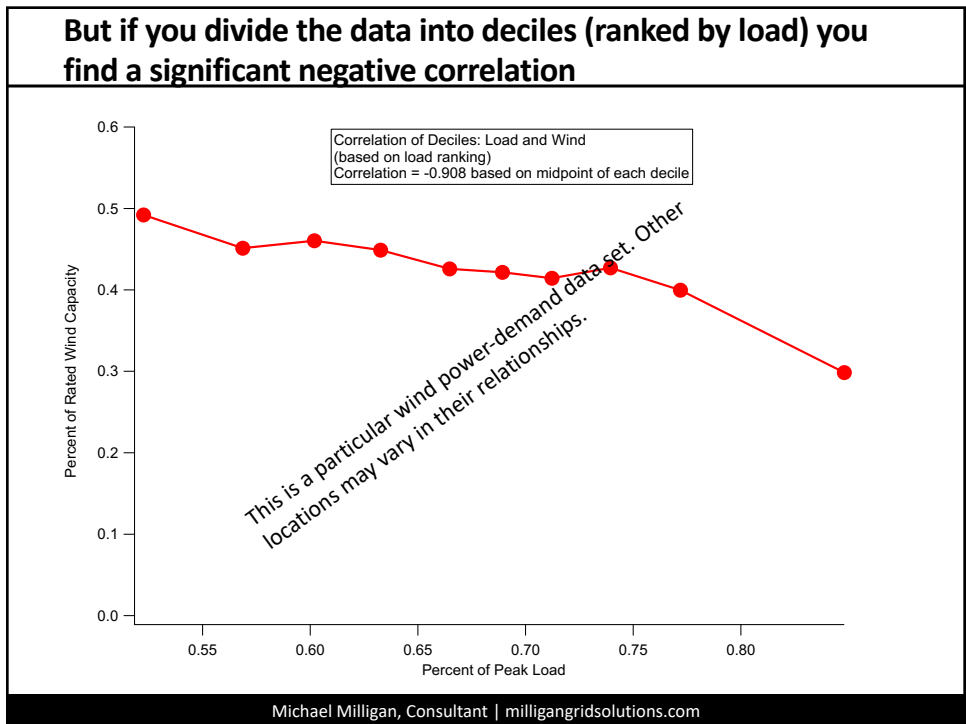
- Weather is common driver
- Hourly wind, solar, and load data must be from same year for consistent analysis and plausible results
- Use of meso-scale weather models or actual VG production is state of the art (same as integration studies)
- Preserves underlying correlations between wind, solar, and load with temperature, other weather phenomena



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This reference addresses wind but is relevant for solar

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IEEE TRANSACTIONS ON SUSTAINABLE ENERGY, VOL. 3, NO. 4, OCTOBER 2012

Assessment of Simulated Wind Data Requirements for Wind Integration Studies

Michael Milligan, *Senior Member, IEEE*, Erik Ela, *Member, IEEE*, Debra Lew, *Member, IEEE*, David Corbus, *Member, IEEE*, Yih-huei Wan, *Senior Member, IEEE*, and Bri-Mathias Hodge, *Member, IEEE*

Abstract—Wind integration studies are now routinely undertaken by utilities and system operators to investigate the operational impacts of the variability and uncertainty of wind power on the grid. There are widely adopted techniques and assumptions that are used to model the wind data used in these studies. As wind penetration levels increase, some of the assumptions and methodologies are no longer valid and new methodologies have been devised. Based on involvement in conducting studies, reviewing studies, and/or developing datasets for studies in the Western Interconnect, the Eastern Interconnect, Hawaii, and other regions, the authors report on the evolution of techniques to better model the wind power output for cases with high penetrations of wind energy.

Index Terms—Power system planning, stochastic systems, wind power generation.

wind’s variability and uncertainty [3]–[6]. This is usually performed by comparing a simulation with wind power with some “no-wind” base case. While this appears to be a simple analysis, the many complex interactions among components of the power system and assumptions regarding the no-wind base case all have important influences on integration cost estimates.

Other studies have focused on the operational impacts and total production cost [7]–[10] of wind integration. These studies find that operating cost can be substantially reduced with wind. This conclusion is driven primarily by the essentially zero marginal cost of wind, which in turn reduces, sometimes to zero or below, locational marginal prices. While this is an attractive result in the short run for consumers, it is not clear how these prices are sustainable, and whether they provide the right signals to investors and developers of new generation to provide for

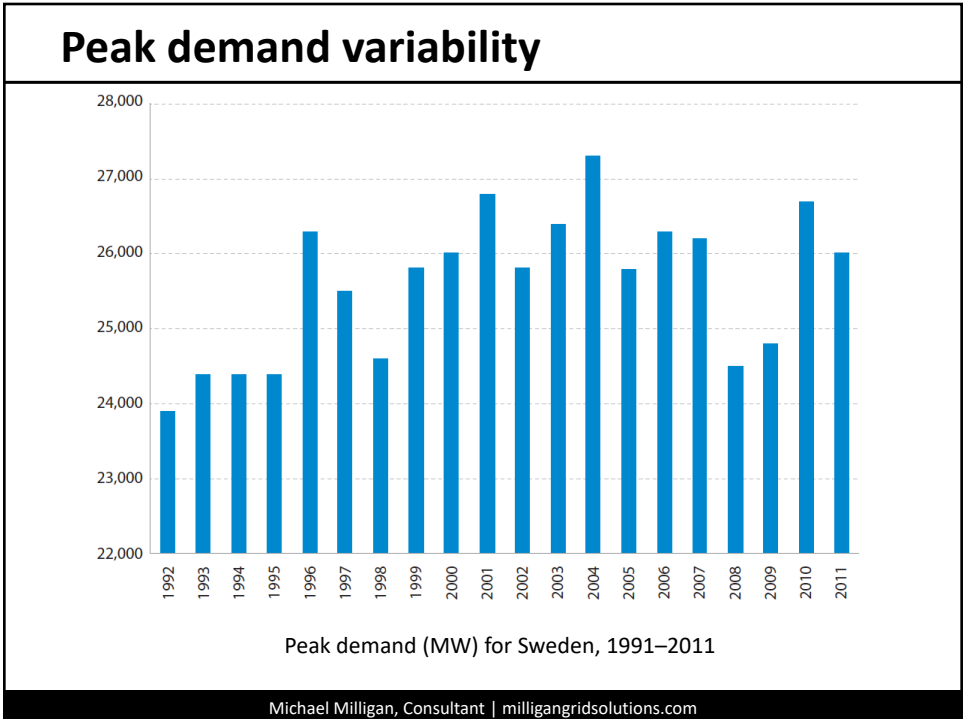
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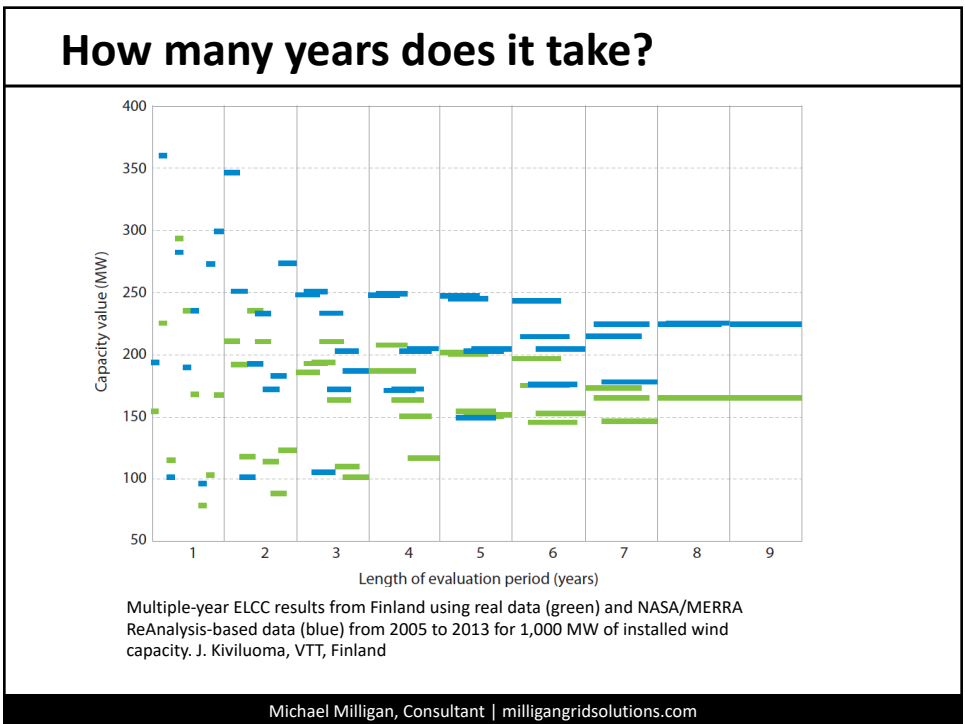


Multi-year considerations become more important as we move to very high levels of wind, solar, storage, DR

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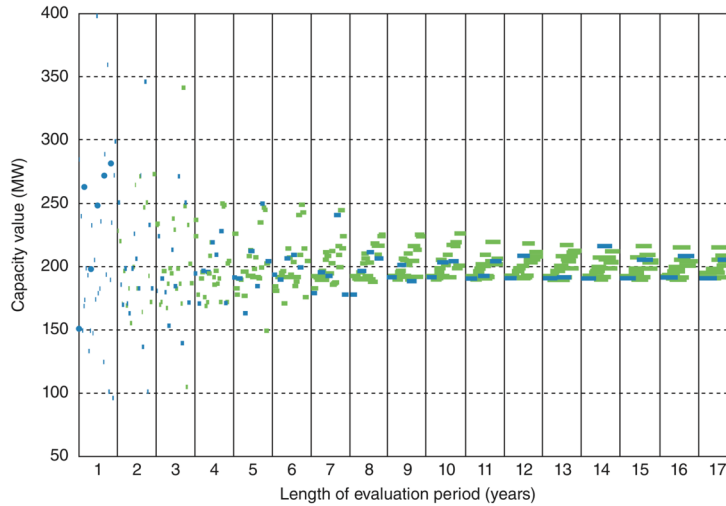


47



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How many years does it take? (2)



Multiple-year ELCC results from Finland using NASA/MERRA ReAnalysis data from 1979 to 2013. Temporally independent year combinations are shown in blue for 1000 MW of installed wind capacity. J. Kiviluoma, VTT, Finland.

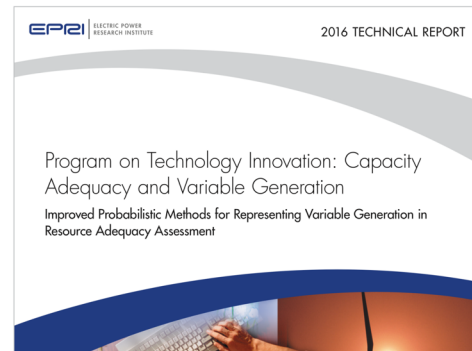
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Extracting weather influence on wind, demand

- **EPRI report**

- Characterize dependence of VG and demand on temperature
- If successful, this method may eliminate need for time-sync'd data
- Results encouraging, but more work is needed to establish the validity of this approach



This report is publicly available.

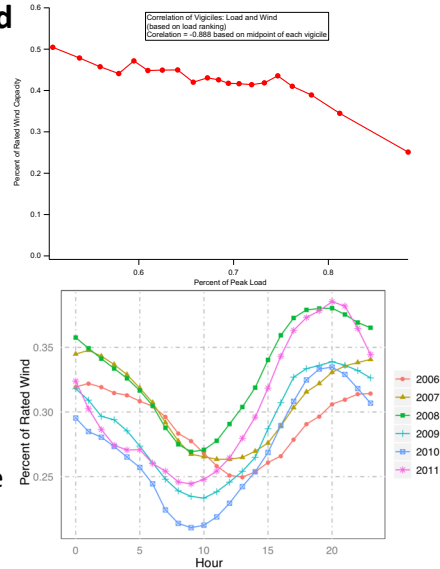
Aidan Tuohy, Eamonn Lannoye, Jody Dillon, Chris Dent, Amy Wilson, S. Zachary, E. Ibanez, M. Milligan: Capacity Adequacy and Variable Generation: Improved Probabilistic Methods for Representing Variable Generation in Resource Adequacy Assessment, Electric Power Research Institute in collaboration with National Renewable Energy Laboratory; Heriot-Watt University, Edinburgh, UK; Durham University, Durham, UK; Ecar Energy Ltd, Ireland.

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Long term data considerations

- **Kajala’s Temperature-based Wind Power Model for reliability (unpublished paper, BPA)**
 - Mahalanobis distance metric, nearest neighbor with adapted weighting scheme
 - Finds difference in LOLP when comparing non-temperature approach vs. temperature approach
 - Promising approach: May represent wind variability in appropriate manner, but method needs additional validation and meteorological grounding
 - Normalized wind generation in the NW



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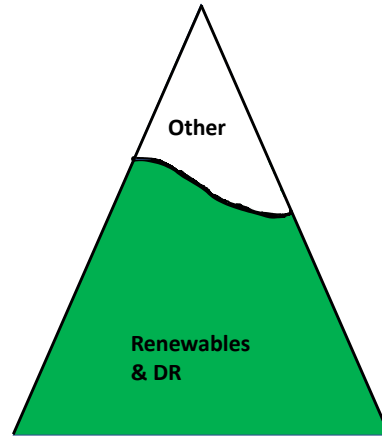


What is changing: Very high RE penetrations, DR, storage

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RA's role will not diminish

- **But it may change**
- **"energy-first" planning**
 - Focus on clean energy first
 - Then "fill in" to achieve RA
- **Fill in with**
 - Storage
 - DR
 - Quick-start thermal
 - Other
- **Will we ever *not* want to assess risks associated with meeting future demand?**

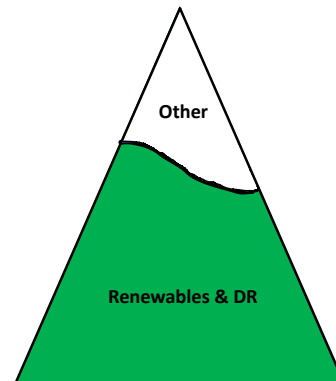


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ESIG Workshop: 100% Renewable

- **What is needed for resource assessment?**
- **Consensus of the RA working group:**
 - Move to more EUE, LOLH, less on daily LOLE
 - Better multiple-year data sets for demand, wind, solar
 - Better accounting for DR
 - Better algorithms to match wind, solar, demand, hydro, chronological long-term data sets, such as EPRI report, Kajala (cited earlier)



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How does weather affect RE?

Typical El Niño Winters

Typical La Niña Winters

A Theory of Special Relativity for Power System Modelers

- A modeler in year 55 with 15 years of data would conclude 0d/15y reliability —
- A modeler in year 70 with 10 years of data would conclude 3d/10y —

Climate.gov

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Long-term adequacy challenges

- How does a RE power system maintain adequacy in the long-term?

Figure 10. Optimal distribution of wind capacity using 1996 data

Figure 11. Optimal distribution of wind capacity using 1997 data

Likely jet stream split over MN

- What type of emergency reserve is needed when there is insufficient DR, storage?

Milligan, M. R.; Artig, R. (1999). Choosing Wind Power Plant Locations and Sizes Based on Electric Reliability Measures Using Multiple-Year Wind Speed Measurements, Prepared for the U.S. Association for Energy Economics Annual Conference, 29 August—1 September 1999, Orlando, Florida; 11 pp.; NREL Report No. CP-500-26724. Available at <http://www.nrel.gov/docs/fy99osti/26724.pdf>

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Other trends that must be considered

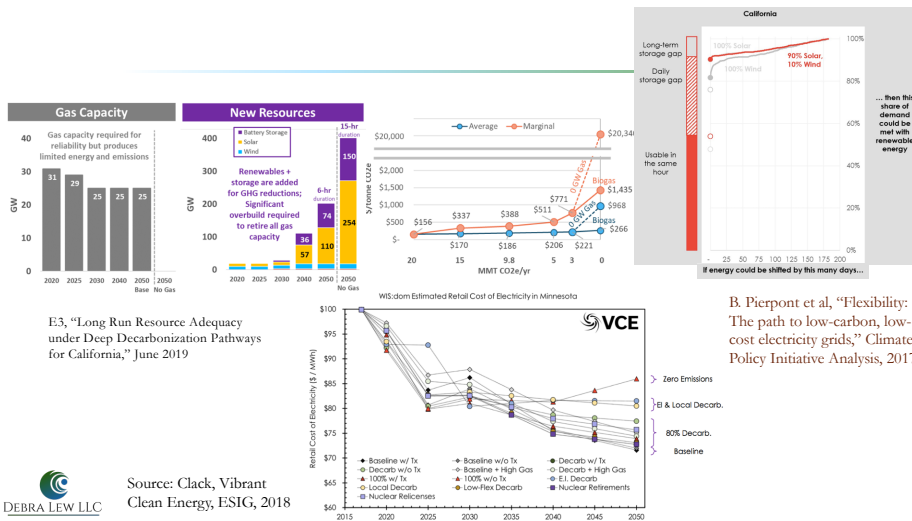
- Increasing dispatchable demand
- More cheap storage
- How to account for DERs
- Will it be possible to supply varying levels of RA at different rates? (\$)
- My assessment
 - We will always want to know the basic answer to the RA question: Have we built/planned enough?
 - Does EUE really tell us significantly more than LOLH?
 - Timing is similar
 - Depth of shortfall differs
 - Better data sets are critical
 - Emergency reserve?
 - The “last 10% or 20%” will be difficult – should we then start on another sector (transportation, etc.)?
 - What if we evaluate in terms of \$/carbon reduction?



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The last 20% can be challenging

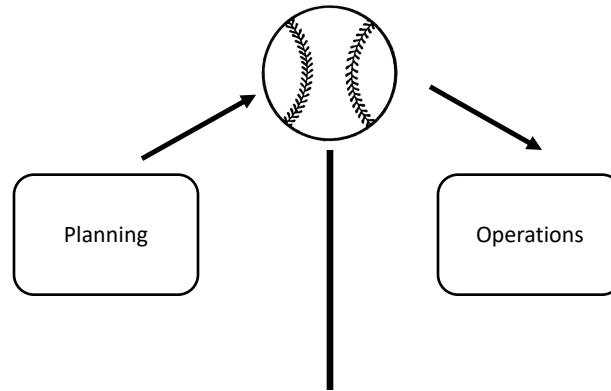


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Modeling: In the weeds

- Traditional reliability modeling has ignored commitment and dispatch, focusing on installed capacity

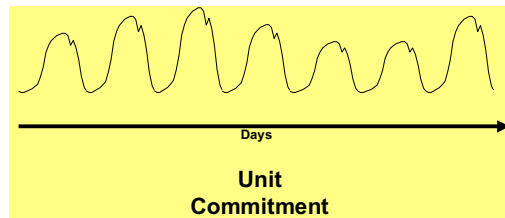
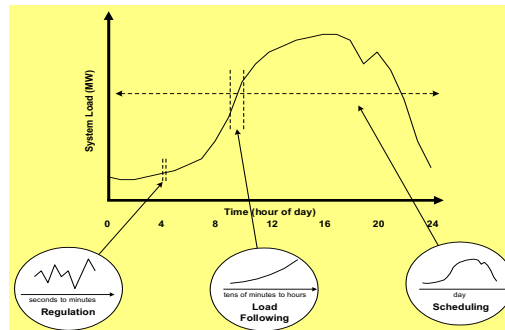


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Hybrid models: LOLP based on dispatch

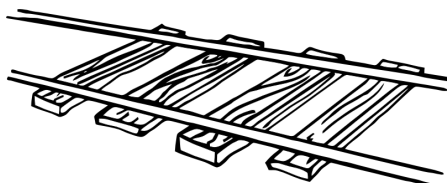
- To properly model DR, storage in a way that they would be used in practice → economic optimization
- Monte Carlo
- Controversy: is this really capturing reliability?
- Round-trip modeling?



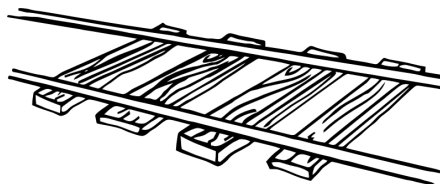
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- **We need to connect the train tracks**



Reliability



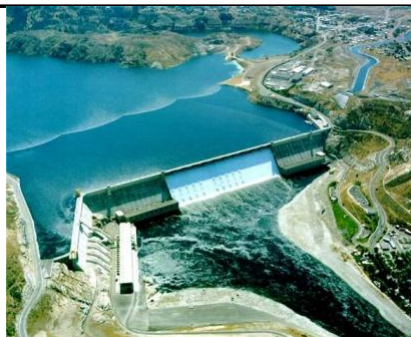
Economics

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Characterization of storage

- **MW capacity**
- **Energy limit**
- **State of charge**
- **Utilize simple characterizations for full reliability modeling**
 - Net demand peak shaving
 - Other

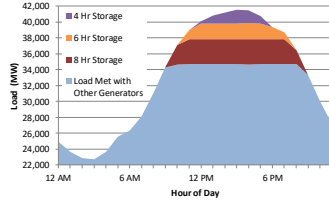


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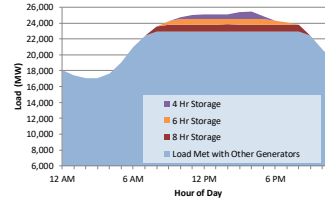
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Synergy of PV and medium-duration storage

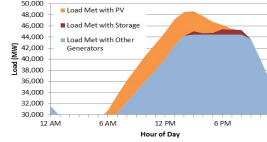
Florida has narrow peaks well suited for shorter duration storage



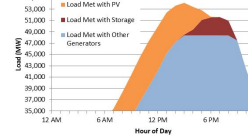
New York has longer peaks so requires longer duration storage



5% Solar PV



10% Solar PV



J. Cochran, NREL, "Integration Studies and Role of Energy Storage," Mar 12, 2019



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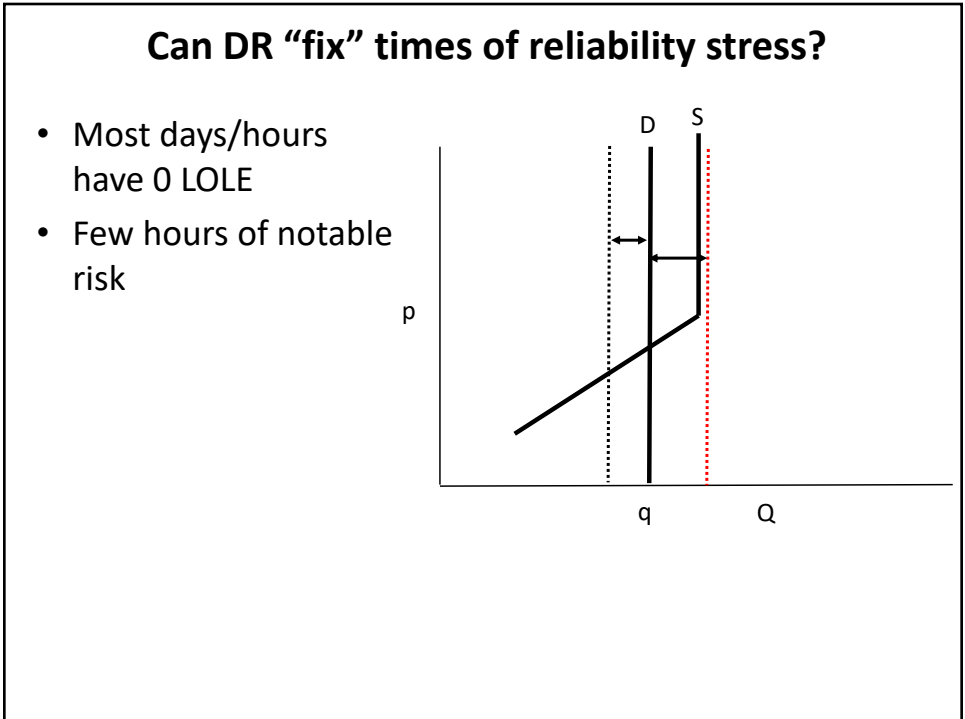
How will increasing dispatchable demand affect resource adequacy?

- **How much DR, and how responsive will it be?**
- How will this affect LOLP targets and how do we calculate it?
- Better long-term data sets
- More LOLH/EUE analysis? What are the targets?
- More/better Monte Carlo?
- Storage
 - Electric vehicles (V2G?)
 - Thermal storage
 - Hot water heaters

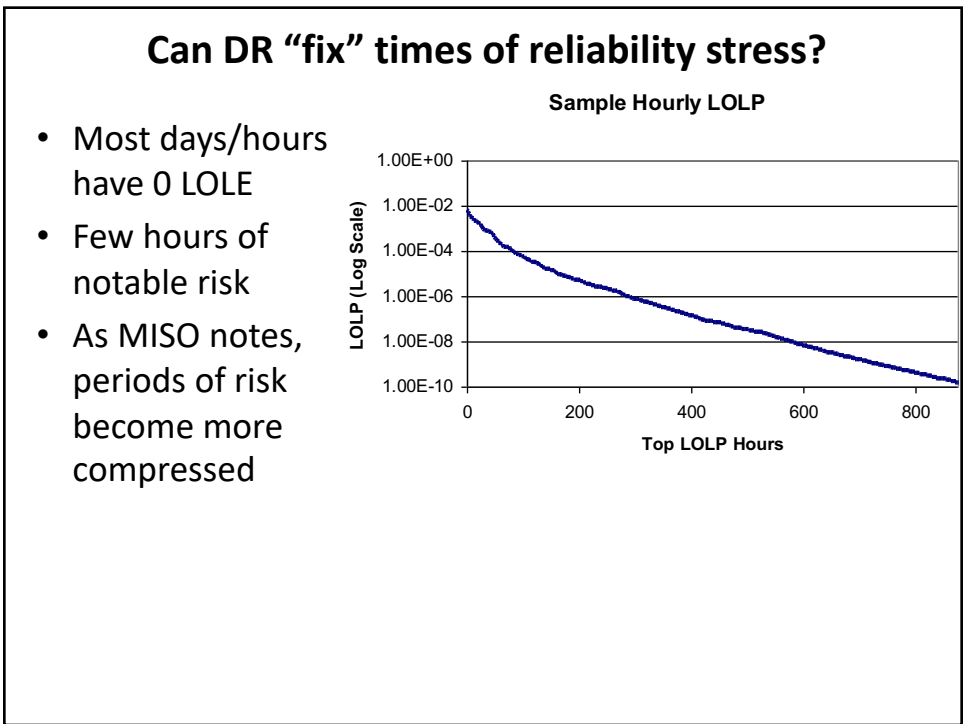


NREL Pix Building Technologies / 23095.JPG

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Example of DR providing regulation

- The following example is intended to show the powerful impact of resource diversity – how can many disparate resources be combined to produce the regulation needed by the power system operator
- This type of aggregation may be possible for many other grid services, including balancing
- “Everybody doesn’t have to supply everything.”

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DR can also provide regulating reserves



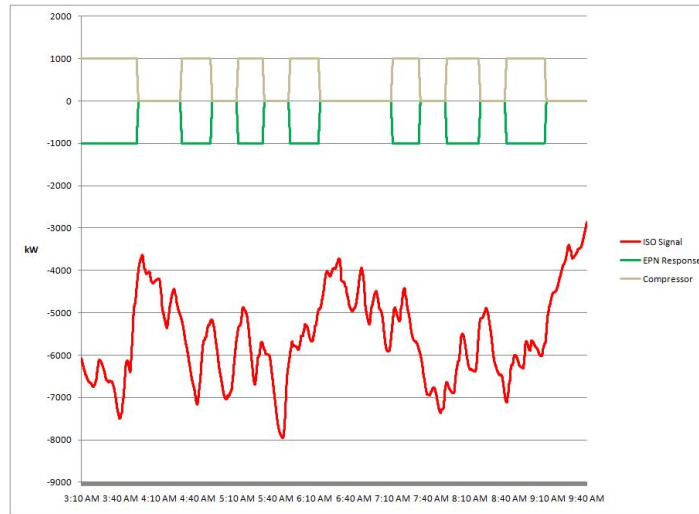
This slide is beginning of simple animation of composite DR response

<http://enbala.com/solutions.html>

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Resource Response

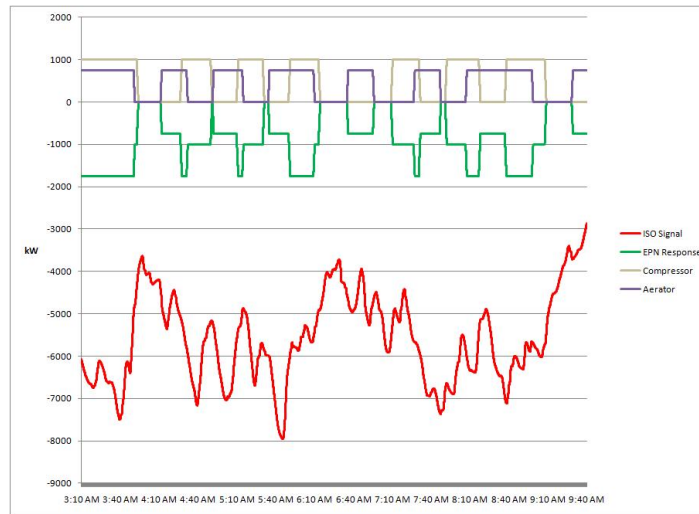


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Resource Response

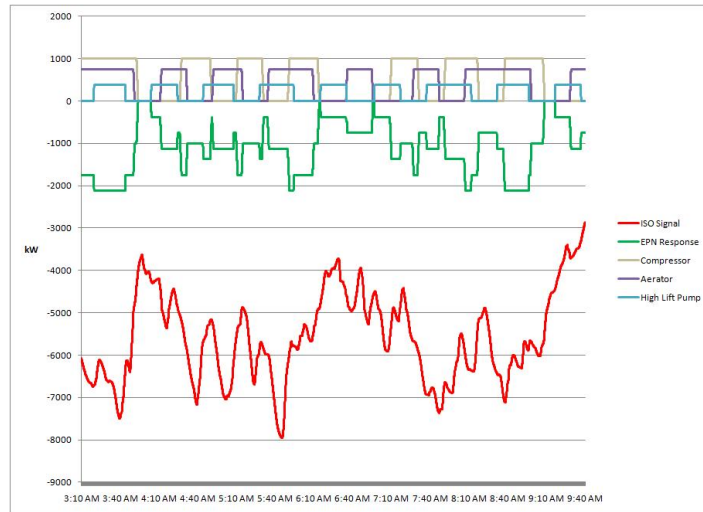


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Resource Response

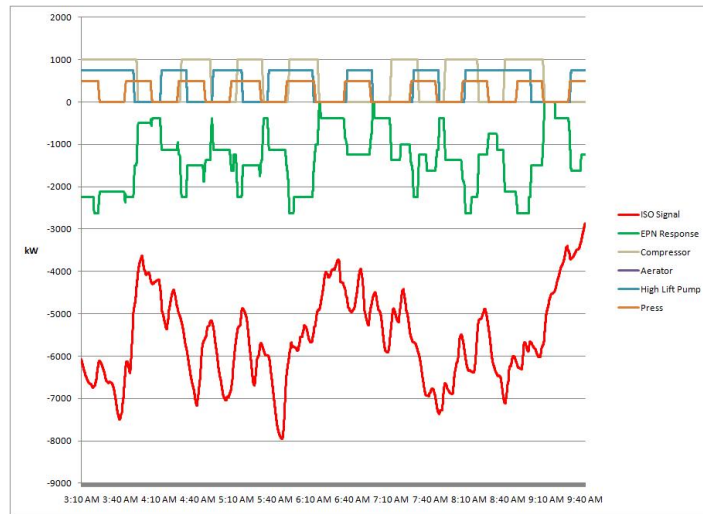


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Resource Response

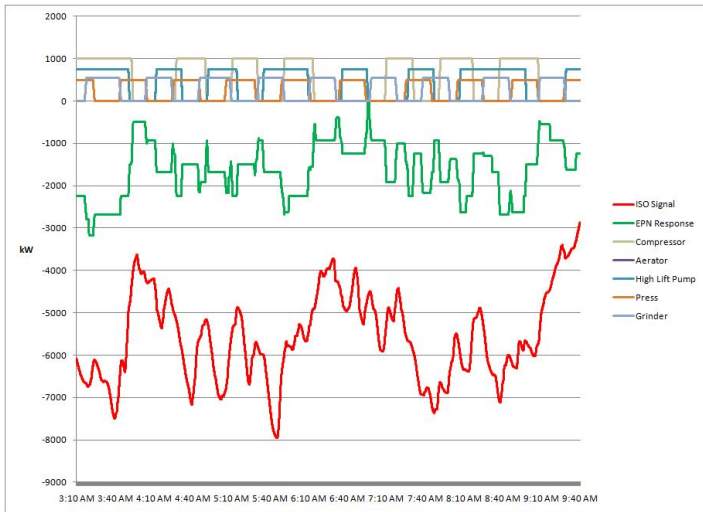


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Resource Response

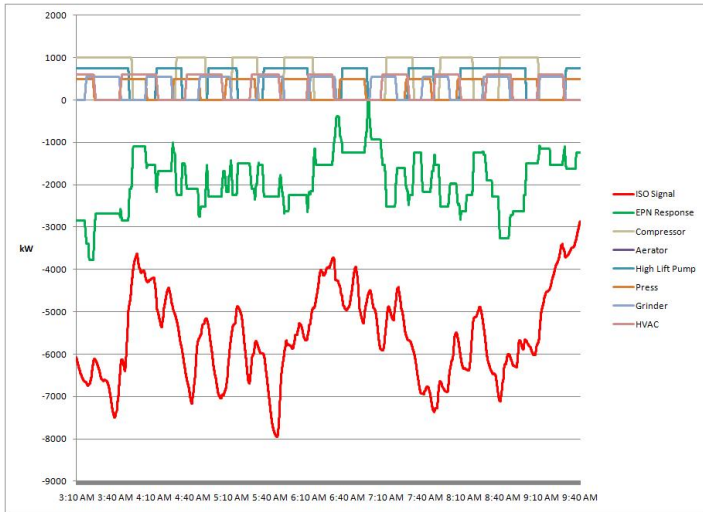


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Resource Response

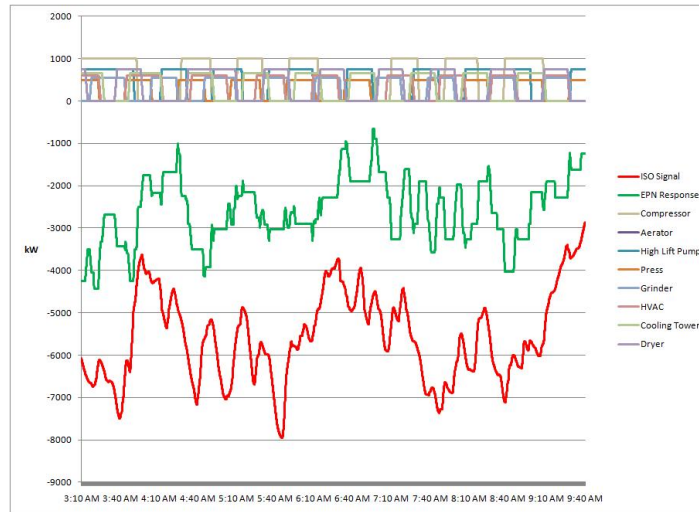


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Resource Response

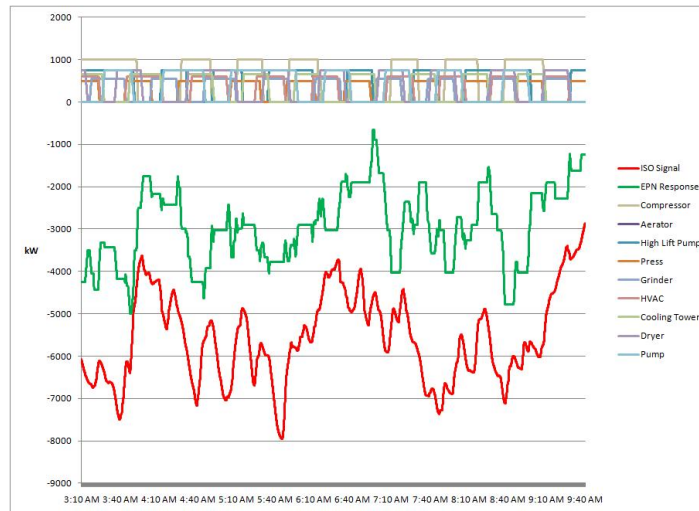


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Resource Response

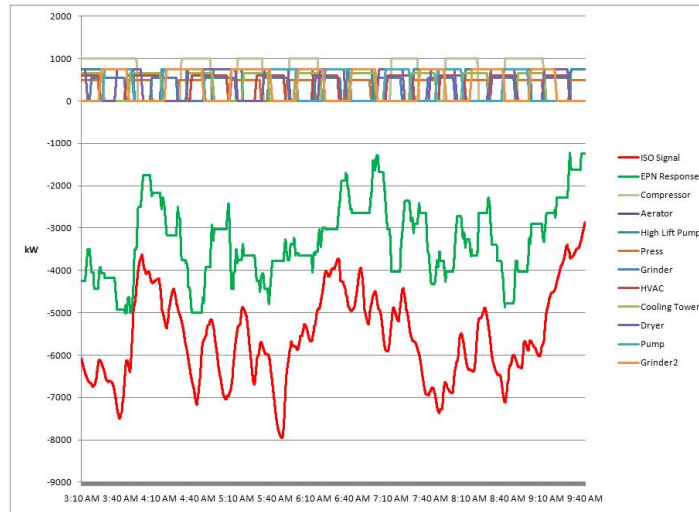


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Resource Response

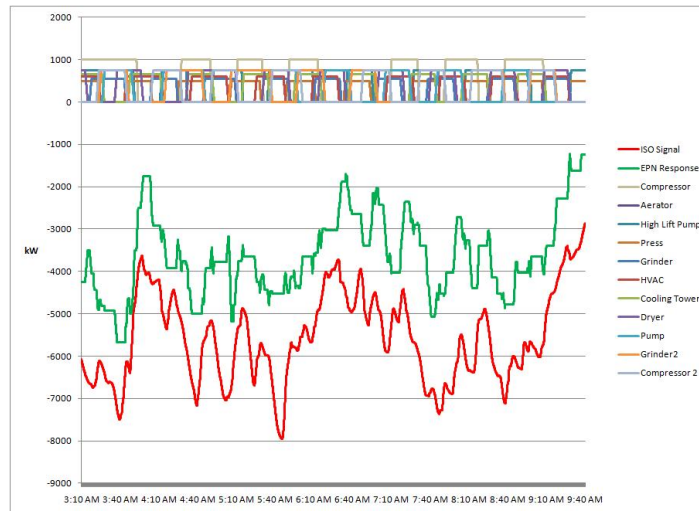


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Resource Response

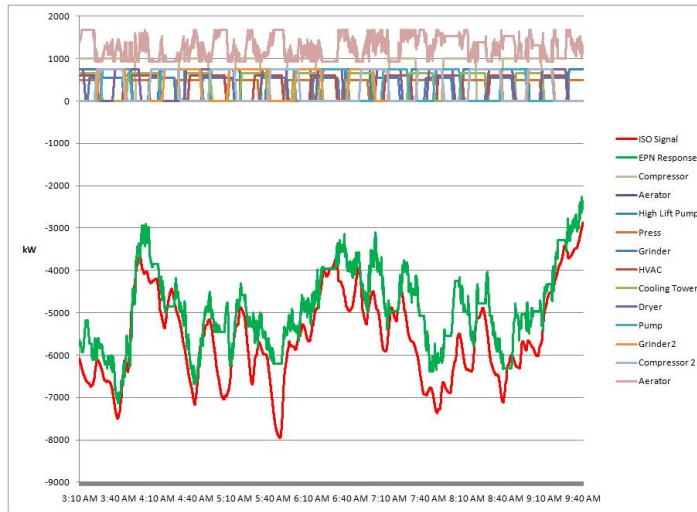


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Resource Response

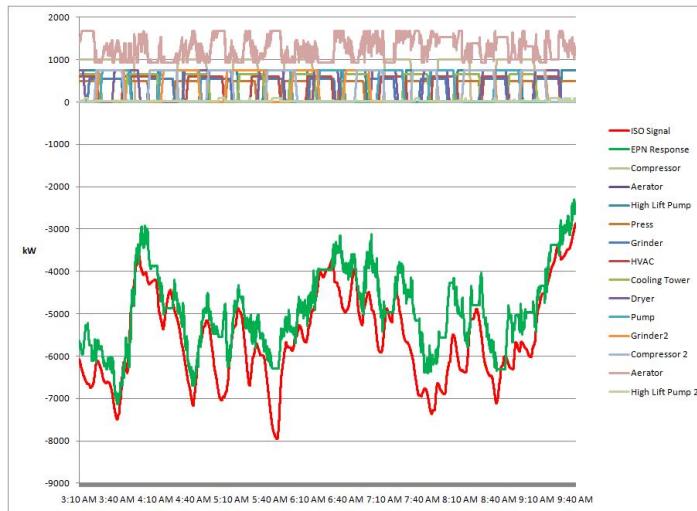


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Resource Response

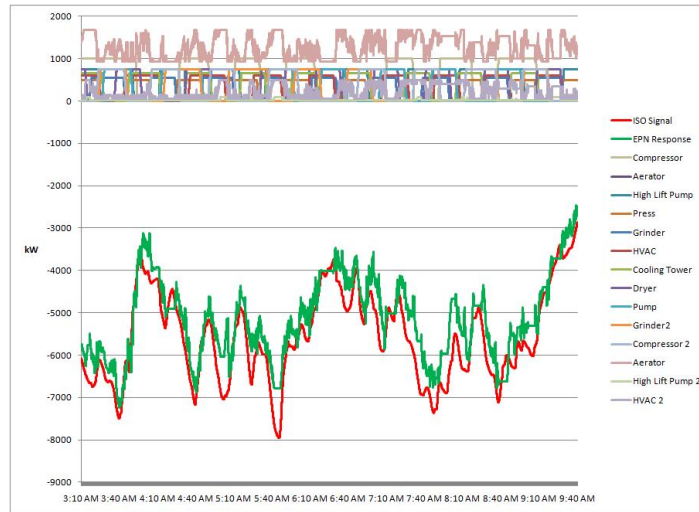


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Resource Response

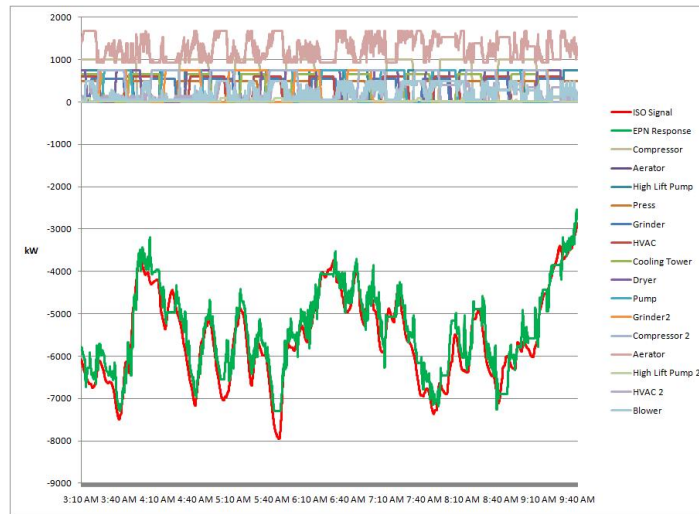


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Resource Response

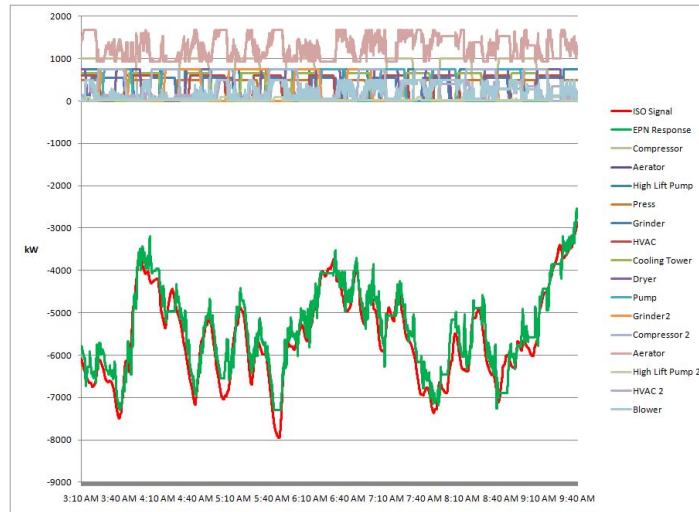


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Resource Response

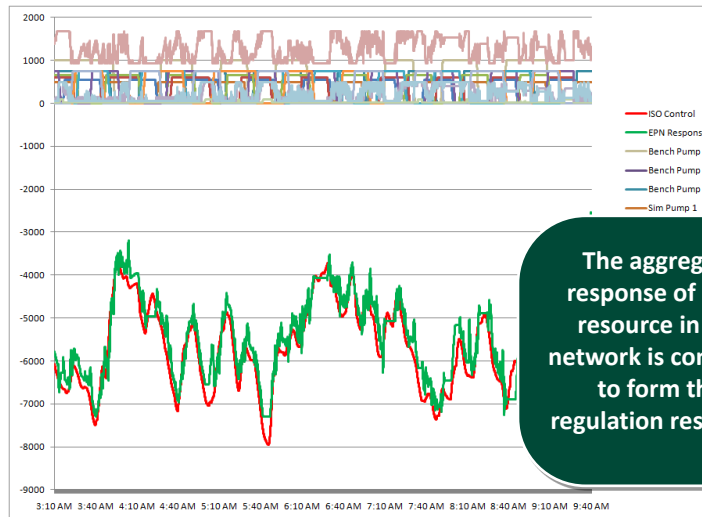


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Regulation – Resource Response



The aggregate response of each resource in the network is compiled to form the regulation response

<http://enbala.com/solutions.html>

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Composition of resources

- **The Enbala regulation example is compelling**
- **How can this be translated to other grid services, and to longer time frames?**

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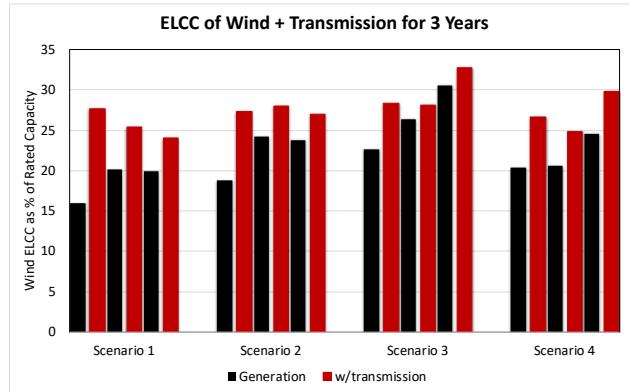


Large Interconnections

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Transmission can play a critical role

- Increasing transmission links and associated operational coordination can reduce the need for installed capacity



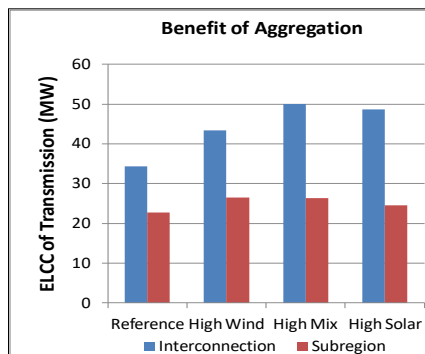
Adapted from Eastern Wind Integration and Transmission Study <https://www.nrel.gov/docs/fy11osti/47078.pdf>

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Transmission can play a critical role

- Increasing transmission links and associated operational coordination can reduce the need for installed capacity



Ibanez and Milligan (2012), "Impact of Transmission on Resource Adequacy in Systems with Wind and Solar Power." IEEE Power and Energy Society General Meeting, Summer 2012, San Diego, and "A Reliability-Based Assessment of Transmission Impacts in Systems with Wind Energy". Available at www.nrel.gov/publications

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Summary

- RA assessments are here to stay but will evolve
- Lots of moving parts, even before RE considered
- Which metrics: LOLE, LOLH, EUE? (All of the above?)
- How much DR do we have, and how do we account for it?
- Long-term data sets are more important than ever
- Emergency reserve? In what form?
- Society: is it more valuable to chase the last 10-15% RE in the power system, or should more attention be aimed to other sectors?

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Why applying LOLE to ramping can be problematic

- **Proposal: Calculate LOLE resulting from inability to ramp fast enough to keep up with changing net demand**
- **This approach may have some value, but must be interpreted correctly**
- **All tools, including dispatchable demand and renewable curtailment should be considered**

See "Flexibility Metrics and Standards Project, CPUC Workshop (CES-21), astrape.com

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From CPS to BAAL

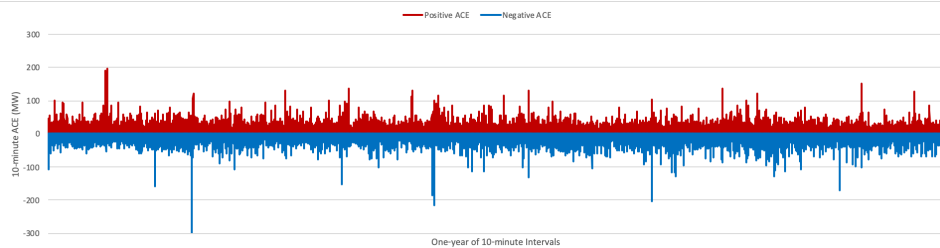
- **CPS2 required 90% of all 10-min area control error (ACE) be within L10 limits**
(https://www.nerc.com/files/BAL-001-0_1a.pdf)
- **Pass-fail, no ceiling of imbalance size**
- **Under CPS2, reliability is maintained**
 - with 10% of these ACE values exceeding L10
 - The math: 10% of the 52,560 10-minute periods per year can exceed L10. ***This is 5,256 10-minute periods; potentially just over one month/year during which ACE may exceed L10 to comply with the standard***

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1d/10y LOLE-flex makes no sense

- ACE = area control error; measures unintended flows between neighbors
- Graph is from a SW utility that is aiming to a 0.2d/y ramp target, which is inconsistent with its historical operations

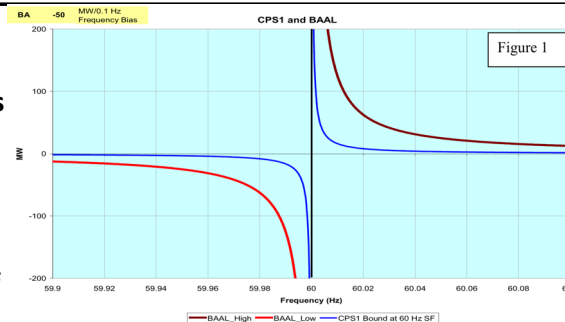


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Balancing Area Authority Limits (BAAL)

- Control is more relaxed under BAAL than CPS2
- Anecdotally some BAAs in the West were compliant with BAAL while their comparable CPS2 score was 65-70%
- Achieving some type of 1d/10y ramping compliance ignores the nature of the interconnected system and reliability standards and experience for many decades



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Renewables are Flexible

	Inverter-Based			Synchronous				Demand Response
	Wind	Solar PV	Storage/Battery	Hydro	Natural Gas	Coal	Nuclear	Demand Response
Disturbance ride-through								
Reactive and Voltage Support	Excellent	Very Good	Very Good	Excellent	Good	Good	Good	Good
Slow and arrest frequency decline (arresting period)	Excellent	Excellent	Excellent	Excellent	Good	Good	Good	Good
Stabilize frequency (rebound period)	Very Good	Very Good	Very Good	Excellent	Excellent	Good	Good	Good
Restore frequency (recovery period)	Good	Good	Good	Excellent	Excellent	Good	Good	Good
Frequency Regulation (AGC)	Very Good	Very Good	Excellent	Excellent	Excellent	Good	Good	Excellent
Dispatchability/Flexibility	Good	Good	Excellent	Excellent	Good	Good	Good	Good

● Excellent
 ◐ Very Good
 ◑ Good
 ◒ Limited
 ○ Incapable

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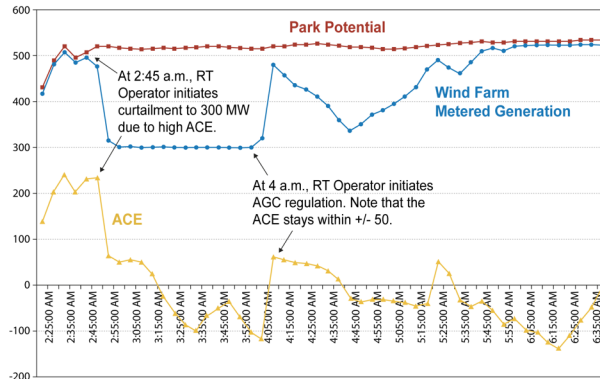
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Renewables are flexible

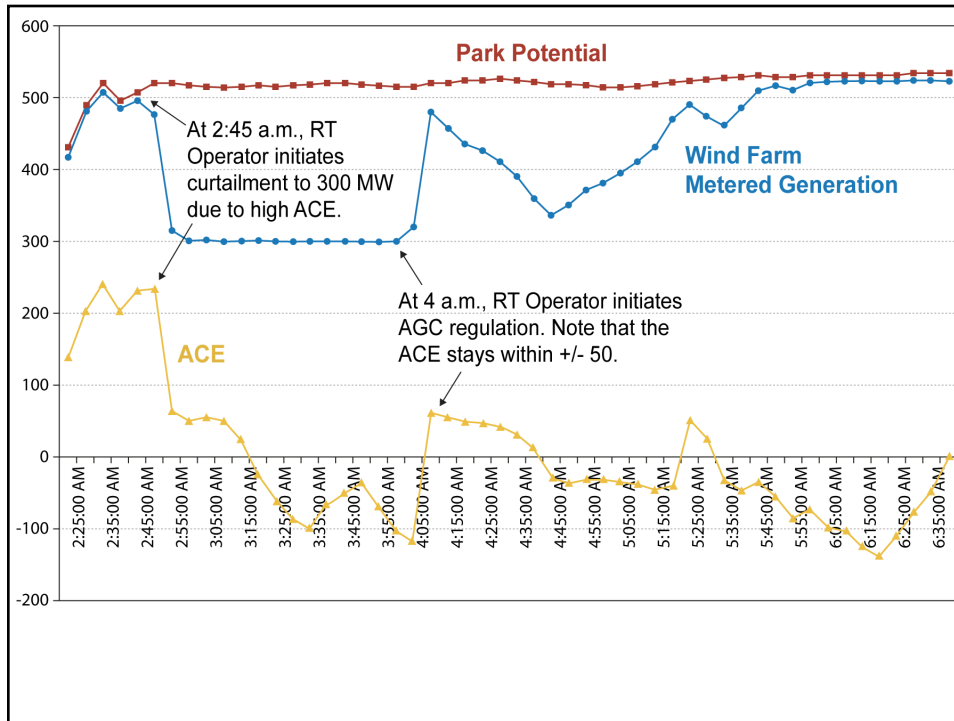
- Wind can provide synthetic inertial control and primary and secondary frequency response
- Wind can follow economic dispatch signals, and can be incorporated into economic dispatch or market operations
- This example shows how Public Service Company of Colorado improved its Area Control Error (ACE) using controllable wind energy during a period of very high wind and low demand
- Next slide enlarges the graph

Source: Public Service Company of Colorado



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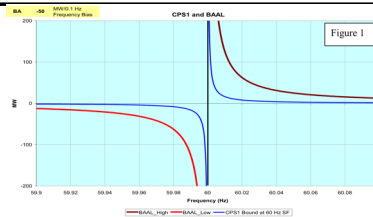
98



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Summary: Flexibility

- Flexibility is increasingly important
- BUT – LOLP-based flexibility assessments may not be useful
 - What target?
 - How does this type of analysis true up with actual NERC Balancing Standards?
- Wind/solar can provide significant flexibility, faster response than thermal units
 - Whether to dispatch wind/solar is an economic question, not a reliability question (usually)



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Hypothetical LOL event

- Assume triggered by insufficient resources
- In which time frame would it unfold?
 - Regulation: arc furnace or similar
 - Load following most likely

System Load (MW)

Time (hour of day)

seconds to minutes
Regulation

tens of minutes to hours
Load Following

day
Scheduling

Days

Unit Commitment

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What is context (the BAA)?

• Island system

- Hawaii can't abide by NERC balancing – needs more stringent requirements because of small size, no neighbors
 - Disturbance (DCS) 15-minutes is ok for interconnection, but not small island system
- As (net) demand increases as LOL event unfolds, do you
 - Run with lean operating reserves?
 - Maintain operating reserves and curtail?
- How long is event?
- How much dispatchable demand exists?



And how, when, do you know it is a potential LOL event, not just an up-ramp?

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What is context (the BAA)? (cont)

• Interconnected system

- BAA within an interconnection
- Event begins to unfold
- Situational awareness is critical
- Does shortage trigger reserve sharing group?
 - This is different than the usual contingency because it is slow (contingency is very fast)
- How to make up the energy?
 - Short-term emergency transactions with neighbors
 - Within the BAA there are no additional resources available to commit/dispatch
- What is the depth of dispatchable demand?

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Appendix: Some examples of recent and current practice

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MISO's Renewable Integration Impact Assessment RIIA*

- Uses ELCC as metric with 0.1d/y target
- Intent is to calculate ELCC of wind fleet
- Proposal to allocate this ELCC based on the performance of each wind plant during peak/near-peak periods
- MISO LOLEWG report
<https://cdn.misoenergy.org/2018%20LOLE%20Study%20Report89286.pdf>

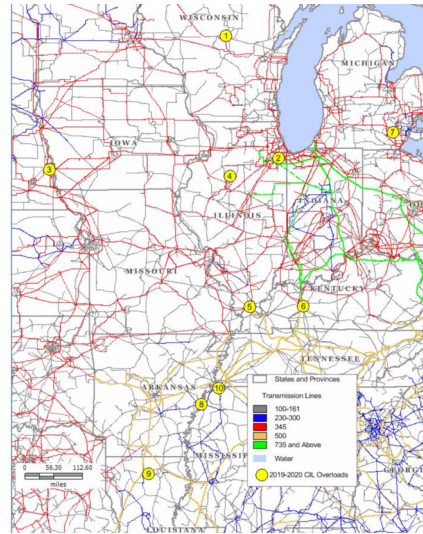
See MISO's Home Page for RIIA: <https://www.misoenergy.org/planning/policy-studies/Renewable-integration-impact-assessment/#nt=>

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MISO's Renewable Integration Impact

Assessment RIIA

- MISO LOLEWG process account for deliverability constraints using iterative process
- EFORd calculated over prior 5-year period
- Interested in monthly or seasonal RA, driven by concern over scheduled maintenance that MISO has no control over



MISO 2019-2020 Planning Import Constraint Map from LOLEWG Report

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MISO (cont)

Pooled EFORd GADS Years	2013-2017 (%)	2012-2016 (%)	2011-2015 (%)	2010-2014 (%)	2009-2013 (%)	2008-2012 (%)
LOLE Study Planning Year	2019-2020 PY LOLE Study	2018-2019 PY LOLE Study	2017-2018 PY LOLE Study	2016-2017 PY LOLE Study	2015-2016 PY LOLE Study	2014-2015 PY LOLE Study
Combined Cycle	5.37	4.62	3.56	3.78	3.92	4.74
Combustion Turbine (0-20 MW)	23.18	29.02	24.2	23.58	18.39	27.22
Combustion Turbine (20-50 MW)	15.76	13.48	13.94	16.03	53.12	25.27
Combustion Turbine (50+ MW)	5.18	6.19	5.94	5.69	5.61	5.76
Diesel Engines	10.26	10.42	13.12	12.51	14.00	9.83
Fluidized Bed Combustion	*	*	*	*	**	**
HYDRO (0-30MW)	*	*	*	*	**	**
HYDRO (30+ MW)	*	*	*	*	**	**
Nuclear	*	*	*	*	**	**
Pumped Storage	*	*	*	*	**	**
Steam - Coal (0-100 MW)	4.60	5.14	5.99	7.12	8.45	8.82
Steam - Coal (100-200 MW)	*	*	*	*	6.39	6.85
Steam - Coal (200-400 MW)	9.82	9.77	8.64	8.46	8.44	8.33
Steam - Coal (400-600 MW)	*	*	*	7.04	6.99	6.98
Steam - Coal (600-800 MW)	8.22	7.90	7.42	7.58	7.36	**
Steam - Coal (800-1000 MW)	*	*	*	*	**	**
Steam - Gas	11.56	11.94	11.68	10.18	8.79	**
Steam - Oil	*	*	*	*	**	**
Steam - Waste Heat	*	*	*	*	**	**
Steam - Wood	*	*	*	*	**	**
MISO System Wide Weighted	9.28	9.16	8.21	7.98	7.67	7.55

*MISO system-wide weighted forced outage rate used in place of class data for those with less than 30 units reporting 12 or more months of data
 **Prior to 2015-2016PY the NERC class average outage rate was used for units with less than 30 units reporting 12 or more months of data

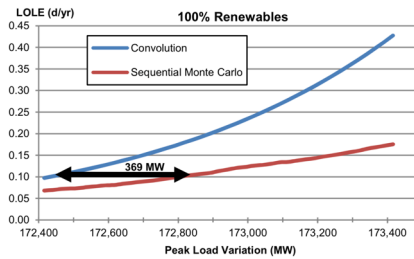
Table 4-1: Historical Class Average Forced Outage Rates

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MISO's LOLEWG and Sample Work

- **MISO established an LOLE working group; 2019 study**
 - PRM based on UCAP = 7.9% to each LSE
 - Provides zonal Capacity Import and Export Limits, accounted for in RA study
 - Incorporated firm sales to neighbors, imports from neighbors
 - Extensive ELCC analysis of renewables (see also Wind Capacity Credit Report below)
 - Dispatchable demand assessed
 - 5-year data window
 - Temperature adjustments to demand
 - PMAPS paper compared convolutions and Sequential Monte Carlo
- **MISO is excellent example**



MISO has long history of high-quality RA and ELCC work that includes wind/solar, and is a good resource for wide range of excellent work on these issues.

<https://www.misoenergy.org/stakeholder-engagement/committees/loss-of-load-expectation-working-group/>
<https://cdn.misoenergy.org/2019%20Wind%20and%20Solar%20Capacity%20Credit%20Report303063.pdf>

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PJM's Resource Adequacy Process

- **Reliability Pricing Model (RPM); predicated on determining need for capacity**
- **IRM = installed reserve margin, based on LOLE of 1d/10y**
- **Concern over winter RA because of scheduled maintenance**
- **Represents "rest of the world" network**
- **Calendar-ordered chronology of loads; GE MARS model**

<https://www.pjm.com/directory/manuals/m20/index.html#Sections/Introduction.html>

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PJM Wind Capacity Credit

- **Current method:**
 - Wind capacity factor for hours ending 3pm-6pm, June, July, August
 - Rolling 3 years of data with 11% class average default
- **Move to ELCC for wind and solar, as proposed by committee (link below)**

<https://wired.pjm.com/-/media/committees-groups/subcommittees/irs/20190313/20190313-item-05-calculation-of-capacity-values-for-wind-and-solar-capacity-resources.ashx>

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California Public Utilities Commission

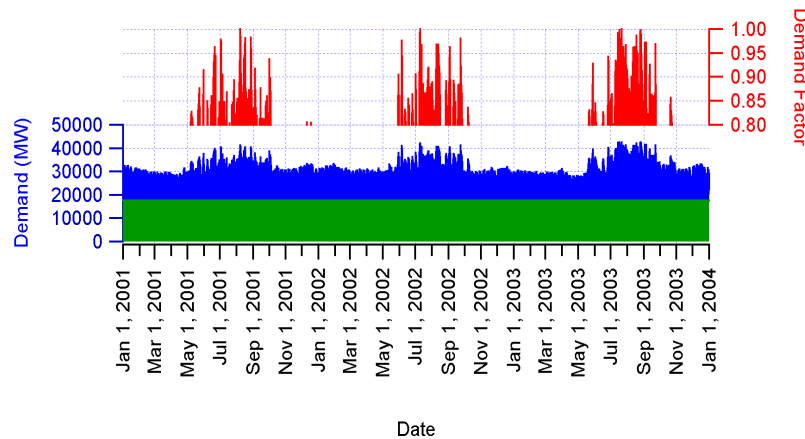
- **CPUC coordinates with the CAISO**
- **Resource adequacy target of 2.4h/y**
- **Qualifying capacity (QC) for wind, solar based on ELCC**
- **Secondary analysis of deliverability**
 - Net qualifying capacity (NQC) = QC
 - $NQC < QC$ if congestion prevents partial delivery
 - If resource can't be delivered during times of LOLH then it is classified as energy-only
- **Non-dispatchable hydro, geothermal based on prior 3 years of data, if available**

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- **Monthly ELCC; however, the target is not clear; monthly LOLH is most often zero**



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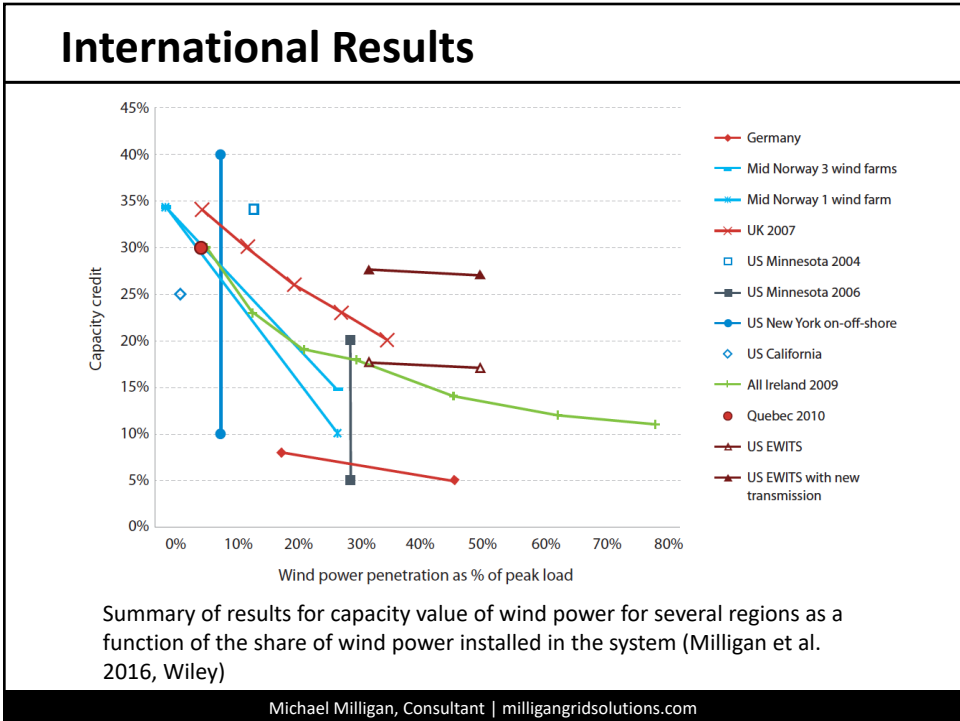
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California Public Utilities Commission

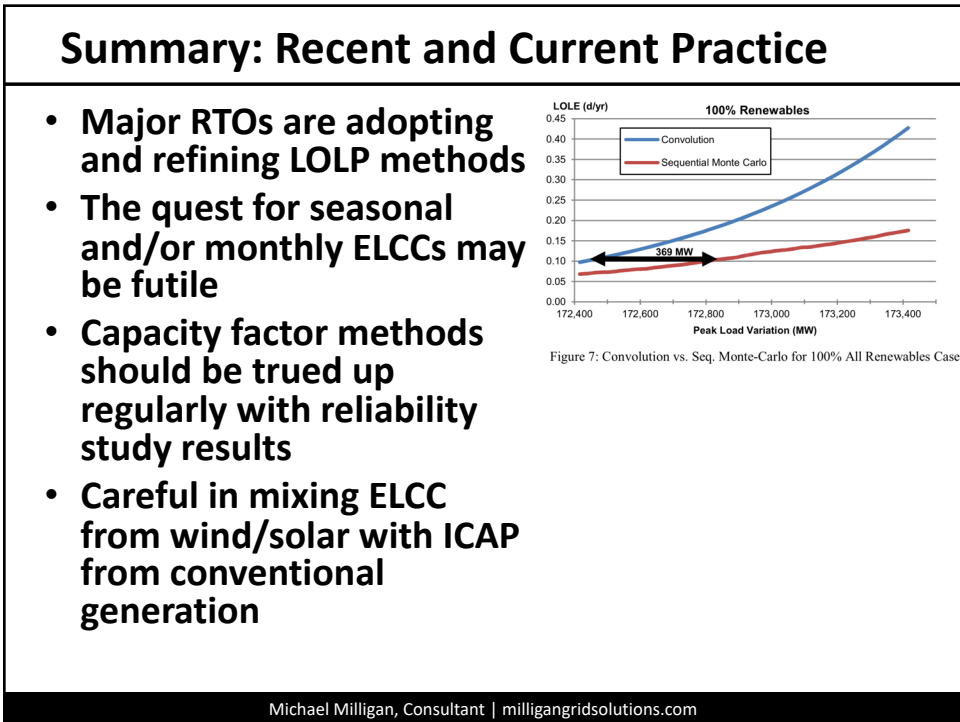
- **Conventional plants' NQC is based on 4-hour maximum output (not ELCC)**
- **Details can be found in Rule R.17-09-020**
- **Interest in monthly ELCC**
 - Monthly LOLE, LOLH, etc. are nearly always zero outside of peak months → artificial "reliability" construct
- **Assessment**
 - Mixes apples and oranges: would be consistent if ELCC were used for all resources
 - Exception is that planned maintenance could result in LOLE outside of peak periods

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Appendix: The pursuit of simplicity

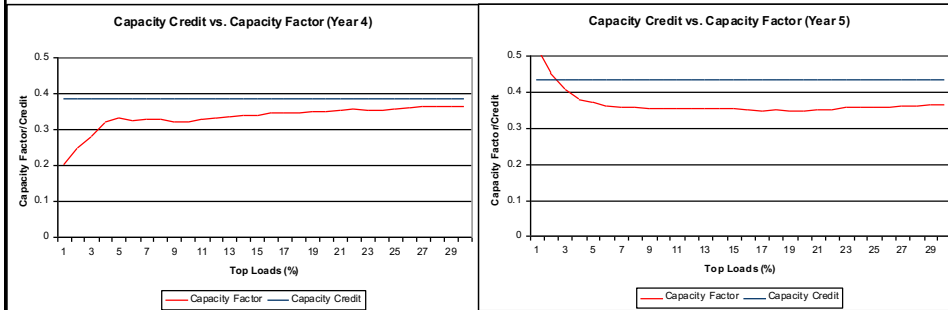
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Other Approaches	
<ul style="list-style-type: none"> • Many entities use an approximation method • Common approximation is capacity factor over some defined peak period • Most have not compared the approximation to a reliability-based metric <p><i>ELCC can yield non-intuitive results. For example, if resource A is added before B, then resource A will “sop up” much of the reliability need. If B is added before A, then the reverse is true. Thus the ELCC of a resource depends, in part, on the order in which it was added to the RA model.</i></p>	
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Peak-period capacity factors may not match ELCC

- VG-load relationship is only part of the equation
- Capacity factor, even during peak periods, won't necessarily match ELCC

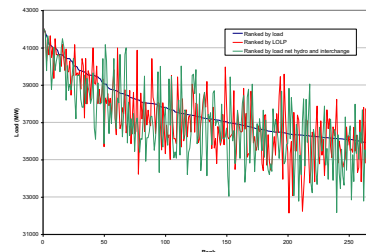


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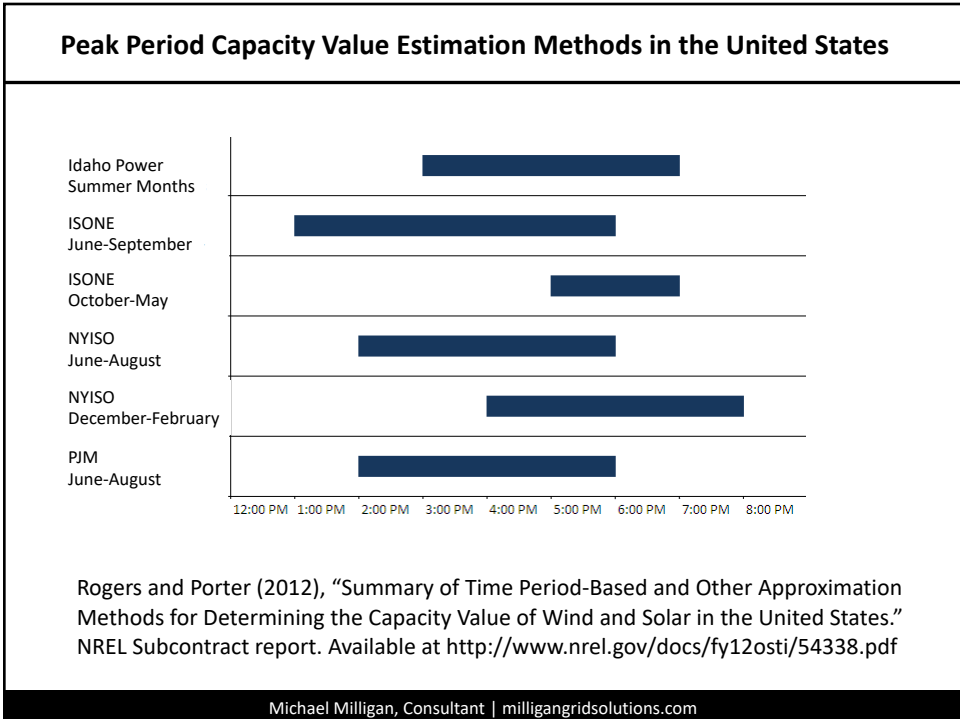
Mis-match between peak c.f. and ELCC

- Results from factors that affect LOLE, and therefore ELCC
- Scheduled maintenance
- Availability of imports, hydro
- Unusual weather years

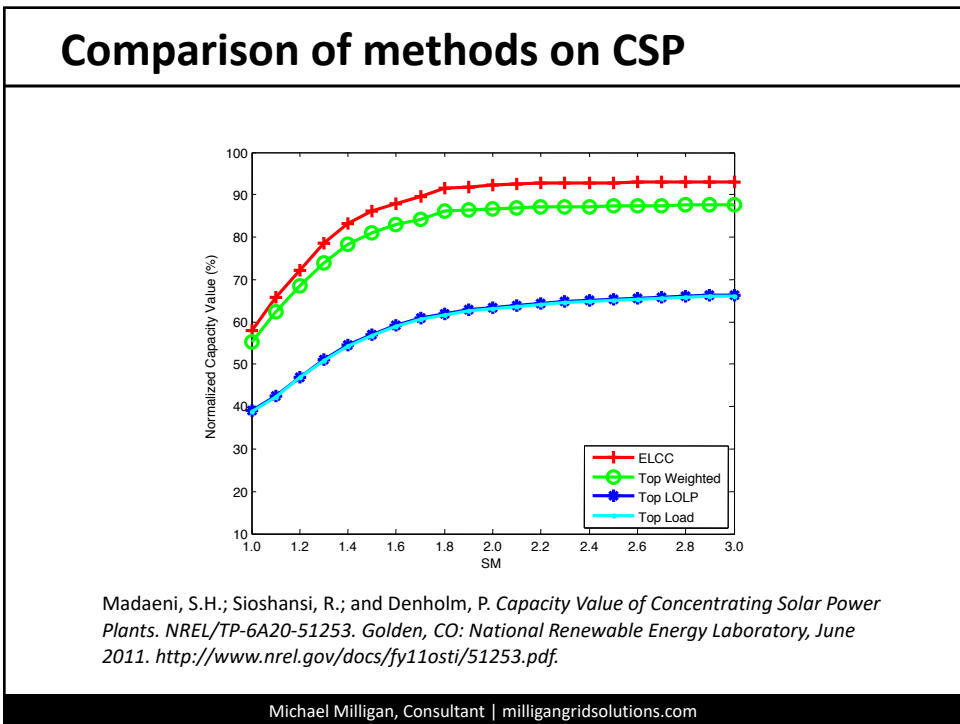


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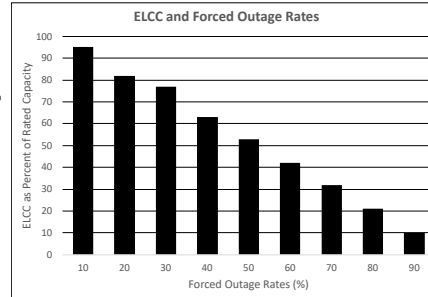
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PRM is a hard habit to kick

- Suppose we agree UCAP is close enough to use for generators. We calculate ELCC for wind/solar.
- UCAPs + ELCC = ?
- What is the correct PRM relative to total UCAP?
- What about sum of all ICAPS + wind/solar ELCC = ?

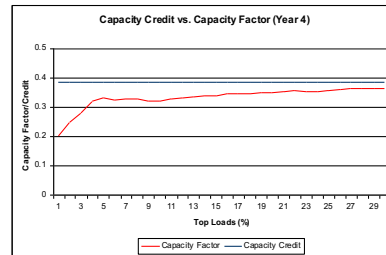


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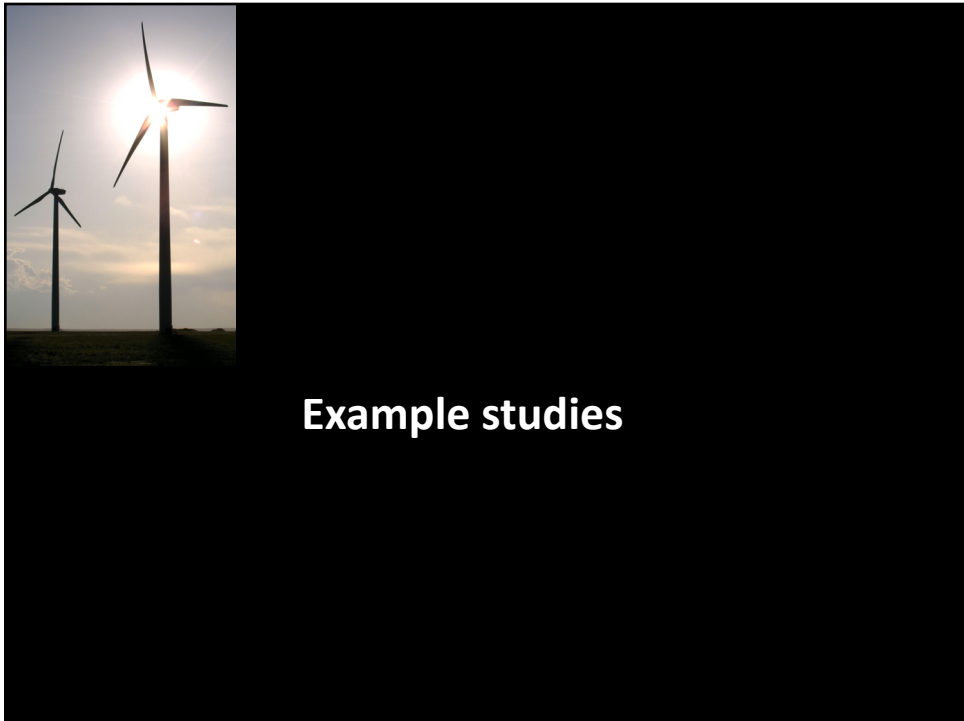
Summary: Pursuit of Simplicity

- Simplified assessments of capacity value will introduce at least some inaccuracy
- Be careful mixing
 - UCAP and ELCC
 - ICAP and ELCC
 - Other inconsistent metrics



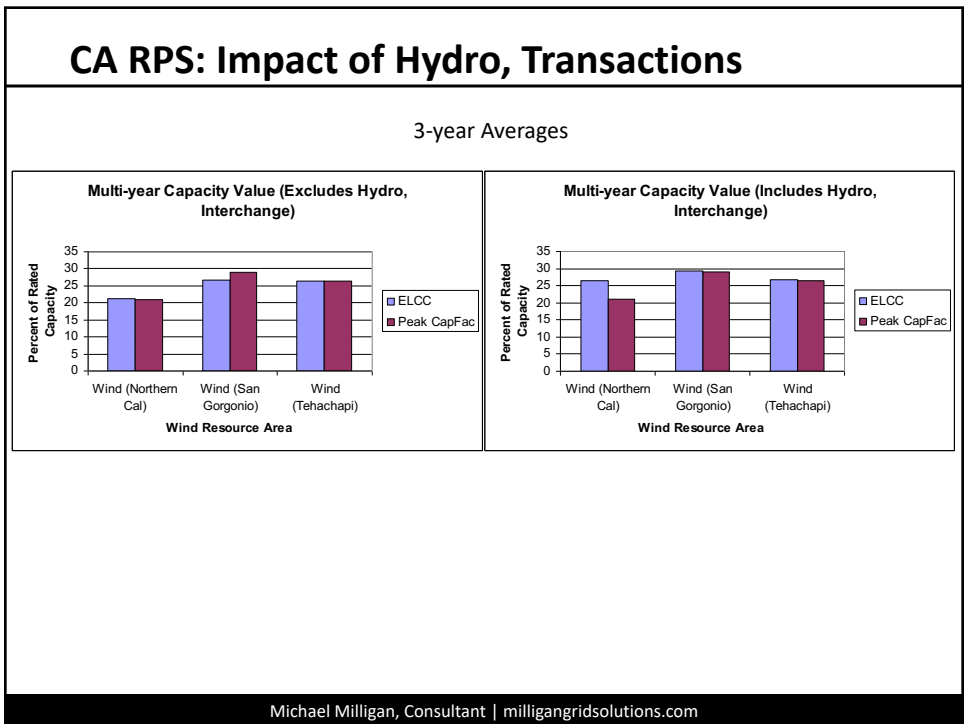
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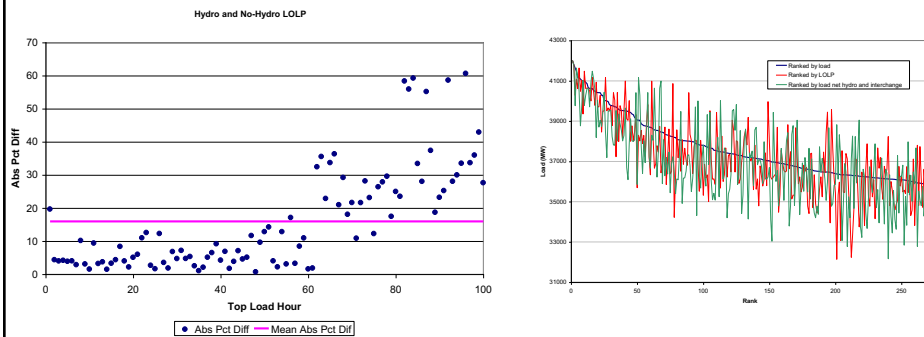
Example studies

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CA RPS Study: Hydro and Interchange

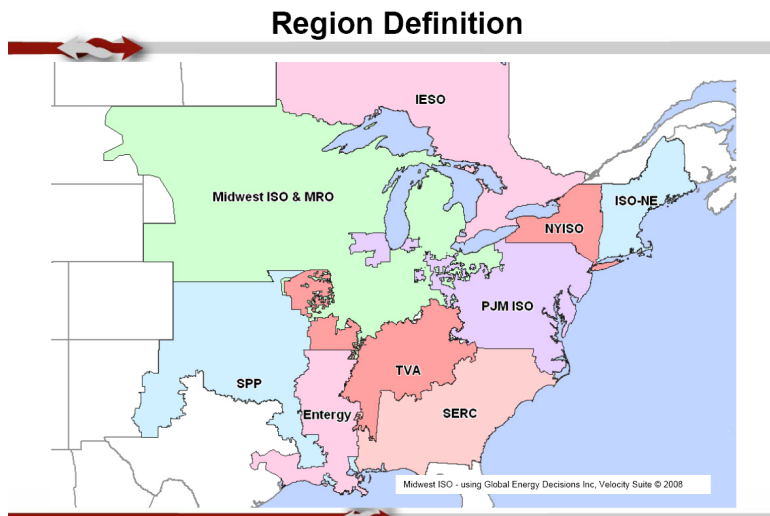


- Hot, late summer into October
- Hydro runoff had ended
- Thermal plants went out on planned maintenance Oct 1

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Eastern Wind Integration and Transmission Study



Circa 2009 data, report in 2011 at <https://www.nrel.gov/docs/fy11osti/47078.pdf>

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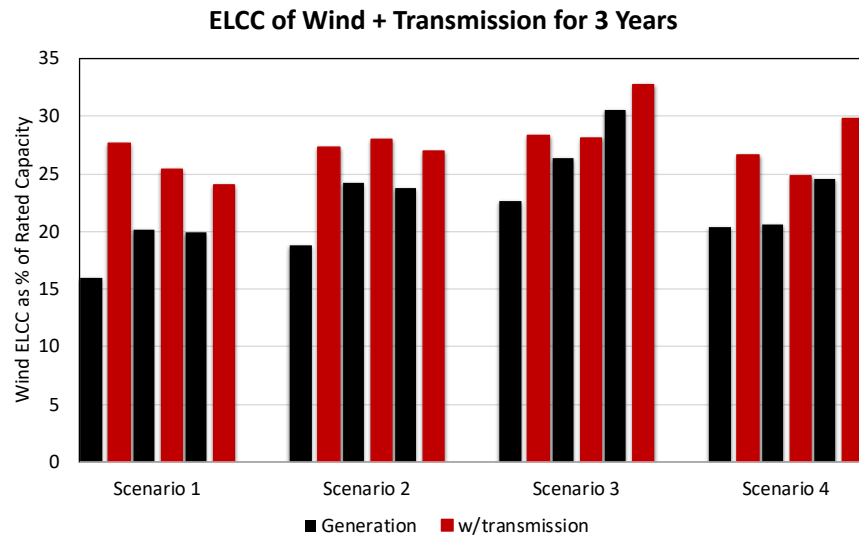
Total Study System ELCC Results

- The subsequent graphs contain ELCC results calculated for the Full Eastern Interconnect Study System under the following Transmission Sensitivities:
 - Stand-Alone (Isolated) Zone
 - Without Transmission Overlay (Existing Transmission)
 - Infinite Tie Limits (Copper-Sheet)
- The findings from Full Study System results were:
 - The ELCC of Wind Increases as the Transfer Capability between Zones Increases
 - The “Copper-Sheet” sensitivity represents the highest achievable ELCC for Wind in the Eastern Interconnect based on the 2004, 2005 & 2006 historical load and wind profiles

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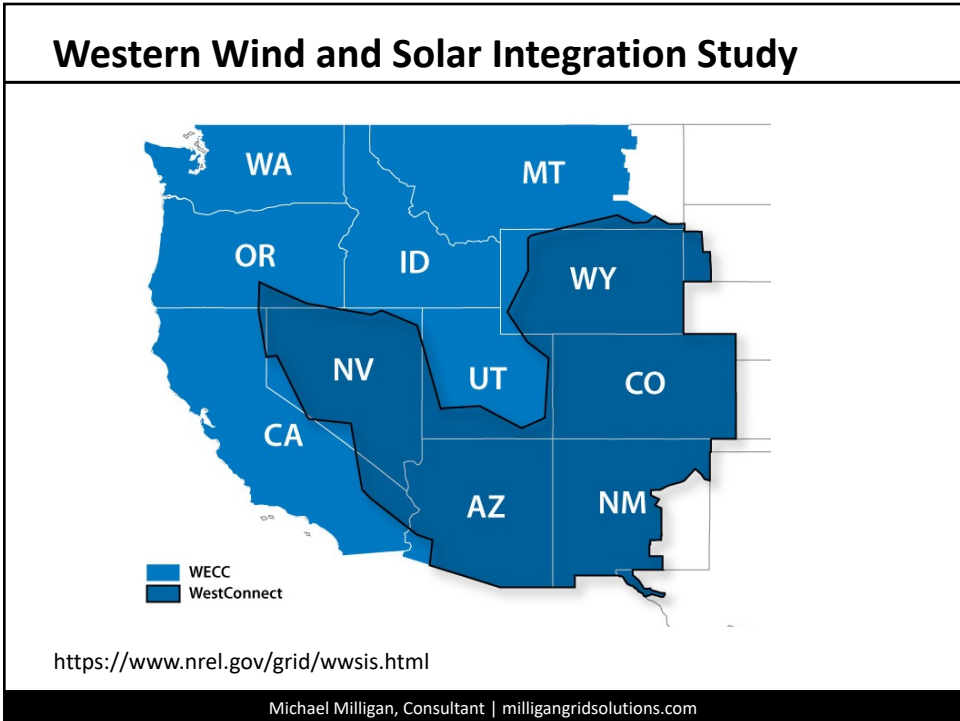
LOLP and ELCC depend on footprint and transmission



Adapted from Eastern Wind Integration and Transmission Study <https://www.nrel.gov/docs/fy11osti/47078.pdf>

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Capacity Values

Penetration	Total MW	Wind MW	CSP MW	PV MW
0%	0	0	0	0
10% Wind, 1% Solar	11490	10,290	600	600
20% Wind, 3% Solar	23350	19,950	1,700	1,700
30% Wind, 5% Solar	35740	29,940	2,900	2,900

LOLE (days/yr)	Wind + CSP+PV	Wind only	CSP only	PV only
	0	1815	1175	555
	4134	2147	1586	457
	6610	3193	2673	781

LOLE (hours/yr)	Wind + CSP+PV	Wind only	CSP only	PV only
	0	1962	1301	545
	4323	2293	1575	516
	6746	3304	2686	841

Unserved Energy (MWh/yr)	Wind + CSP+PV	Wind only	CSP only	PV only
	0	1913	1243	531
	4300	2228	1574	511
	6665	3222	2685	851

Average	Wind + CSP+PV	Wind only	CSP only	PV only
	0	1896	1240	544
	4262	2223	1578	494
	6674	3240	2682	824

Penetration	Wind + CSP+PV	Wind only	CSP only	PV only
	0%	0%	0%	0%
10%	16%	11%	93%	29%
20%	18%	11%	93%	27%
30%	18%	11%	92%	27%

Penetration	Wind + CSP+PV	Wind only	CSP only	PV only
	0%	0%	0%	0%
10%	17%	13%	91%	32%
20%	19%	11%	93%	30%
30%	19%	11%	93%	29%

Penetration	Wind + CSP+PV	Wind only	CSP only	PV only
	0%	0%	0%	0%
10%	17%	12%	89%	33%
20%	18%	11%	93%	30%
30%	19%	11%	93%	29%

Penetration	Wind + CSP+PV	Wind only	CSP only	PV only
	0%	0%	0%	0%
10%	17%	12%	91%	31%
20%	18%	11%	93%	29%
30%	19%	11%	92%	28%

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IEEE LOLEWG Has Multiple Studies

The screenshot shows the IEEE RRPASC website with the following content:

RRPA
Reliability Risk and Probability Applications

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WG on LOLE Best Practices

Presentations from July 2015 meeting

- Simon Tindemans (Imperial College London), Visualising multidimensional risk profiles in generation adequacy studies
- Donald Brooks (California Public Utilities Commission), Update on CPUC staff LOLE and ELCC Modeling Results
- Gene Preston (PSC), A Simple Calculation Procedure for LOLE, LOLA, and ELEC Calculation of Probabilistic Transmission Line Flows, and Study Results for Extreme Renewables in ERCOT
- John Fazio (WPCC), Adequacy's Role in Resource Planning for the Pacific NW
- Noha Abdel-Karm (NERC), NERC Probabilistic Assessments: Overview & Future Improvements
- Chris Dent (Durham University), Issues in modelling wind-demand relationship in GB
- Amy Wilson (Durham University), Statistical modelling for inclusion of wind generation in industrial adequacy studies
- Paul Denholm (NREL), Some random work on solar and storage capacity credit

Presentations from July 2016 meeting

- Alex Crawford (SPP), SPP LOLE Efforts
- Amy Wilson (Durham University), Accounting for wind-demand dependence when estimating LOLE
- Ben Kujala and John Fazio (WPCC), Incorporating an Adequacy Standard into Resource Expansion Planning for the Pacific NW
- Cindy Bothwell (Johns Hopkins University), System Adequacy with Intermittent Resources – Capacity Value and Economic Distortions
- Daniel Burke (National Grid), GB Security of Supply – International Study on Standards and Implementation
- Gene Preston, Introducing Modeling Errors Into Variable Resources Studies
- Gene Preston, Task Force Upgrading RTS To Include Variable Resources
- John Reinhart (PSC), WSD Capacity Market Seasonal Considerations
- Kevin Carden (Astrape), Seasonal Reliability Modeling in SERVM
- Noha Abdel-Karm (NERC), NERC Project – Increase Analytical Capabilities in the Probabilistic Domain
- Simon Tindemans (Imperial College London), Determining the capacity value of interconnectors, and implications for capacity markets

Presentations from July 2017 meeting

- LOLEWG Summary
- National Grid Security of Supply – International Review
- Security of Supply – International Review of Standards and Implementation Review

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- <http://sites.ieee.org/pes-rrpasc/working-groups/wg-on-lole-best-practices/>

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