

**Evolution of Grid Services:  
Past, Present, Future**

*How will grid reliability be  
maintained in light of the  
changing resource mix?*

**Michael Milligan, Consultant**

FERC, Commissions in Arkansas and  
Minnesota, SPP, PJM, Public Workshops  
in Ohio, Washington DC  
Feb-Mar, 2019

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## Acknowledgements

- **Charlie Smith, Energy Systems Integration Group**
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- **Jim McCalley, Iowa State University**
- **Ron Lehr, Consultant**
- **GridLab**

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## Purpose and Objectives

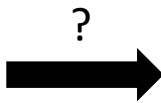
- **This course provides an overview of the evolution of grid services in the power system**
- **Topics include**
  - A review of how the grid “traditionally” recovers from disturbances/contingency events
  - How this recovery will change with potential retirements from large, rotating generation, and the increase in inverter-based generation such as wind, solar, and batteries
  - Which services can be provided by key resources? (next page)

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## Objective: Which resources provide grid services?

- Wind
- Solar PV
- Natural Gas
- Coal
- Nuclear
- Hydro
- DR
- Battery (storage)



### Reliability

- Disturbance ride-through (voltage, frequency)
- Reactive power and voltage control
- Primary frequency response (PFR), including inertial response time scale
- AGC frequency regulation
- Flexibility (ability to quickly respond to, and maintain, set-point/dispatch instructions)

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## Outline

- Electric power system fundamentals
- What happens immediately after a grid disturbance with “traditional resources” (*past and present*)
- Brief description of grid services
- Which types of resources can provide them?
- How can disturbances be contained in the future? (freq response curve)
- How does this compare to PJM’s work?
- What do we know? What do we not know?
- References
  - [Milligan, M. \(2018\). Sources of grid reliability services. \*The Electricity Journal\*, 31\(9\), pp. 1-7.](#)
  - Fact Sheet: Sources of Grid Reliability Services
  - Available at [milligangridsolutions.com](http://milligangridsolutions.com)

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## Introduction

- **Digital revolution\* at the same time as technology revolution**
  - Power electronics/software coupling from DC devices to AC grid: wind, solar, battery, ...
  - Within physical limits we can now specify responses, which can be fast and accurate
  - Important to get the software design right
    - Generalize for different technologies
    - Ensure robust grid service definitions
- **Can the *portfolio* of resources provide the reliability services we need?**
- **Are the proper incentives in place for investment and operations?**

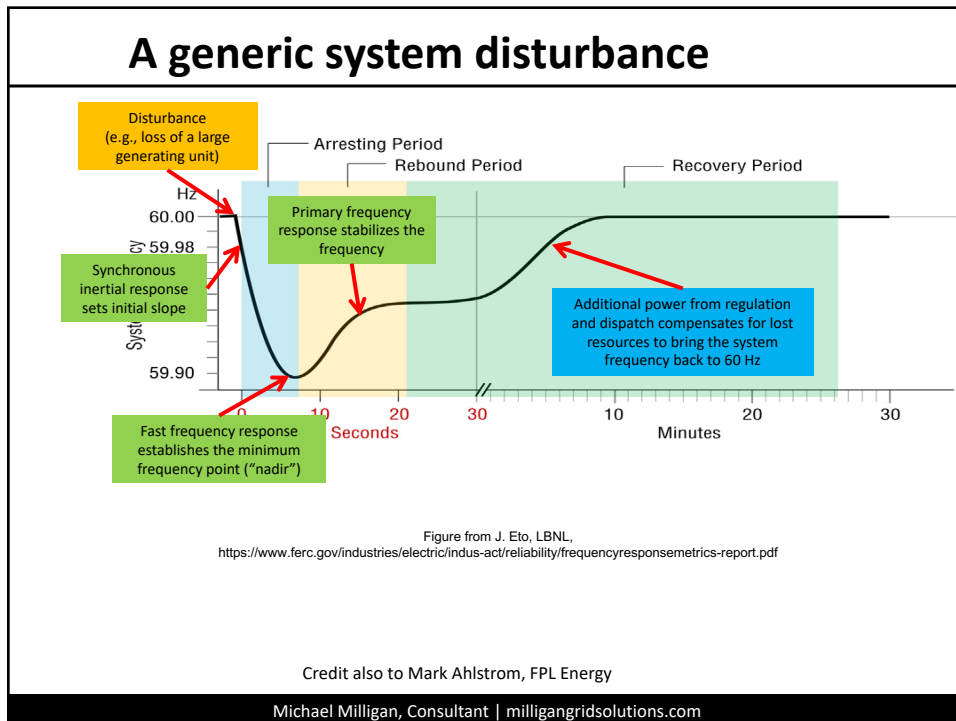
\*Thanks to Mark Ahlstrom for this interesting perspective.

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# What happens immediately after a grid disturbance?

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## Traditional response

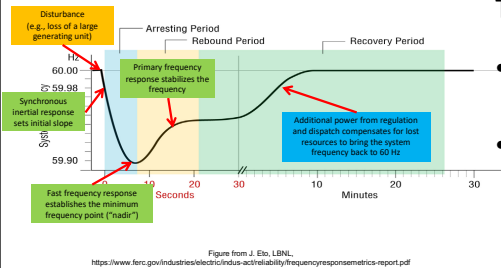


Figure from J. Eto, IJNL,  
<https://www.ferc.gov/industries/electric/indus-act/reliability/frequencyresponsemetrics-report.pdf>

### Traditional responders

- Large thermal units, hydro provides inertial response
- Gas, coal, hydro fast frequency response to arrest the frequency drop (typically about 10% of units actually provide this service)
- Primary response stabilizes frequency
- AGC and dispatch contribute to recovery

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**The Future: What happens in low-inertia systems with power-electronics grid interface?**

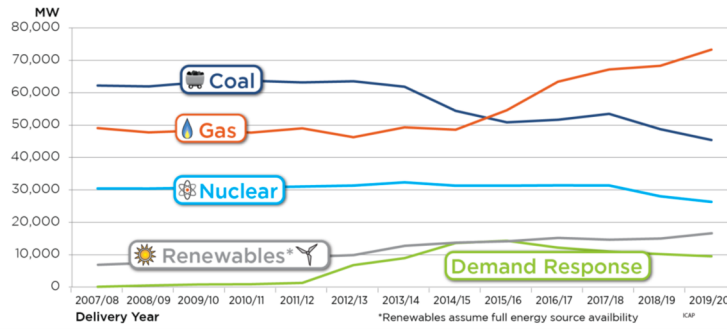
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## Less traditional, more power-electronics-coupled devices



PJM's Evolving Resource Mix and System Reliability

Figure 1. PJM Cleared Installed Capacity by Delivery Year



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## A generic system disturbance

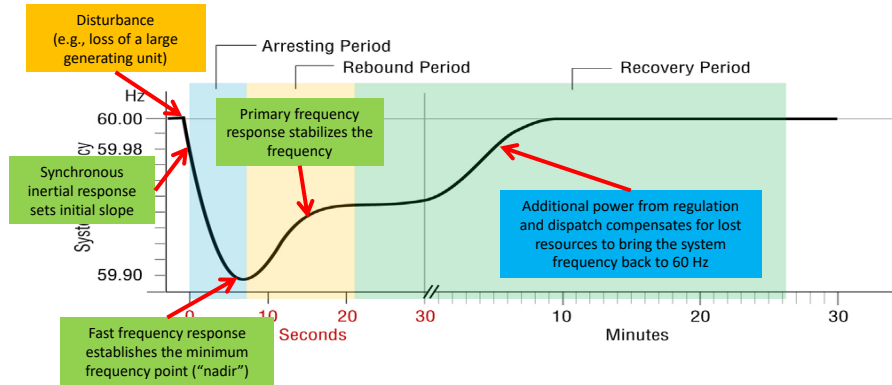
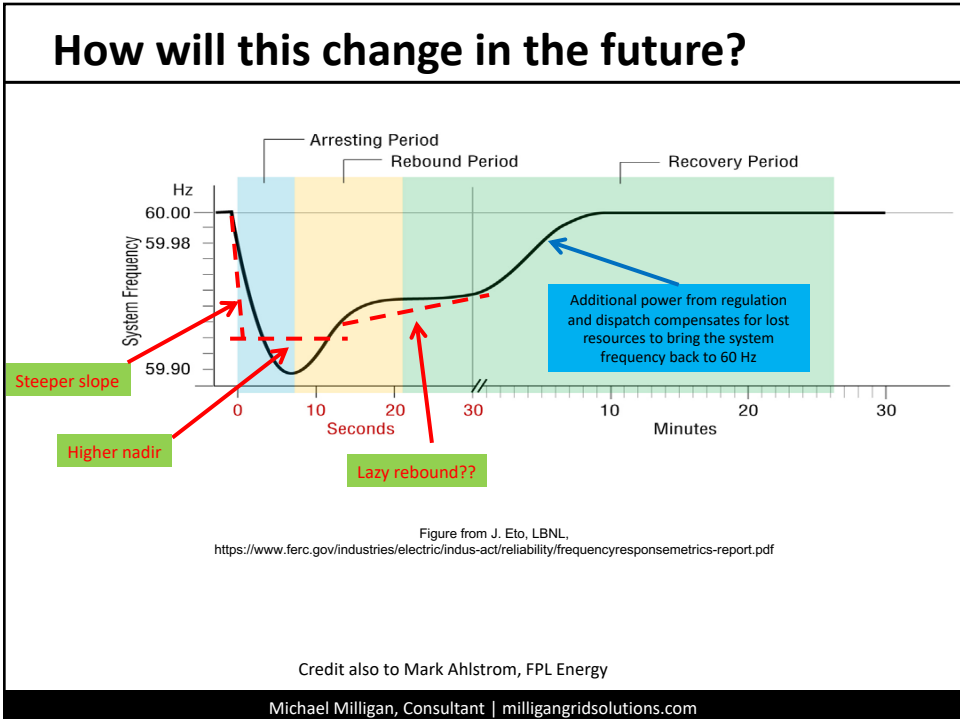


Figure from J. Eto, LBNL, <https://www.ferc.gov/industries/electric/indus-act/reliability/frequencyresponsemetrics-report.pdf>

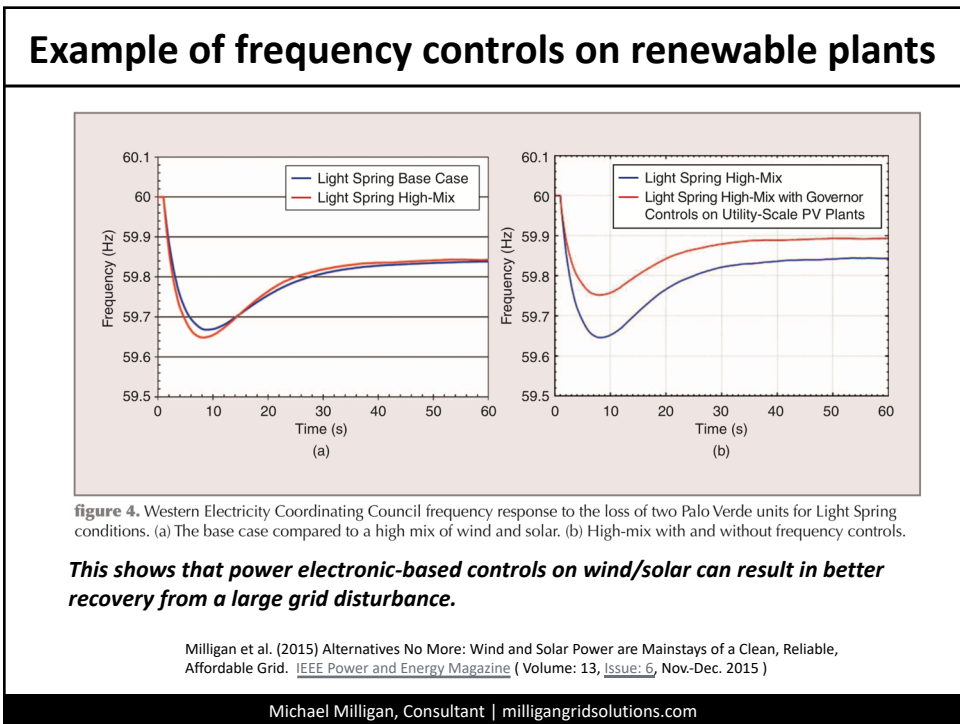
Credit also to Mark Ahlstrom, FPL Energy

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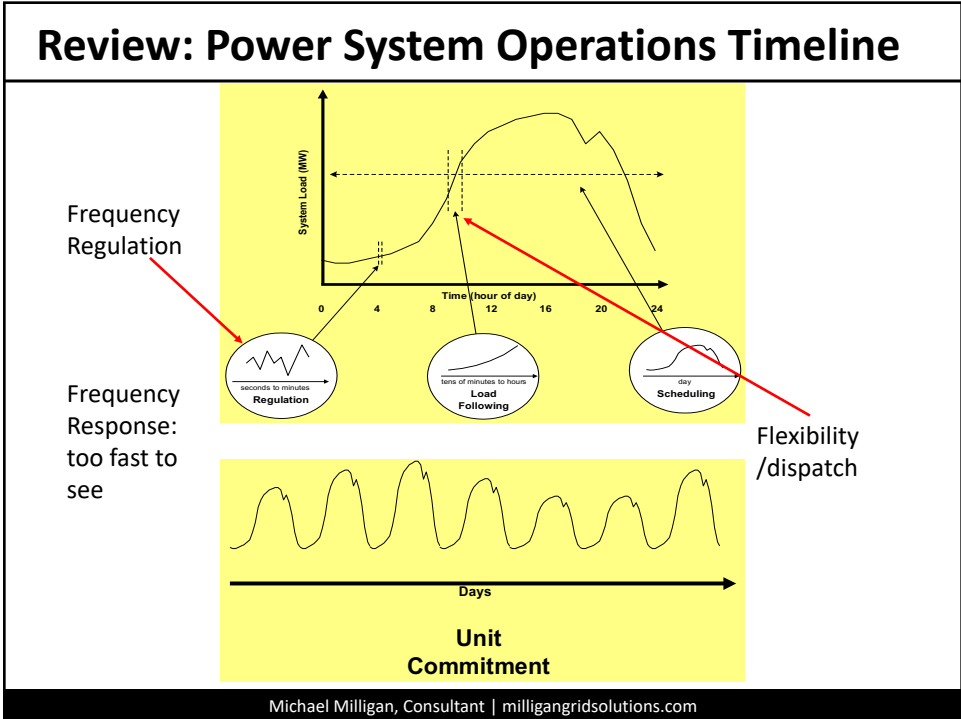
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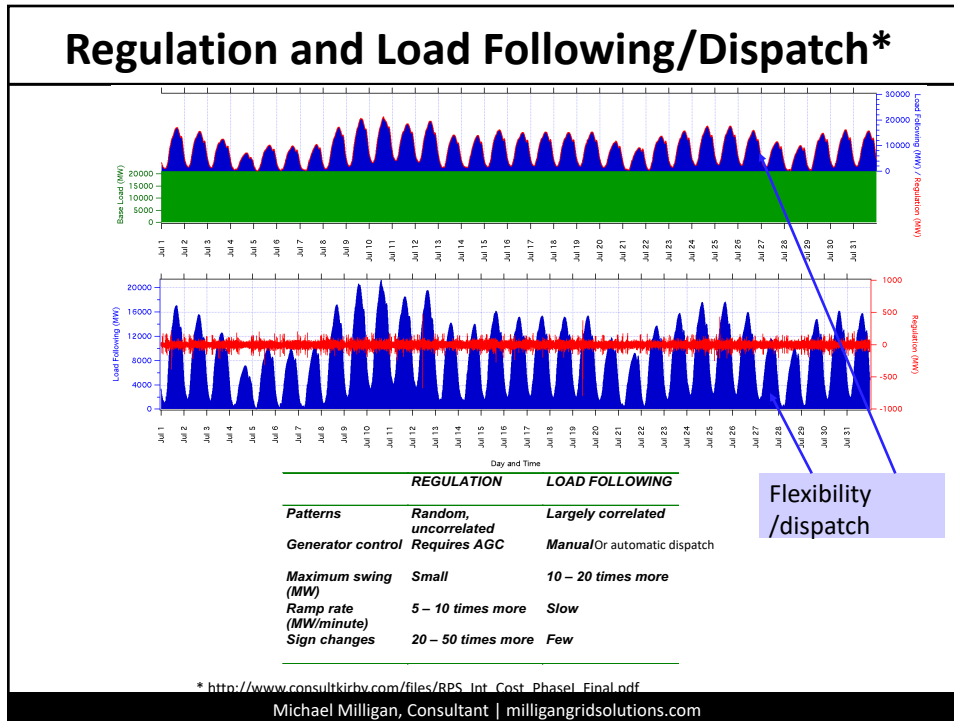
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**Key aspects of this graph can be used to describe grid reliability services**

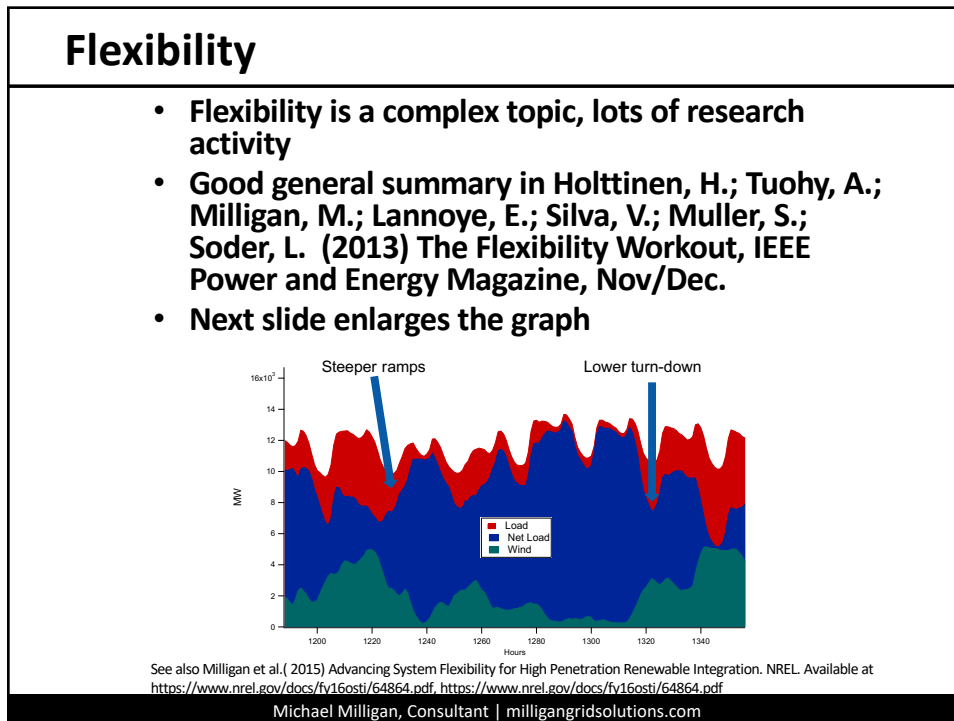
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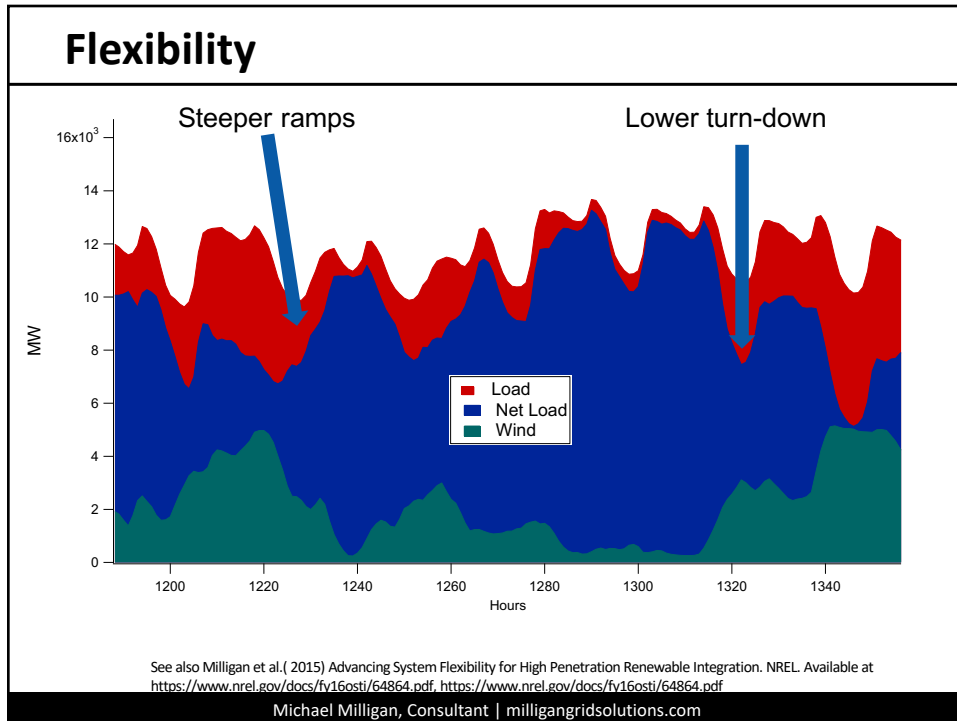
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### Description: Voltage and Frequency ride-through

- **Grid disturbance, such as transmission line or generator tripping offline, may cause voltage and frequency to vary. This may cause other resources, or loads, to also trip offline.**
- **Extreme case could result in blackout**
- **Voltage ride-through: establish ability of a resource to withstand voltage variations within a given range so that it stays online for a given time duration**
- **Frequency ride-through: establish ability of a resource to withstand frequency variations within a given range so that it stays online for a given time duration**

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### Description : Reactive Power and Voltage Support

- Maintaining proper voltages within a small dead-band is critical to keeping the lights on and avoiding equipment damage
- Vector projection of active power & reactive power (VAR) = apparent power
- Maintaining voltage is a key element of stability
- Reactive power can be supplied by generators or other devices such as synchronous condensers

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### Sources of grid services

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

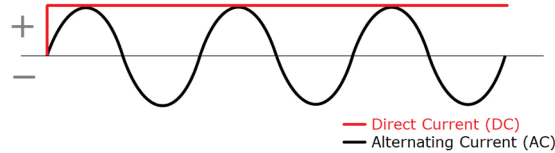
● Excellent 
 ◐ Very Good 
 ◑ Good 
 ◒ Limited 
 ○ Incapable

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## Wind, solar, and battery are non-synchronous

- They produce a DC current, whereas the grid is AC



- To achieve “compatibility” with the grid, the DC must be converted to AC
- This conversion is done thru power electronics: software/hardware that can be configured for multiple responses
- Software can therefore control the hardware, subject to hardware/physics limitations

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## Upward vs. downward response

- Wind and solar can increase or decrease output very quickly—faster than most thermal plants
- Whenever a wind/solar plant is producing output, it can reduce output very quickly in response to an AGC or dispatch command
- However, responding to AGC or dispatch signal to *increase* output requires the wind/solar to operate in a “pre-curtailed” output level and is often uneconomic

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## Wind, solar, and storage are non-synchronous

	Inverter-Based		
	Wind	Solar PV	Storage/ Battery
Disturbance ride-through			
Reactive and Voltage Support			
Slow and arrest frequency decline (arresting period)			
Stabilize frequency (rebound period)			
Restore frequency (recovery period)			
Frequency Regulation (AGC)			
Dispatchability/Flexibility			

- FERC 661A was developed to ensure rigorous ride-through capabilities for wind plants. Not all thermal plants can comply. Solar has capability but was sometimes prevented from responding; FERC Order 828 allows solar response.

Excellent 
 Very Good 
 Good 
 Limited 
 Incapable

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## Wind, solar, and storage

	Inverter-Based		
	Wind	Solar PV	Storage/ Battery
Disturbance ride-through			
Reactive and Voltage Support			
Slow and arrest frequency decline (arresting period)			
Stabilize frequency (rebound period)			
Restore frequency (recovery period)			
Frequency Regulation (AGC)			
Dispatchability/Flexibility			

- Wind and solar can provide reactive and voltage support via the power electronics interface; storage has the same capability. Service can be provided even when not generating.

Excellent 
 Very Good 
 Good 
 Limited 
 Incapable

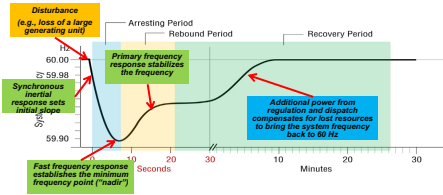
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## Wind, solar, and storage

	Inverter-Based		
	Wind	Solar PV	Storage/ Battery
Disturbance ride-through	🟢	🟡	🟡
Reactive and Voltage Support	🟢	🟢	🟢
Slow and arrest frequency decline (arresting period)	🟡	🟡	🟡
Stabilize frequency (rebound period)	🟡	🟡	🟡
Restore frequency (recovery period)	🟡	🟡	🟡
Frequency Regulation (AGC)	🟡	🟡	🟢
Dispatchability/Flexibility	🟡	🟡	🟢

● Excellent 
 ◐ Very Good 
 ◑ Good 
 ◒ Limited 
 ○ Incapable



- Power electronics can help slow, and arrest, frequency declines after a disturbance. Fast frequency response is nearly immediate.

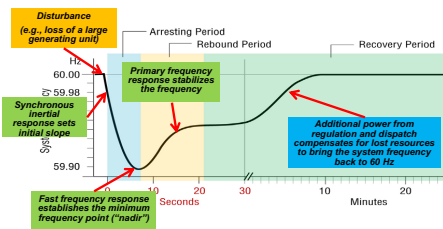
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## Wind, solar, and storage

	Inverter-Based		
	Wind	Solar PV	Storage/ Battery
Disturbance ride-through	🟢	🟡	🟡
Reactive and Voltage Support	🟢	🟢	🟢
Slow and arrest frequency decline (arresting period)	🟡	🟡	🟡
Stabilize frequency (rebound period)	🟡	🟡	🟡
Restore frequency (recovery period)	🟡	🟡	🟡
Frequency Regulation (AGC)	🟡	🟡	🟢
Dispatchability/Flexibility	🟡	🟡	🟢

● Excellent 
 ◐ Very Good 
 ◑ Good 
 ◒ Limited 
 ○ Incapable



- Power electronics can help stabilize frequency during the rebound period. AGC begins responding in seconds if available.

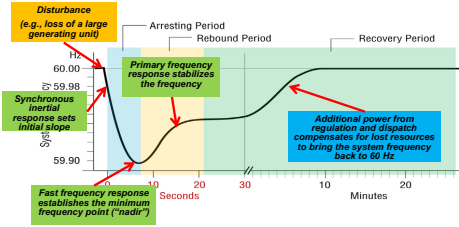
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## Wind, solar, and storage

	Inverter-Based		
	Wind	Solar PV	Storage/Battery
Disturbance ride-through	🟢	🟡	🟡
Reactive and Voltage Support	🟢	🟢	🟢
Slow and arrest frequency decline (arresting period)	🟡	🟡	🟡
Stabilize frequency (rebound period)	🟡	🟡	🟡
Restore frequency (recovery period)	🟡	🟡	🟡
Frequency Regulation (AGC)	🟡	🟡	🟢
Dispatchability/Flexibility	🟡	🟡	🟢

● Excellent 
 ◐ Very Good 
 ◑ Good 
 ◒ Limited 
 ○ Incapable



Can provide downward response any time it is generating.

- Wind, solar, storage can respond to dispatch commands very quickly; must have head room for upward response

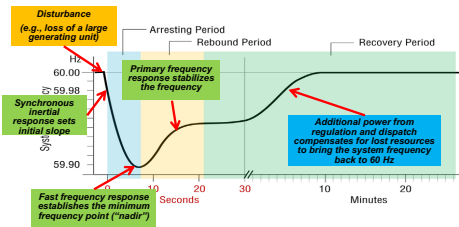
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## Wind, solar, and storage

	Inverter-Based		
	Wind	Solar PV	Storage/Battery
Disturbance ride-through	🟢	🟡	🟡
Reactive and Voltage Support	🟢	🟢	🟢
Slow and arrest frequency decline (arresting period)	🟡	🟡	🟡
Stabilize frequency (rebound period)	🟡	🟡	🟡
Restore frequency (recovery period)	🟡	🟡	🟡
Frequency Regulation (AGC)	🟡	🟡	🟢
Dispatchability/Flexibility	🟡	🟡	🟢

● Excellent 
 ◐ Very Good 
 ◑ Good 
 ◒ Limited 
 ○ Incapable



Can provide downward response any time it is generating.

- Can provide AGC if pre-curtailed; capable of very fast response.

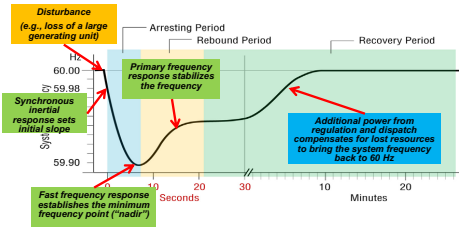
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## Wind, solar, and storage

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

● Excellent 
 ◐ Very Good 
 ◑ Good 
 ◒ Limited 
 ○ Inc



Can provide downward response any time it is generating.

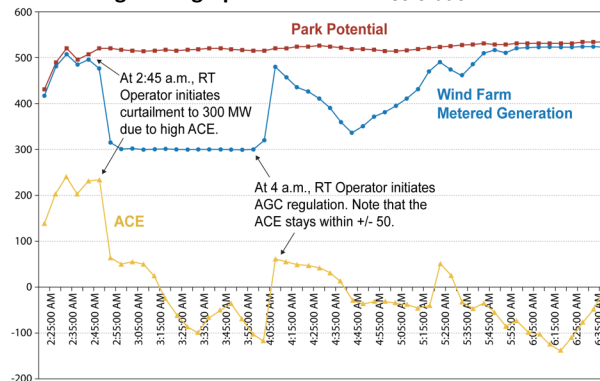
- Can provide upward dispatch if pre-curtailed; capable of very fast response.

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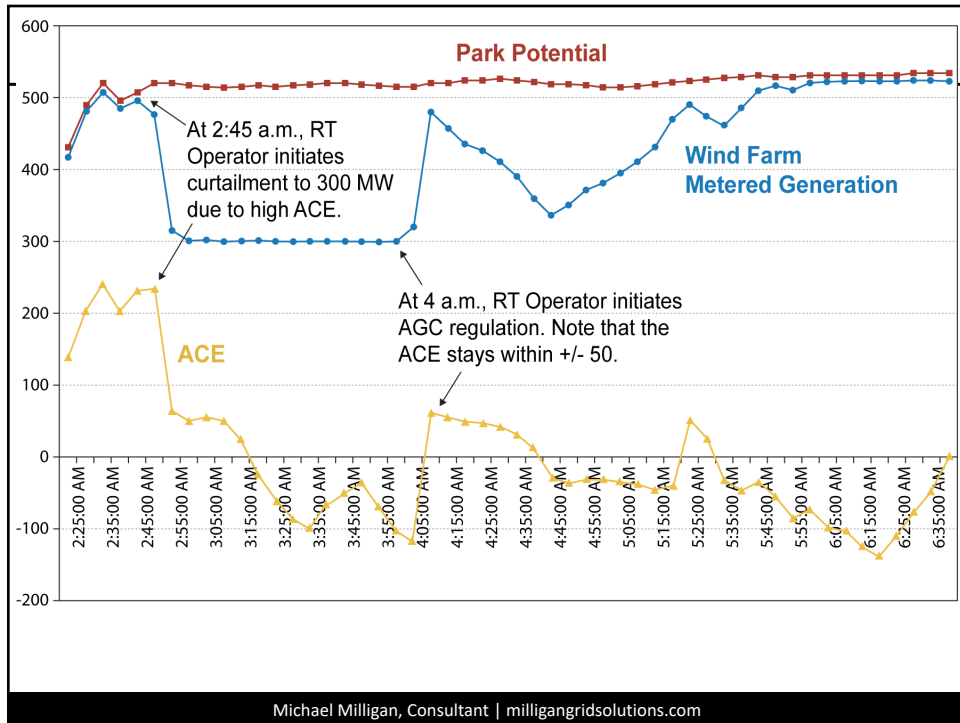
## Example: Utilizing flexible generation from wind - PSCo

- 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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## Hydro power is generally very flexible

	Synchronous
	Hydro
Disturbance ride-through	●
Reactive and Voltage Support	●
Slow and arrest frequency decline (arresting period)	◐
Stabilize frequency (rebound period)	◐
Restore frequency (recovery period)	●
Frequency Regulation (AGC)	●
Dispatchability/Flexibility	●



- Can often provide disturbance ride-thru and voltage control while operating
- Often can provide primary frequency response; but only about 10% of conventional generators provide this service
- Fast AGC and dispatch response; however, run-of-river may be a constraint

● Excellent  
 ◐ Very Good  
 ◑ Good  
 ◒ Limited  
 ○ Incapable

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# Natural gas

The H.F. Lee natural gas power plant near Goldsboro, N.C.  
Credit: [Duke Energy/flickr](#)



	Natural Gas
Disturbance ride-through	🟡
Reactive and Voltage Support	🟢
Slow and arrest frequency decline (arresting period)	🟡
Stabilize frequency (rebound period)	🟢
Restore frequency (recovery period)	🟢
Frequency Regulation (AGC)	🟢
Dispatchability/Flexibility	🟡

- Can often trip offline during disturbances
- Can provide if generating real power
- Sometimes can provide primary frequency response; but only about 10% of conventional generators provide this service
- Good AGC and dispatch response; however, gas market may be a constraint

🟢 Excellent 🟡 Very Good 🟠 Good 🟤 Limited 🟡 Incapable

**A large gas plant may set the contingency reserve level for the region.**

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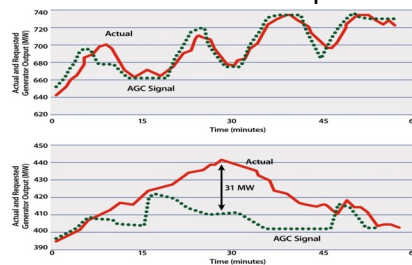
# Coal plants

	Coal
Disturbance ride-through	🟡
Reactive and Voltage Support	🟢
Slow and arrest frequency decline (arresting period)	🟡
Stabilize frequency (rebound period)	🟡
Restore frequency (recovery period)	🟡
Frequency Regulation (AGC)	🟡
Dispatchability/Flexibility	🟡

- Can sometimes trip offline during disturbances
- Can provide if generating real power
- Sometimes can provide primary frequency response; but may have governor locked down
- Generally slow response
- Slow, sometimes inaccurate AGC and dispatch response
- Slow start/stop

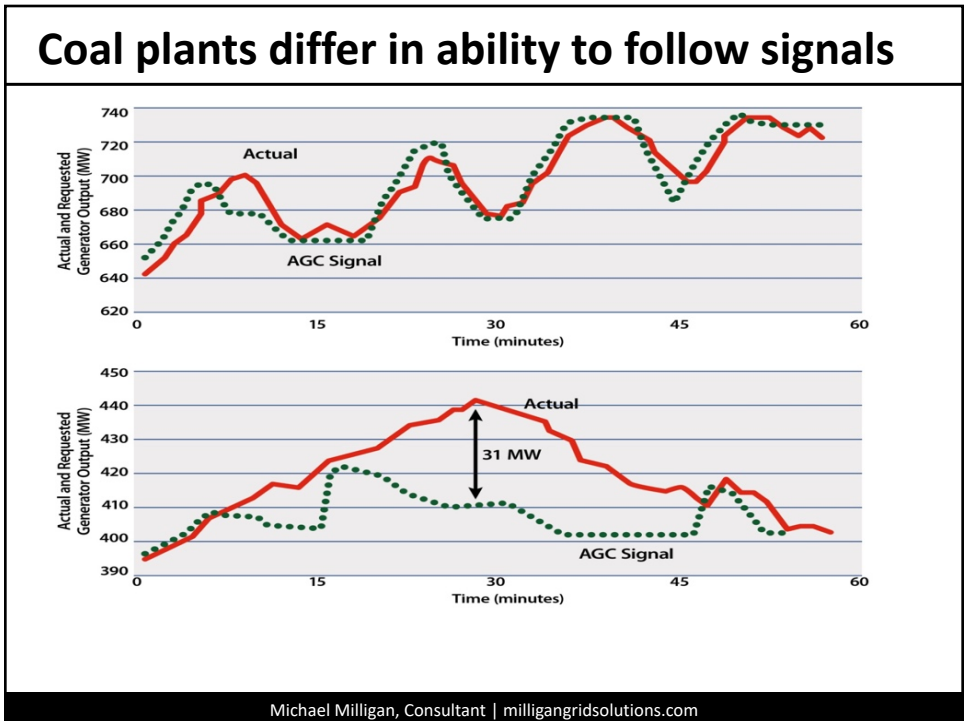
🟢 Excellent 🟡 Very Good 🟠 Good 🟤 Limited 🟡 Incapable

**A large coal plant may set the contingency reserve level for the region.**



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### Nuclear plants

	Nuclear	
Disturbance ride-through	🟡	• Can sometimes trip offline during disturbances
Reactive and Voltage Support	🟢	• Can provide if generating real power
Slow and arrest frequency decline (arresting period)	🟡	• Do not provide primary frequency response in the U.S. • Does not provide AGC or dispatch in the U.S.; therefore no ramping, long start times makes this an inflexible resource
Stabilize frequency (rebound period)	🟡	
Restore frequency (recovery period)	🟡	
Frequency Regulation (AGC)	🟡	
Dispatchability/Flexibility	🟡	

🟢 Excellent 
 🟡 Very Good 
 🟠 Good 
 🔴 Limited 
 ⬜ Incapable

**A large nuclear plant may set the contingency reserve level for the region. This imposes costs on other resources. See Milligan et. al**  
<https://www.nrel.gov/docs/fy11osti/51860.pdf>

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## Demand response

	Demand Response	
Disturbance ride-through		• Can often ride thru if rules don't prevent it
Reactive and Voltage Support		• Can provide even if not generating real power
Slow and arrest frequency decline (arresting period)		• Can provide fast primary frequency response via power electronics
Stabilize frequency (rebound period)		• Can provide very good AGC response (next slide has an example)
Restore frequency (recovery period)		
Frequency Regulation (AGC)		• Fast dispatch, although may be limited
Dispatchability/Flexibility		

Excellent Very Good Good Limited Incapable

A large nuclear plant may set the contingency reserve level for the region. This imposes costs on other resources. See Milligan et. al <https://www.nrel.gov/docs/fy11osti/51860.pdf>

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## Sources of grid services

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

Excellent Very Good Good Limited Incapable

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# Comparison to PJM



PJM's Evolving Resource Mix and System Reliability

Figure 6. Generator Reliability Attribute Matrix

● Exhibits Attribute  
◐ Partially Exhibits Attribute (Inertia & Primary)  
○ Does Not Exhibit Attribute

Resource Type	Essential Reliability Services (Frequency, Voltage, Ramp Capability)					Fuel Assurance (Max Fuel Stored (< 72 hours at 100% Max Output))	In-site Fuel Inventory	Flexibility			Other		
	Frequency Response (Inertia & Primary)	Voltage Control	Regulation	Contingency Reserve	Load Following			Cycle	Short Min. Run Time (< 2 hrs.) / Multiple Starts Per Day	Startup / Notification Time < 30 Minutes	Black Start Capable	No Environmental Restrictions (That Would Limit Run Hours)	Equivalent Reliability Factor
Hydro	●	●	●	●	●	○	◐	●	●	●	●	●	●
Natural Gas - Combustion Turbine	●	●	◐	●	◐	●	○	●	●	●	●	●	◐
Oil - Steam	●	●	●	●	●	●	●	●	○	○	○	○	◐
Coal - Steam	●	●	●	●	●	●	●	◐	○	○	○	○	◐
Natural Gas - Steam	●	●	●	●	●	●	○	●	○	○	○	○	◐
Oil/ Diesel - Combustion Turbine	●	●	○	●	○	●	○	●	●	●	●	○	◐
Nuclear	◐	●	○	○	◐	●	●	○	○	○	○	○	●
Battery/ Storage	◐	◐	●	●	○	○	○	●	●	●	●	●	●
Demand Response	○	○	◐	◐	◐	◐	◐	●	●	●	○	●	●
Solar	◐	◐	○	○	○	○	○	●	●	●	○	●	●
Wind	◐	◐	○	○	◐	○	○	●	●	●	○	◐	●

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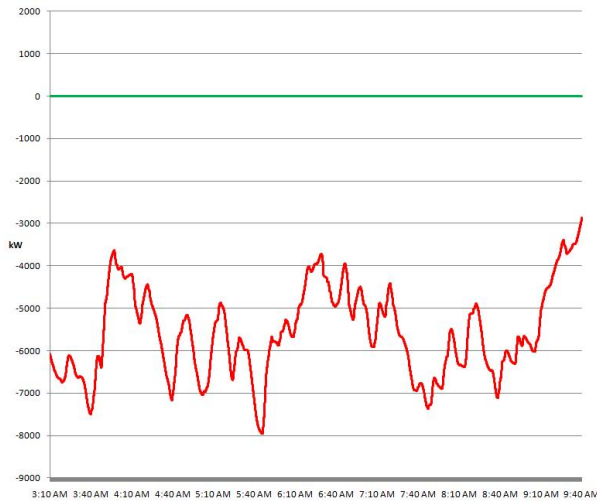
## Example of DR providing regulation

- 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
- “Everybody doesn’t have to supply everything.”

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## DR can also provide regulating reserves



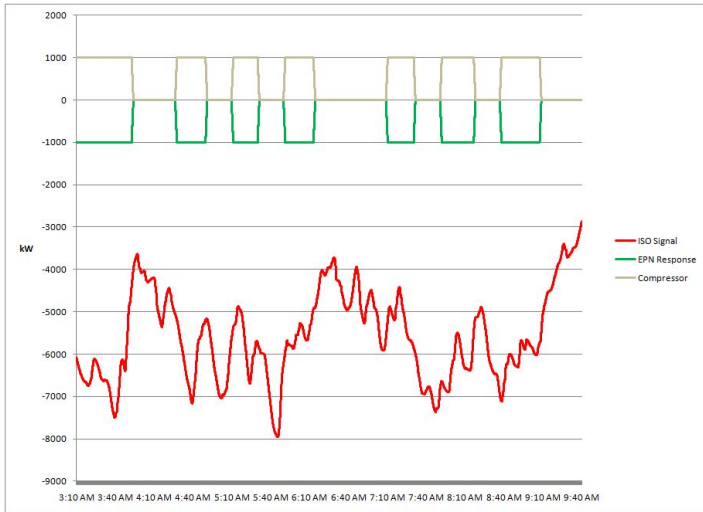
This slide is beginning of simple animation of composite DR response

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

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## Resource Response

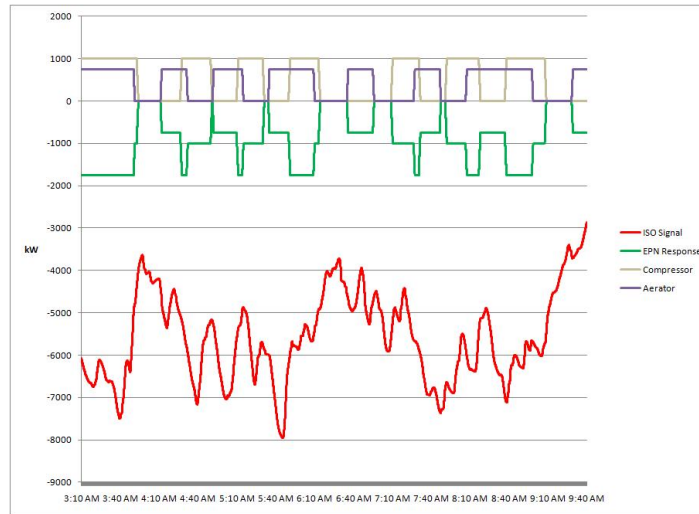


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## Resource Response

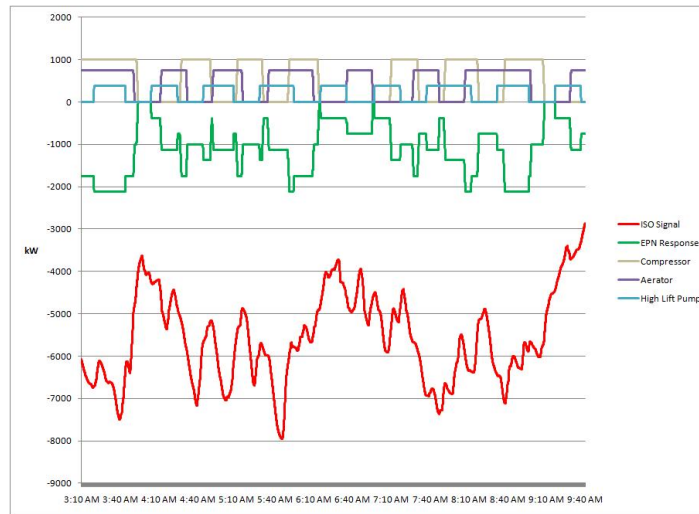


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## Resource Response

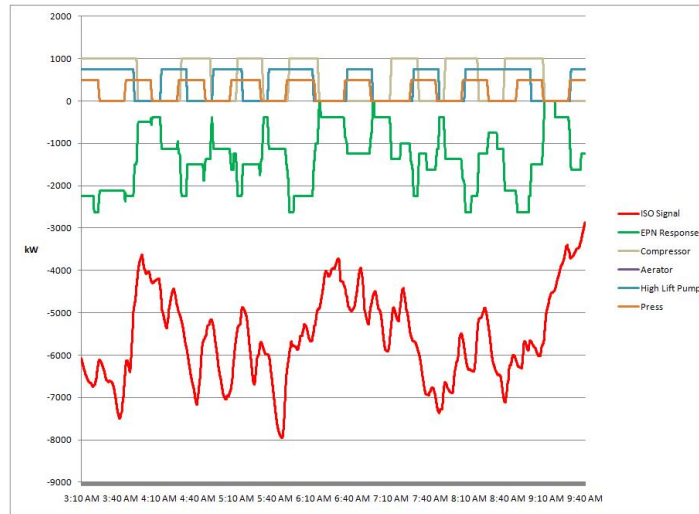


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## Resource Response

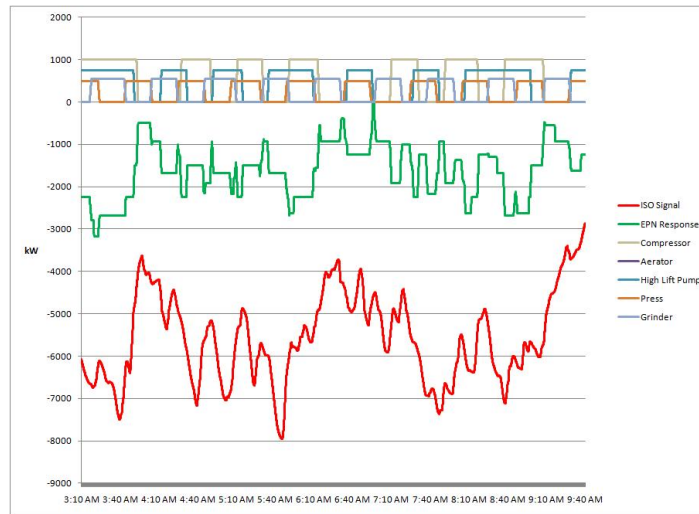


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## Resource Response

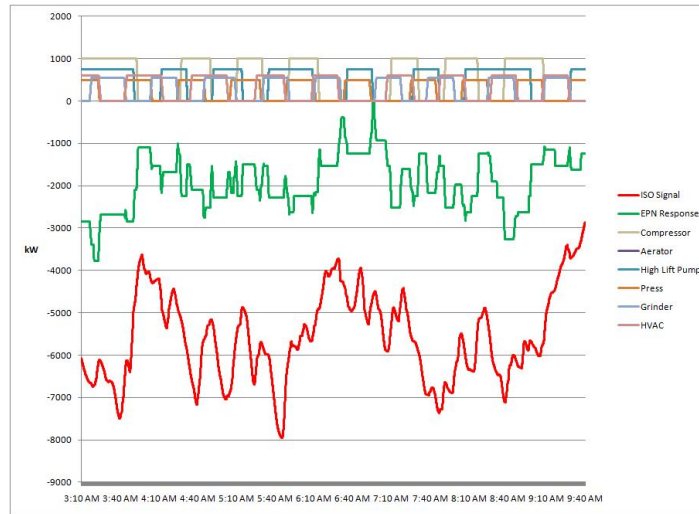


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## Resource Response

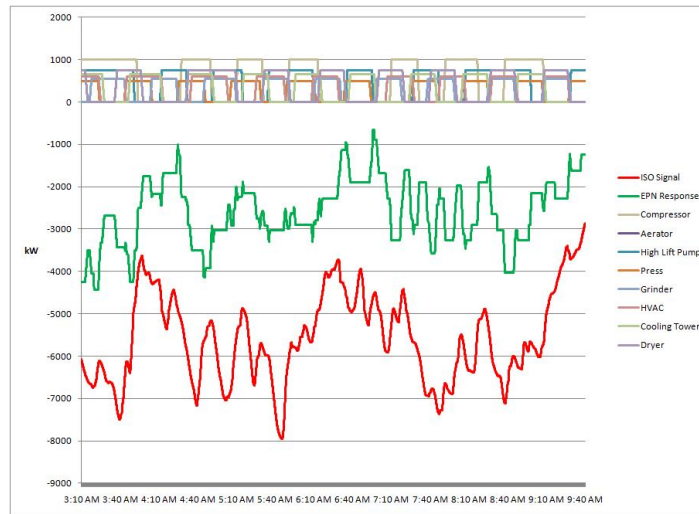


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## Resource Response

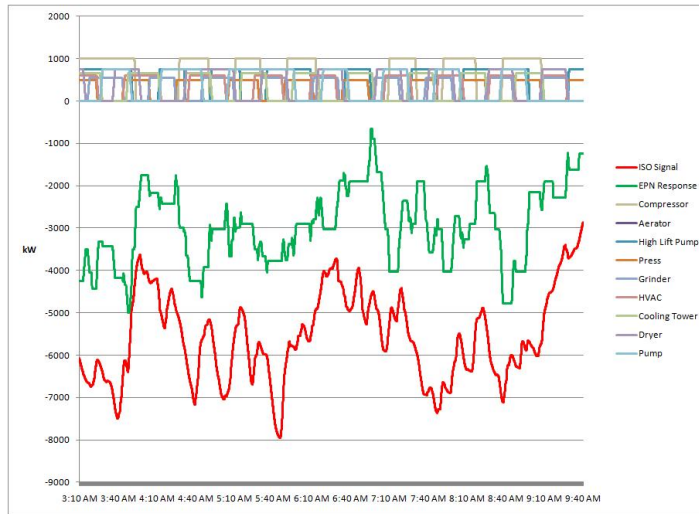


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## Resource Response

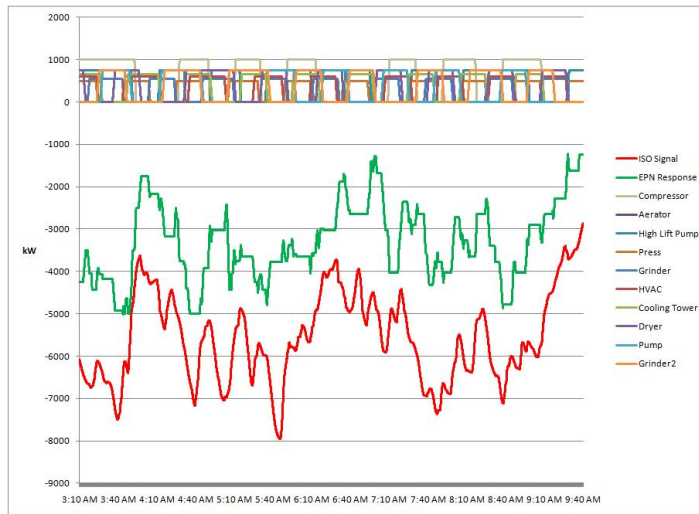


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## Resource Response

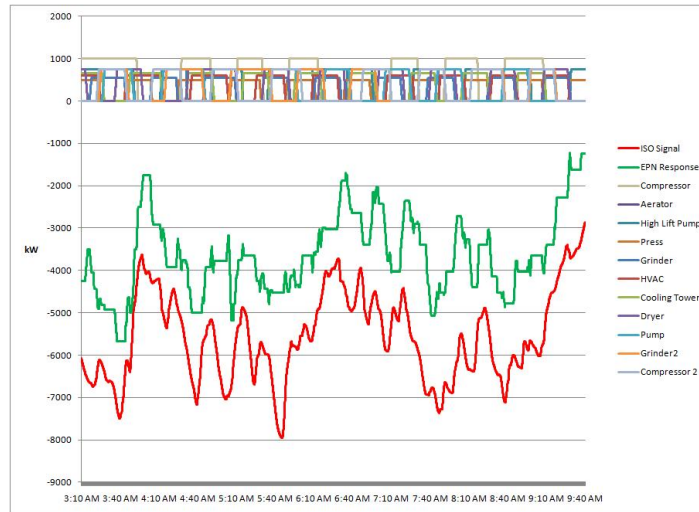


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## Resource Response

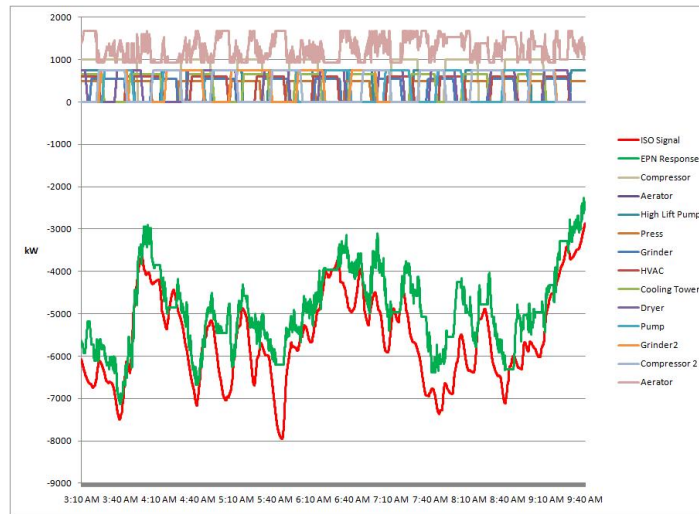


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## Resource Response

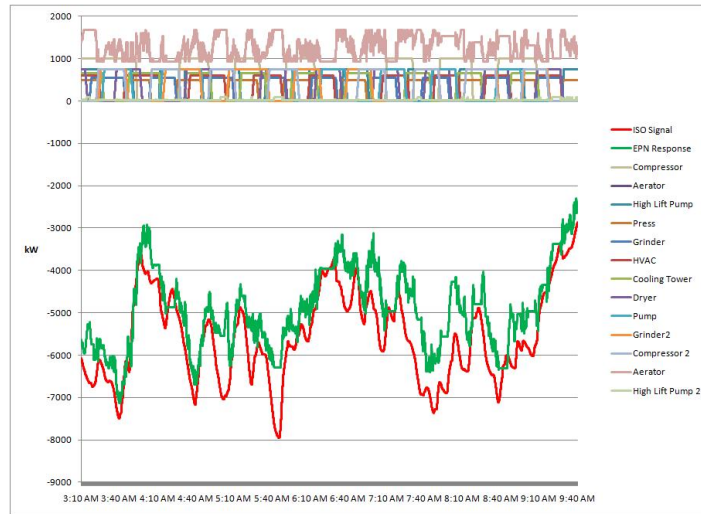


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## Resource Response

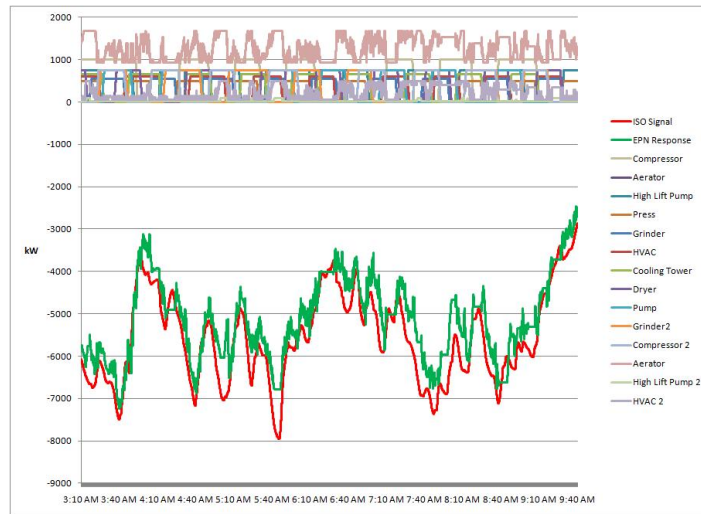


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## Resource Response

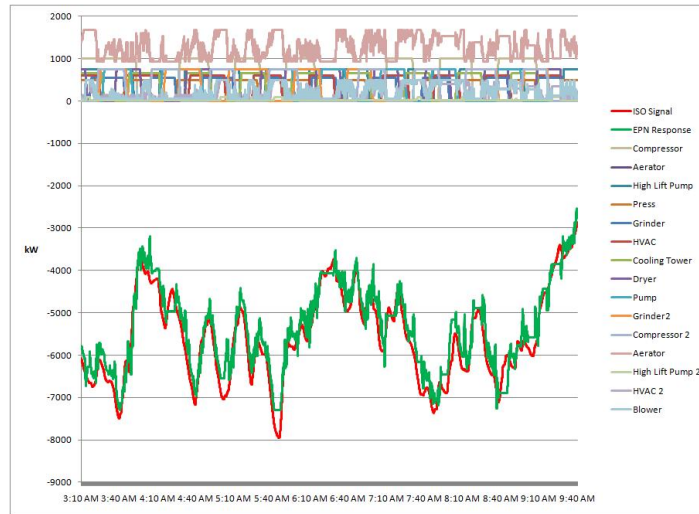


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## Resource Response

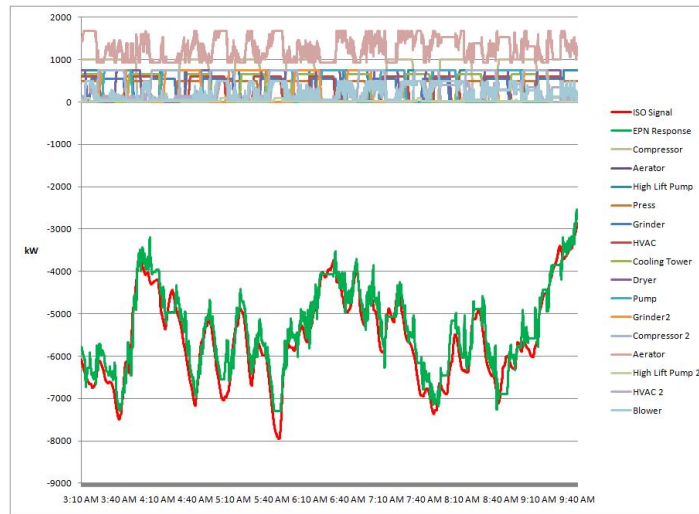


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## Resource Response

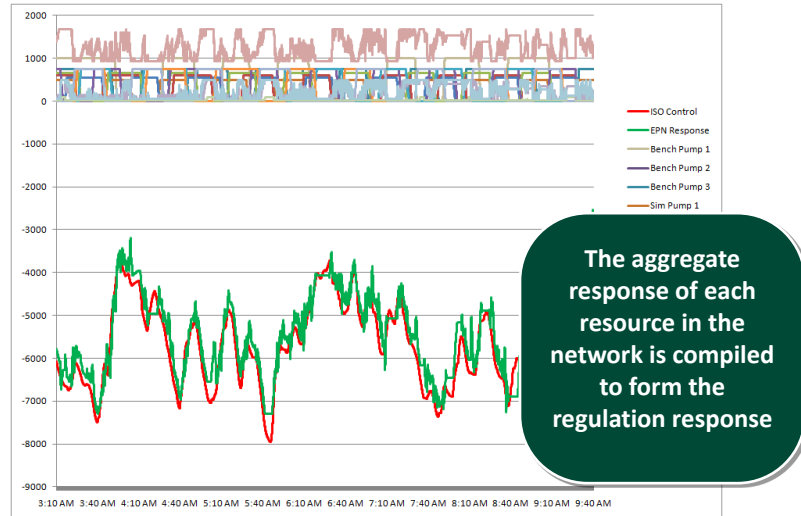


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## Regulation – Resource Response



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## Do we know what we know/don't know?

- **Some traditional units do not provide significant grid services**
- **Power-electronics and controls can significantly improve grid service availability from wind, solar, battery**
- **These devices are often (usually?) faster than conventional resources for all available services**
- **How steep of an inertial response can we handle with large amounts of very fast frequency response?**

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## Summary/conclusion

- **Most resources can supply most services, at least some of the time**
- **Inverter-based resources (wind, solar, battery) are very good providers of many grid services**
- **Not all resources need to supply everything**
- **Grid standards would do well to recognize *performance* → allows for new technology, better performance of old technology**

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## Questions?



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