Overview of Electrical Energy Storage Requirements and Technologies

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MAE 119

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Significant daily and seasonal load variations occur

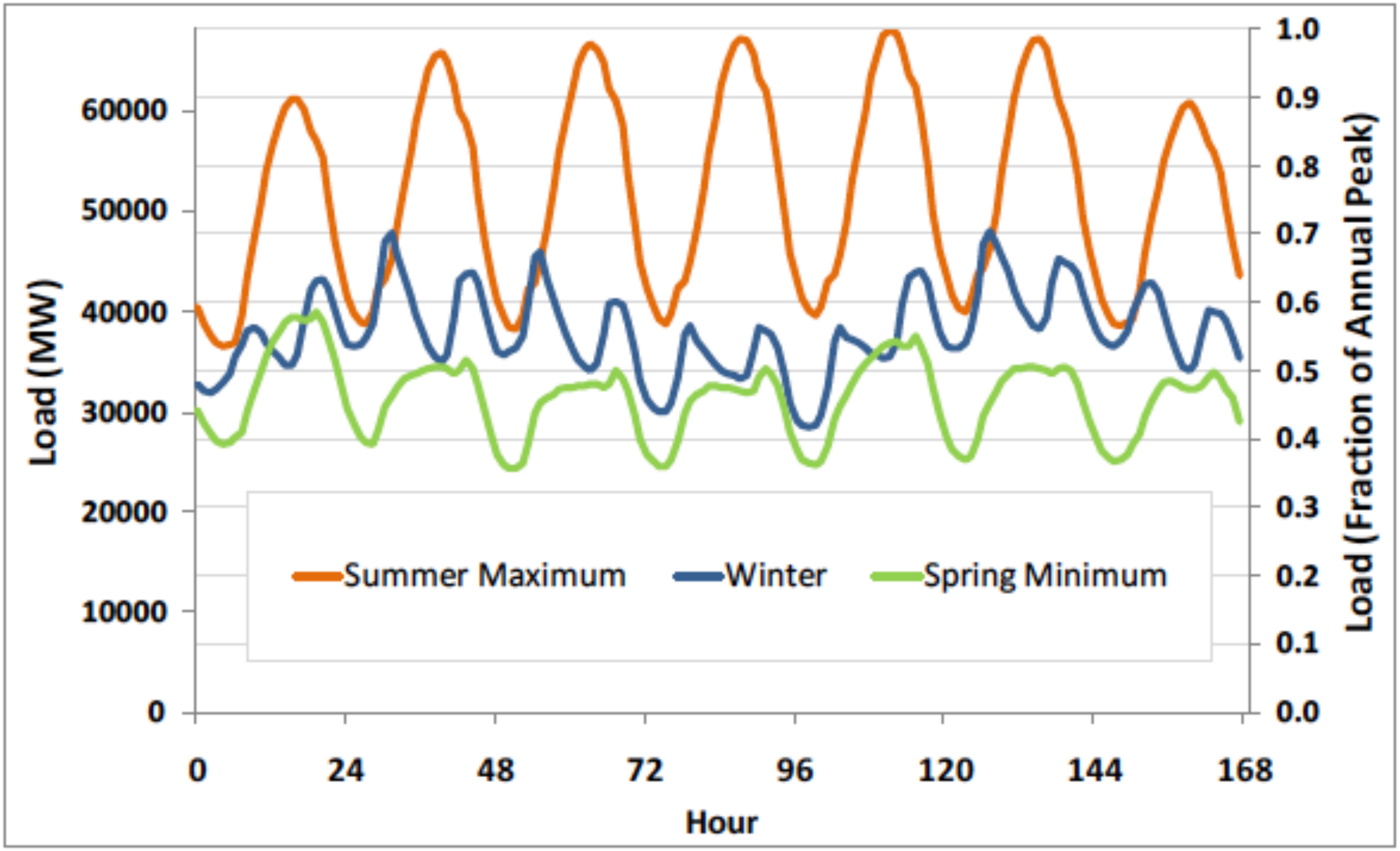


Figure 2.1. Hourly loads from ERCOT 2005

Denholm, 2010 NREL

Load Following & Regulation

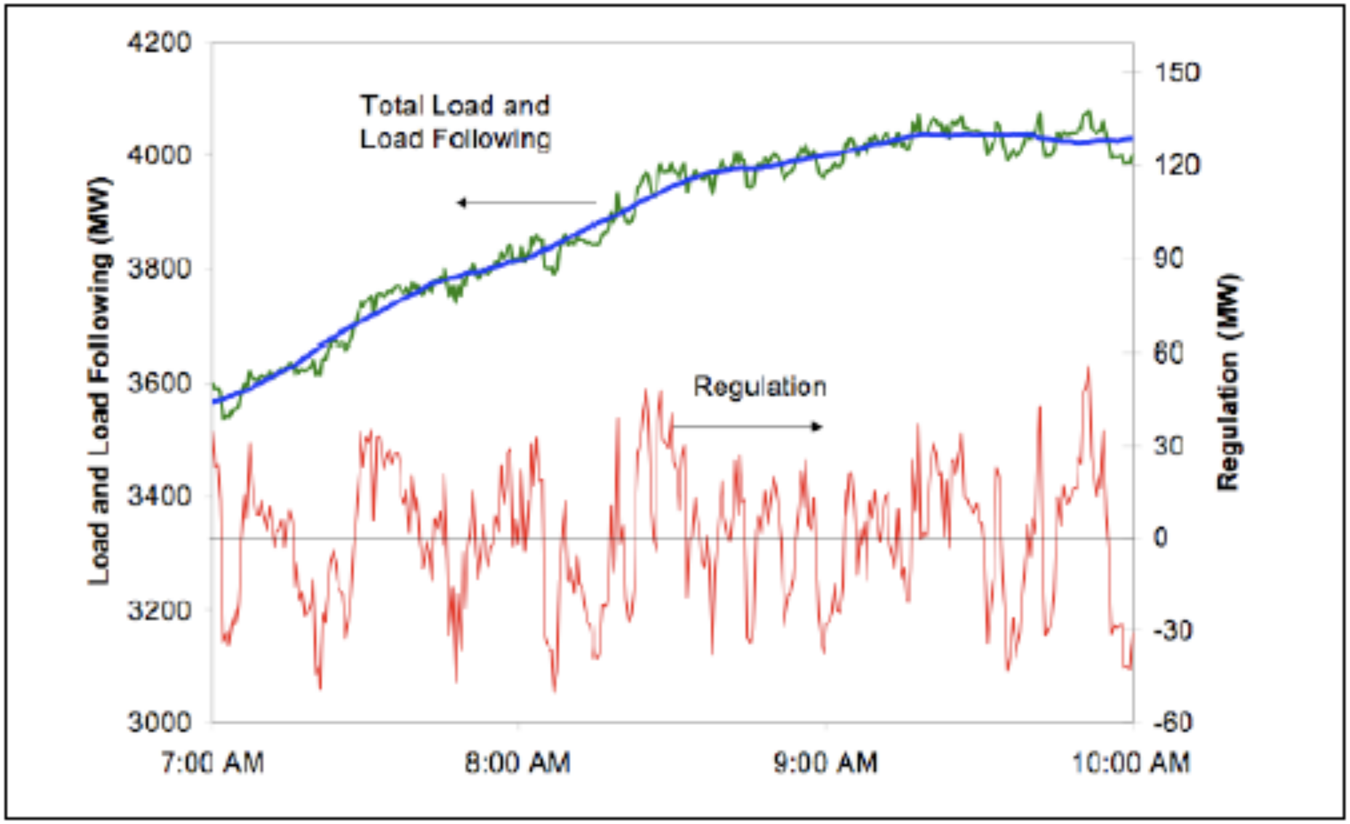


Figure 2.2. System load following and regulation. Regulation (red) is the fast fluctuating component of total load (green) while load following (blue) is the slower trend (Kirby 2004)

Denholm, NREL 2010

Optimal (lowest cost) & Reserve Contraint Requirements Impact Generation Dispatch Planning

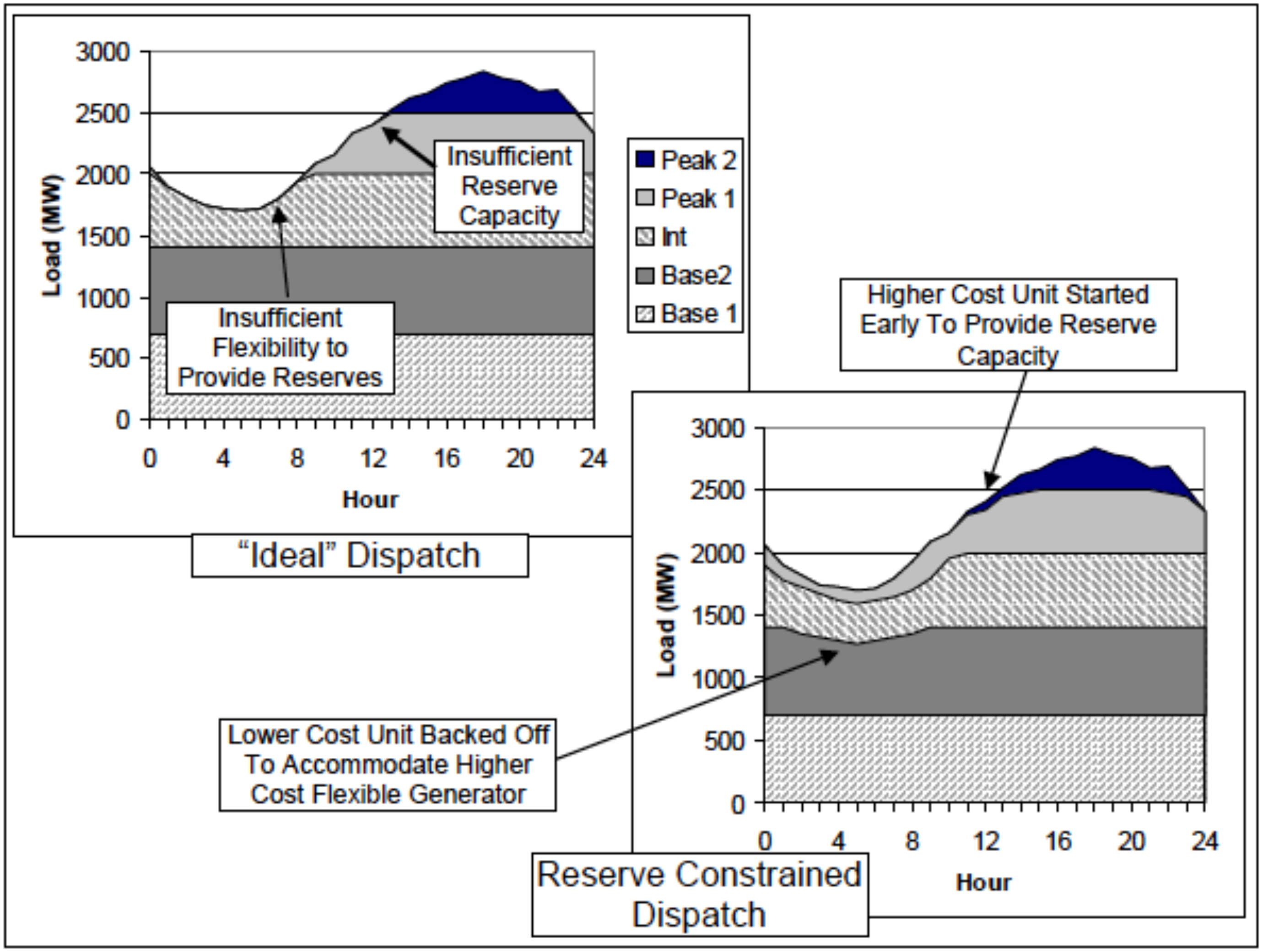


Figure 2.3. Optimal and reserve constrained dispatch

Denholm, NREL 2010

Historical uses and needs for energy storage in grid w/ renewables

Table 3.2. Traditional Major Grid Applications of Energy Storage

Application	**Description**	**System Benefits when Provided by Storage**	**Timescale of Operation**
Load Leveling/ Arbitrage	Purchasing low-cost off-peak energy and selling it during periods of high prices.	Increases utilization of baseload power plants and decrease use of peaking plants. Can lower system fuel costs, and potentially reduce emissions if peaking units have low efficiency.	Response in minutes to hours. Discharge time of hours.
Firm Capacity	Provide reliable capacity to meet peak system demand.	Replace (or function as) peaking generators.	Must be able to discharge continuously for several hours or more.
Operating Reserves			
Regulation	Fast responding increase or decrease in generation (or load) to respond to random, unpredictable variations in demand.	Reduces use of partially loaded thermal generators, potentially reducing both fuel use and emissions.	Unit must be able to respond in seconds to minutes. Discharge time is typically minutes. Service is theoretically "net zero" energy over extended time periods.
Contingency Spinning Reserve[24]	Fast response increase in generation (or decrease load) to respond to a contingency such as a generator failure.	Same as regulation.	Unit must begin responding immediately and be fully responsive within 10 minutes. Must be able to hold output for 30 minutes to 2 hours depending on the market. Service is infrequently called.[25]
Replacement/ Supplemental	Units brought on-line to replace spinning units.	Limited. Replacement reserve is typically a low-value service.	Typical response time requirement of 30-60 minutes depending on market minutes. Discharge time may be several hours.

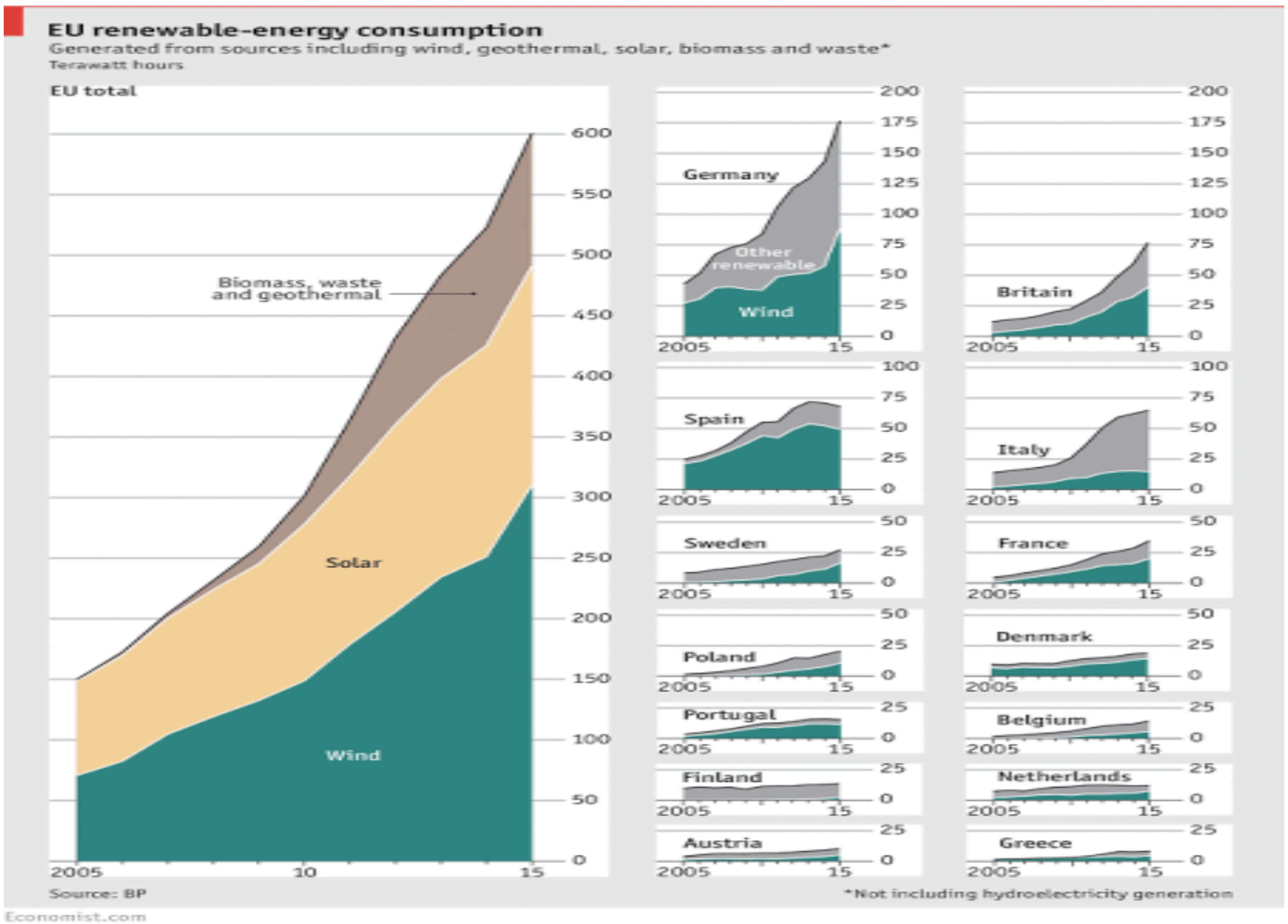
Denholm, NREL 2010

Historical uses and needs for energy storage in grid w/ renewables (cont'd)

Ramping/Load Following	Follow longer term (hourly) changes in electricity demand.	Reduces use of partially loaded thermal generators, potentially reducing both fuel use and emissions. Price is "embedded" in existing energy markets, but not explicitly valued, so somewhat difficult to capture.	Response time in minutes to hours. Discharge time may be minutes to hours.
T&D Replacement and Deferral	Reduce loading on T&D system during peak times.	Provides an alternative to expensive and potentially difficult to site transmission and distribution lines and substations. Distribution deferral is not captured in existing markets.	Response in minutes to hours. Discharge time of hours.
Black-Start	Units brought online to start system after a system-wide failure (blackout).	Limited. May replace conventional generators such as combustion turbines or diesel generators.	Response time requirement is several minutes to over an hour. Discharge time requirement may be several to many hours.[26]
End-Use Applications			
TOU Rates	Functionally the same as arbitrage, just at the customer site.	Same as arbitrage.	Same as arbitrage.
Demand Charge Reduction	Functionally the same as firm capacity, just at the customer site.	Same as firm capacity.	Same as firm capacity.
Backup Power/ UPS/Power Quality	Functionally the same as contingency reserve, just at the customer site.	Benefits are primarily to the customer.	Instantaneous response. Discharge time depends on level of reliability needed by customer.

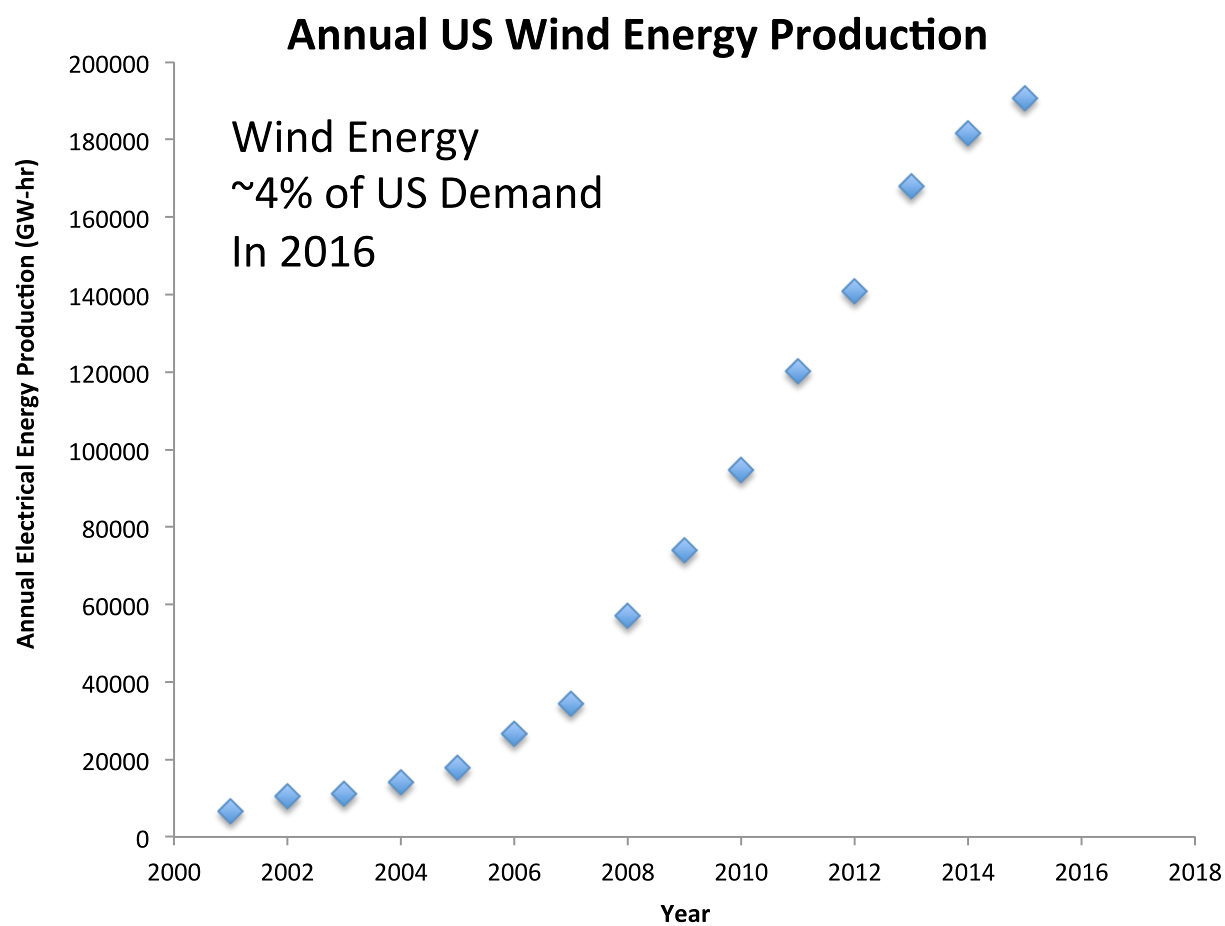
Denholm, NREL 2010

Renewable Electrical Energy Generation is Growing



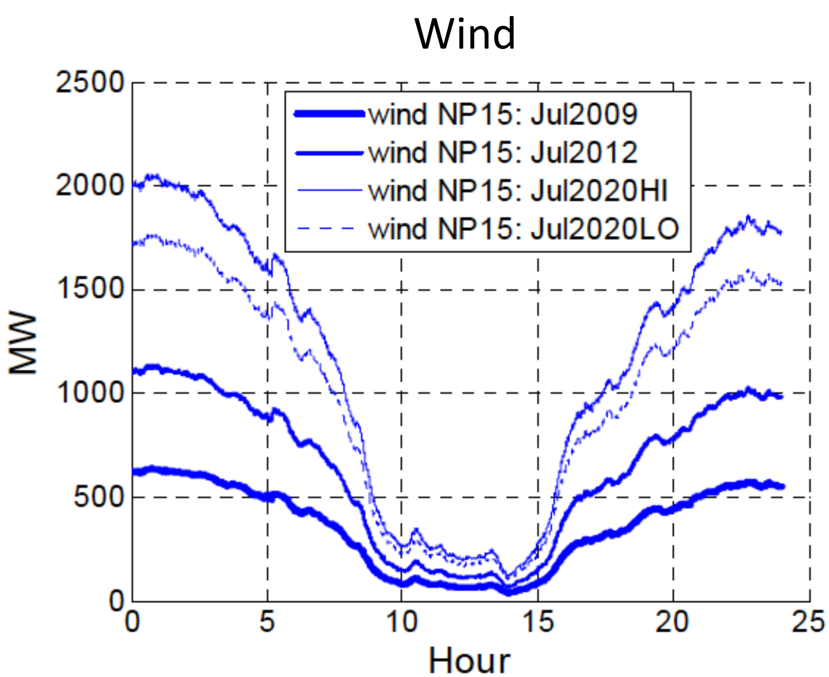
Economist, 2017

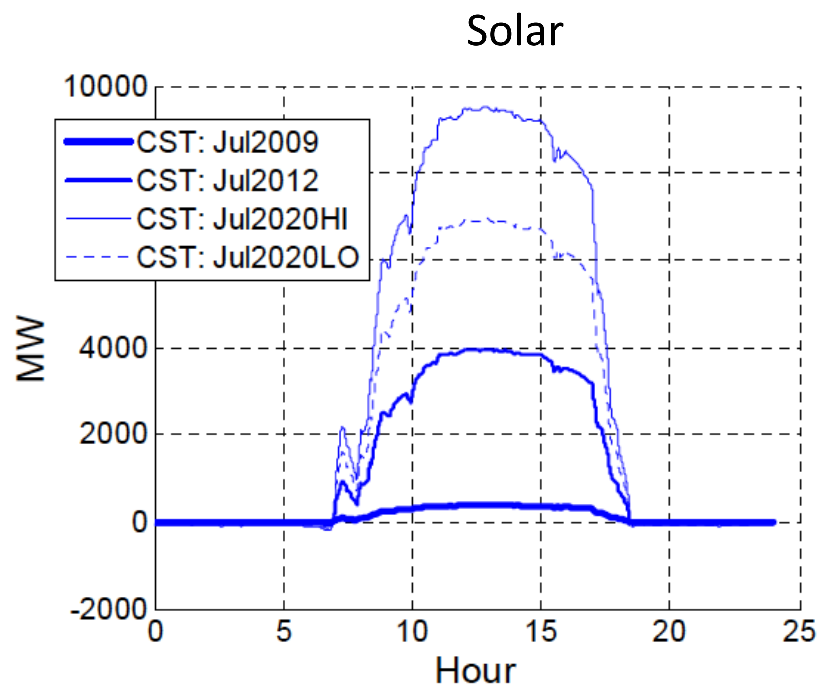
Renewable Electrical Energy Generation is Growing



U.S. DOE EIA

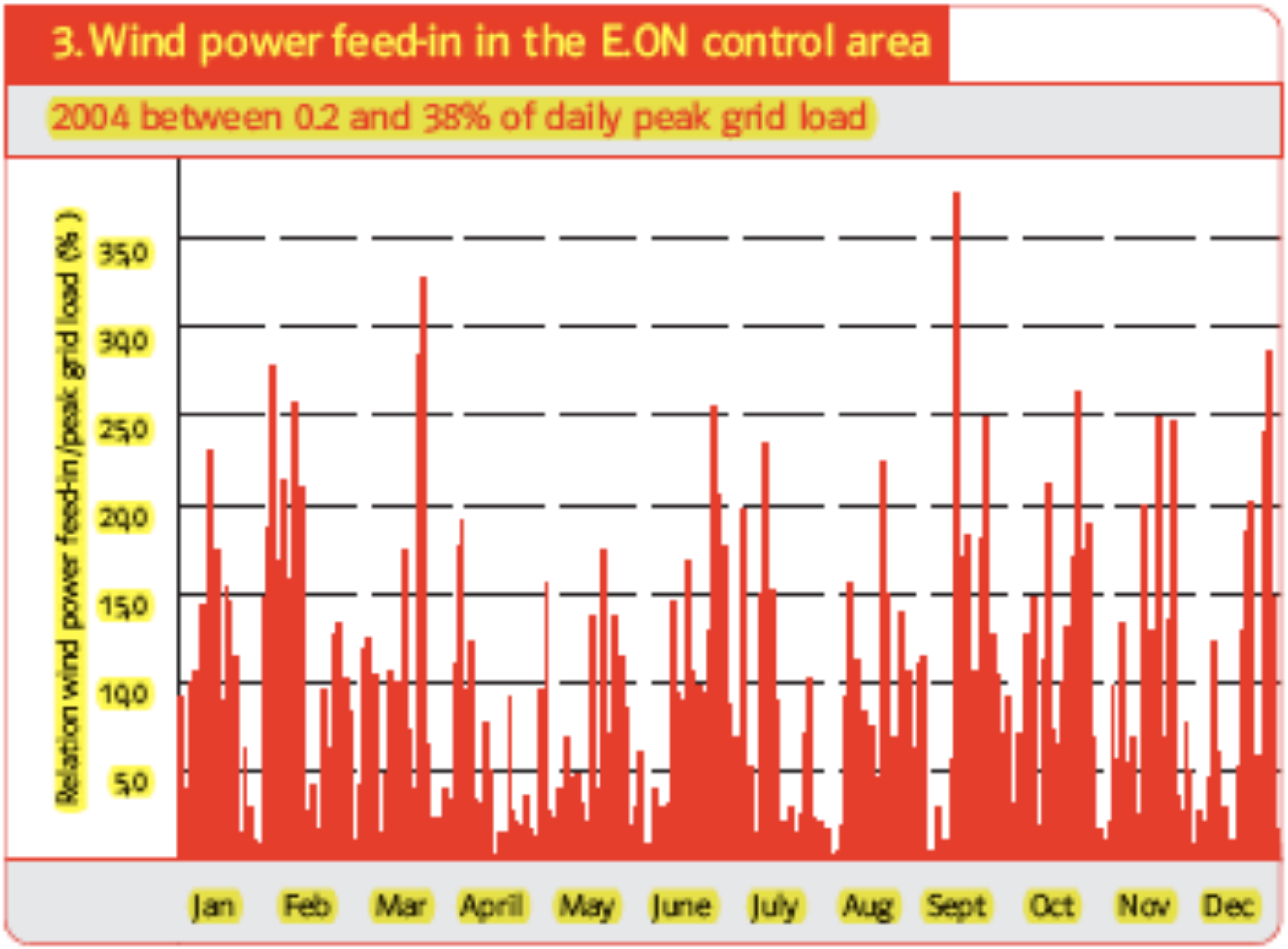
Diurnal & Seasonal Variability of Wind & Solar Production





CEC, 2010

Similar example of wind variability in Germany



Source: E.On Netz, “Wind Report 2005

Q: What is impact of increased variable generation (VG) on power grid?

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Denholm, NREL 2010

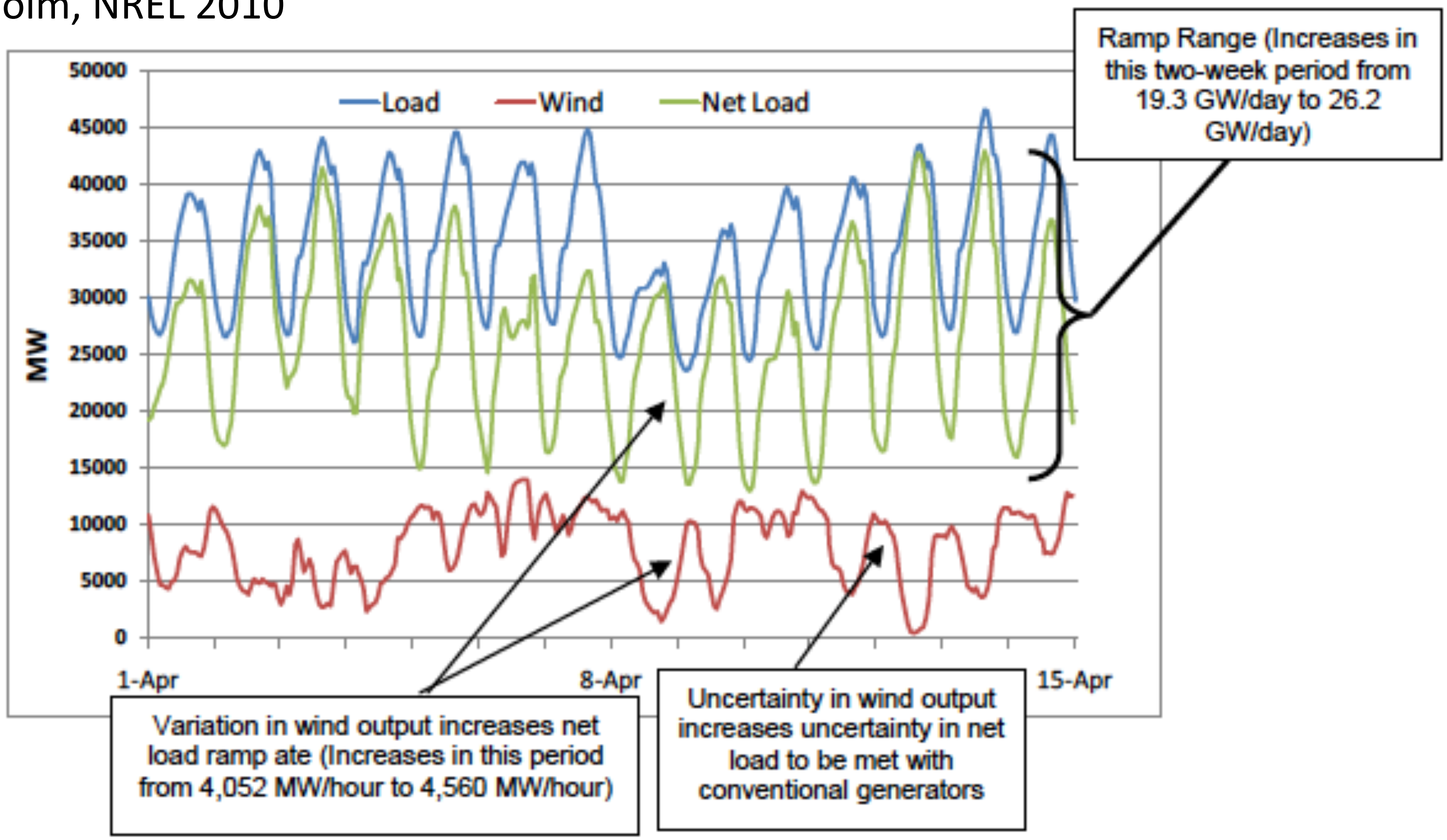

Figure 4.1. Impact of net load from increased use of renewable energy

A: Increases in Uncertainty in Net Load, Ramp Range

Q: What is impact of variable generation (VG) on power grid?

- Increased need for frequency regulation
- Increased ramp rate for dispatchable sources
- Increased uncertainty in *net* load (after VG is removed)
- Increased ramp range for dispatchable sources
- **Net impact**: ~5-10% increase in energy costs at moderate wind market fraction (i.e. ~10%)

Denholm, NREL 2010

Dispatch schedule for low wind market share

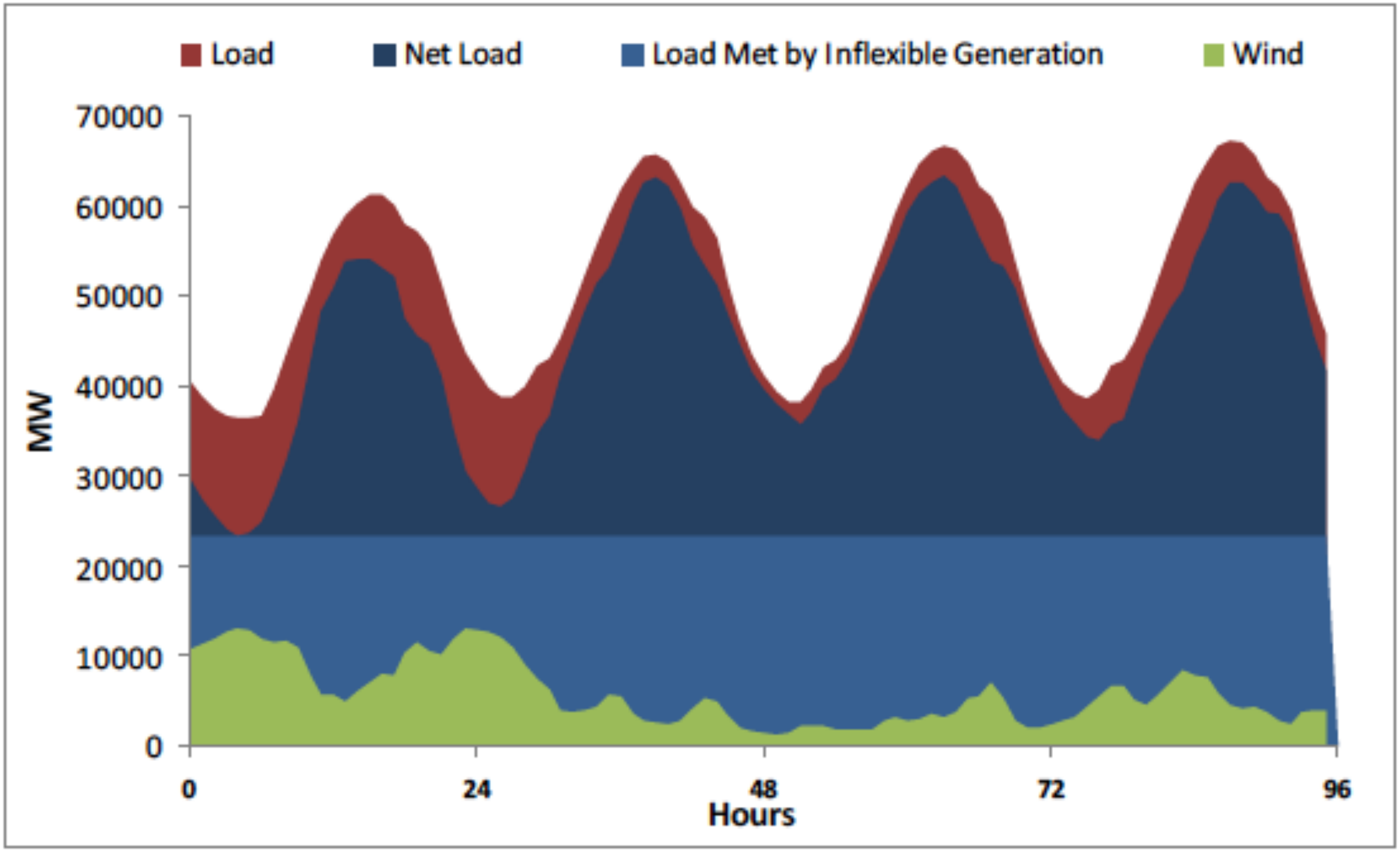

Figure 4.2. Dispatch with low VG penetration (wind providing 8.5% of load)

Denholm, NREL 2010

Dispatch schedule for larger wind market share

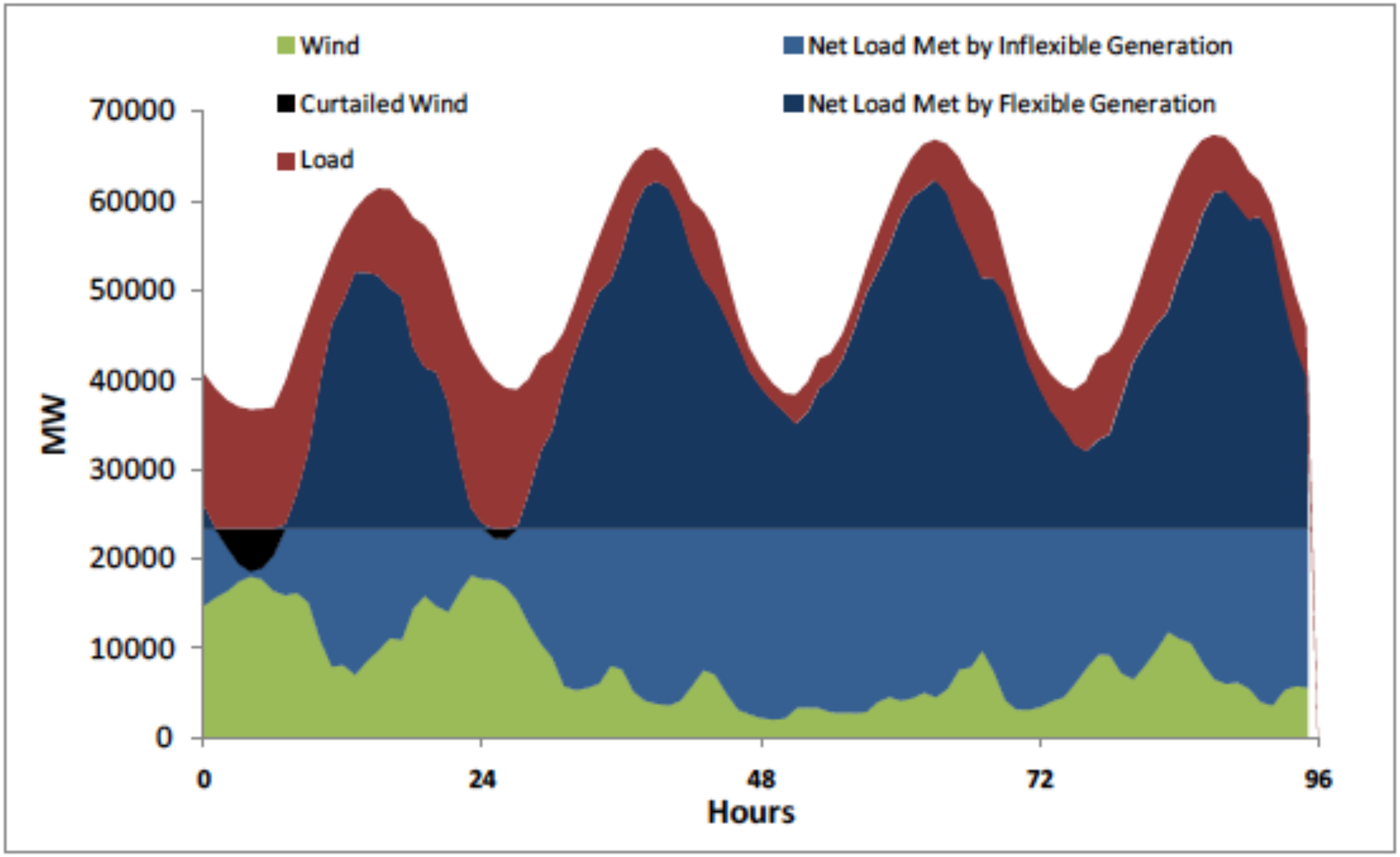

Figure 4.3. Dispatch with higher VG penetration (wind providing 16% of load)

Denholm, NREL 2010

Dispatch schedule for larger wind market share

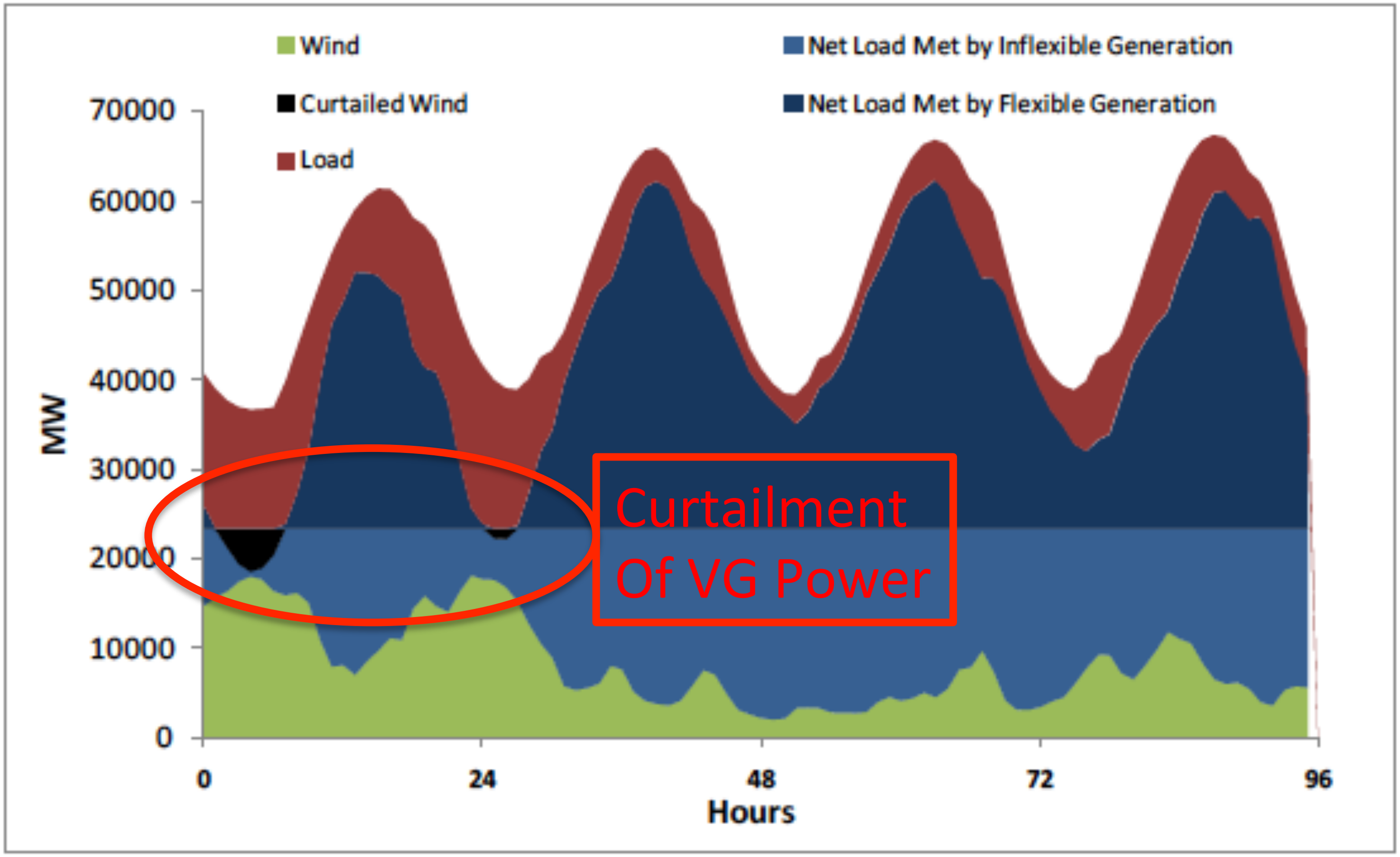

Figure 4.3. Dispatch with higher VG penetration (wind providing 16% of load)

Denholm, NREL 2010

Evidence that this occurs… producers selling energy below their costs…

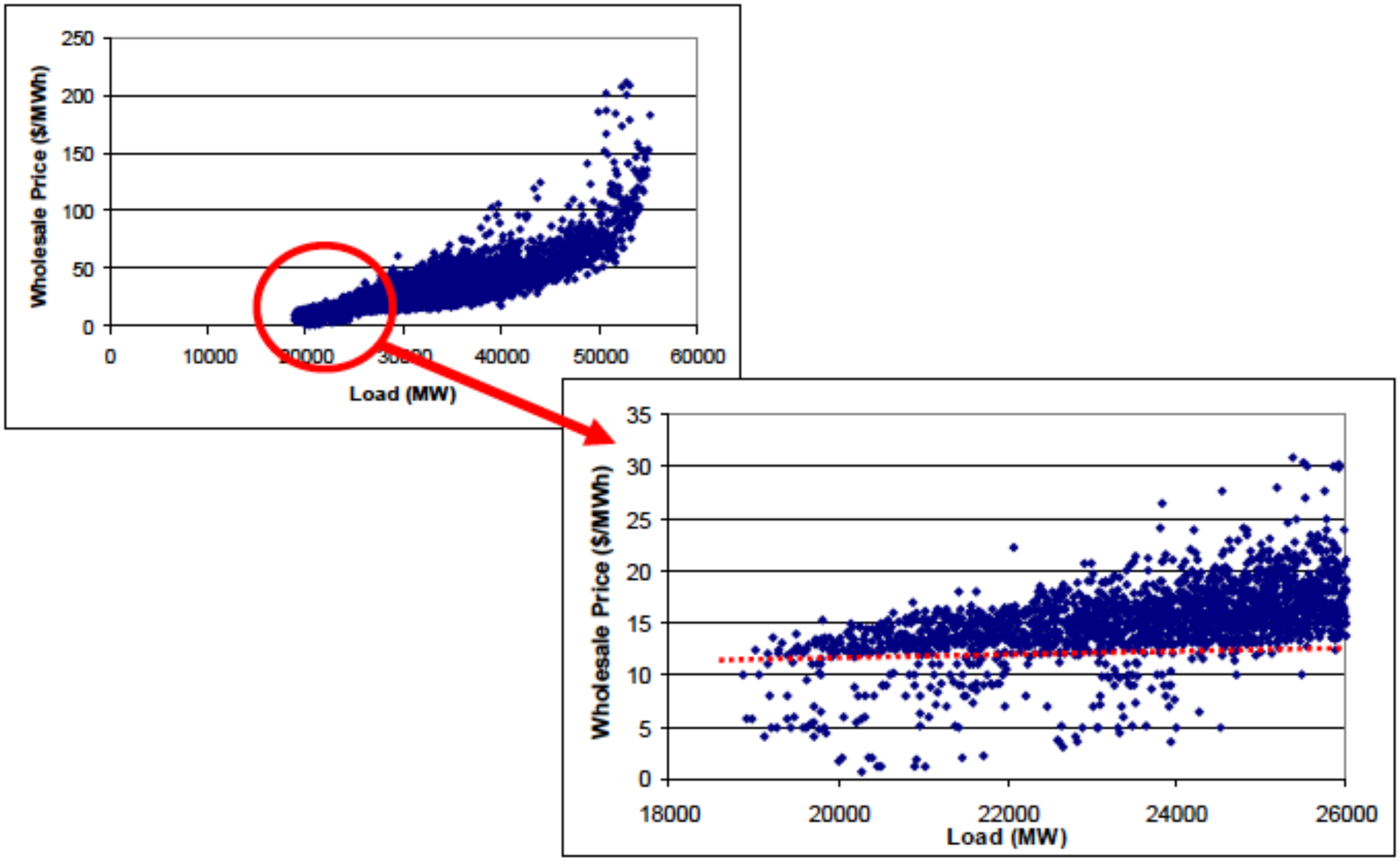

Figure 4.4. Relationship between price and load in PJM in 2002

Denholm, NREL 2010

Evidence that this occurs… producers selling energy below their costs…

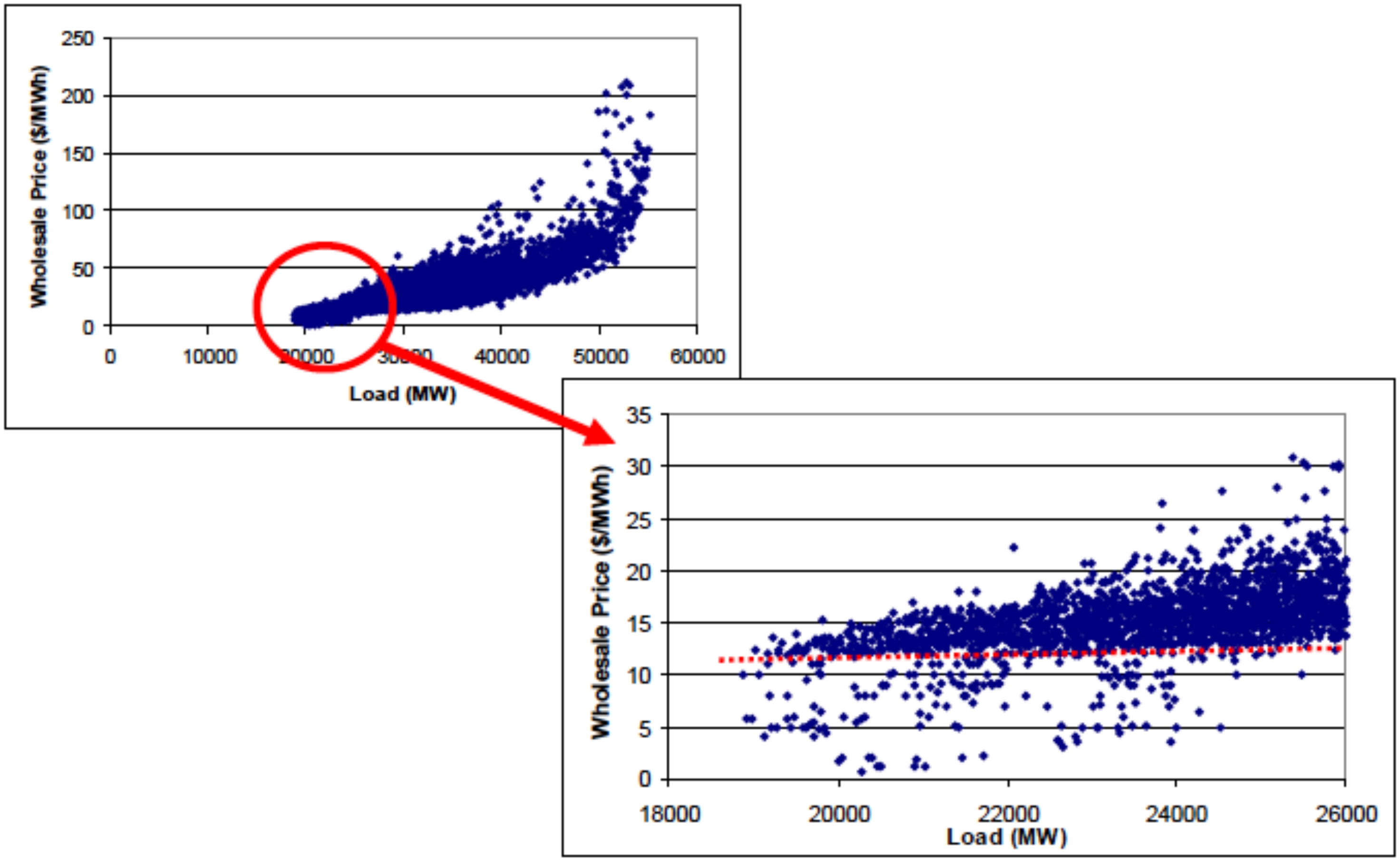

Figure 4.4. Relationship between price and load in PJM in 2002

Denholm, NREL 2010

More flexible conventional system reduces VG curtailment ➔ will permit higher economic VG fraction

Denholm NREL 2010

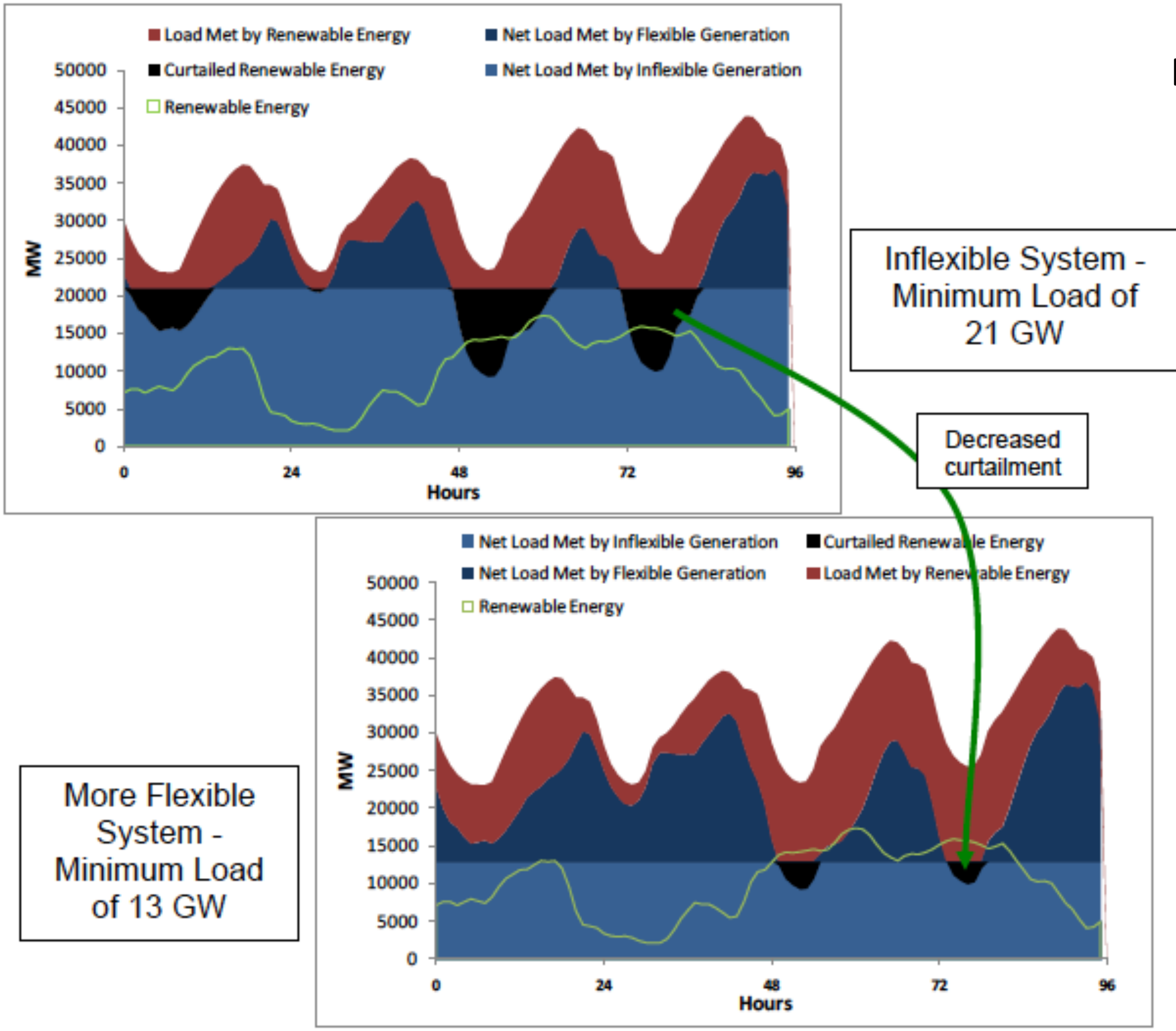

Figure 4.6. Effect of decreasing minimum load point on increased use of RE

ERCOT
Study wtih
19GW Wind
/11GW Solar;
61GW peak
demand

Storage enables higher economic VG market fraction

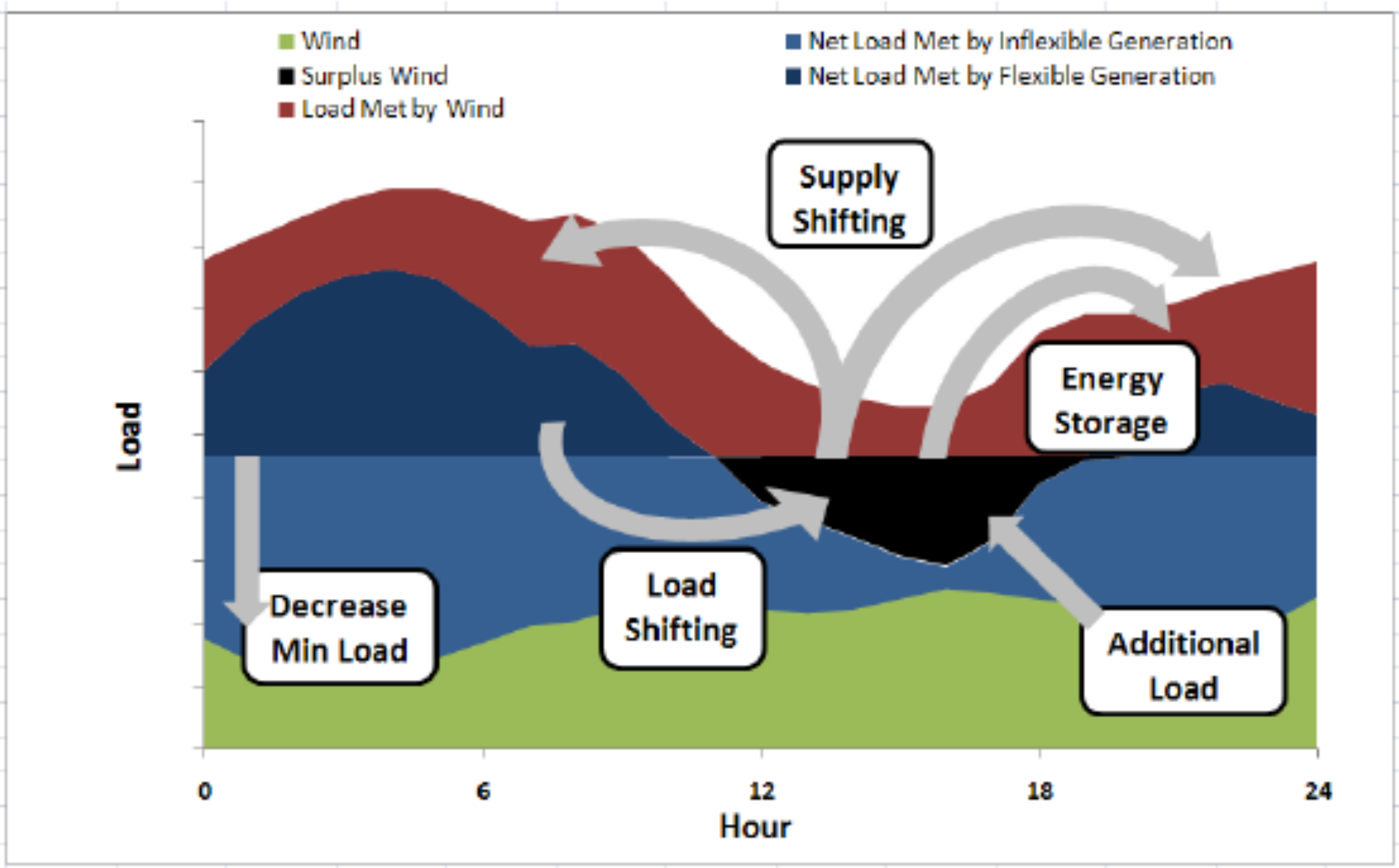

Figure 4.10. Option for increasing the use of VG by decreasing curtailment

Denholm, NREL 2010

Storage reduced VG curtailment ➔ VG market fraction

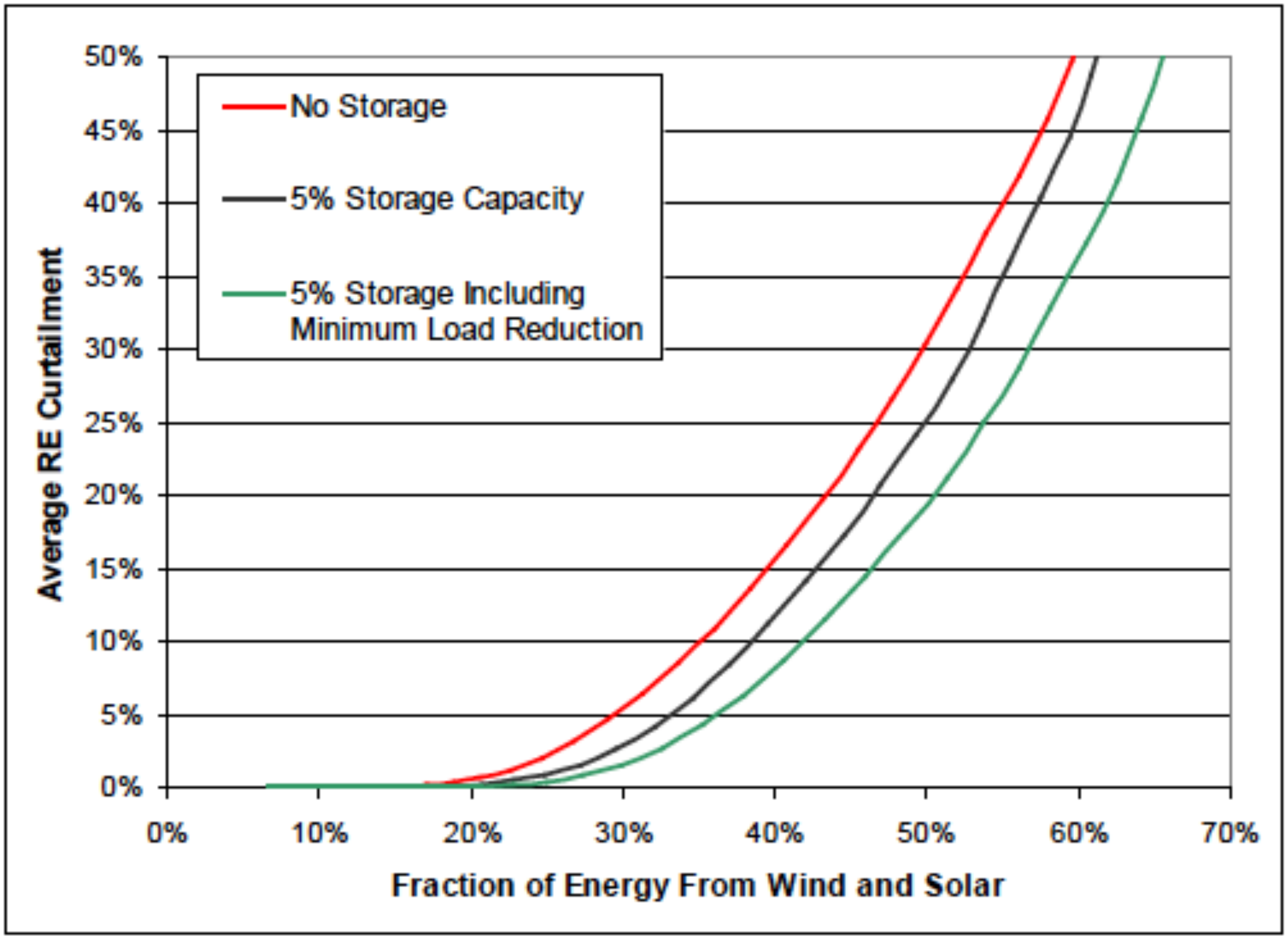

Figure 4.11. Reduction of curtailment resulting from addition of energy storage

Denholm, NREL 2010

Range of Storage Technologies Exist

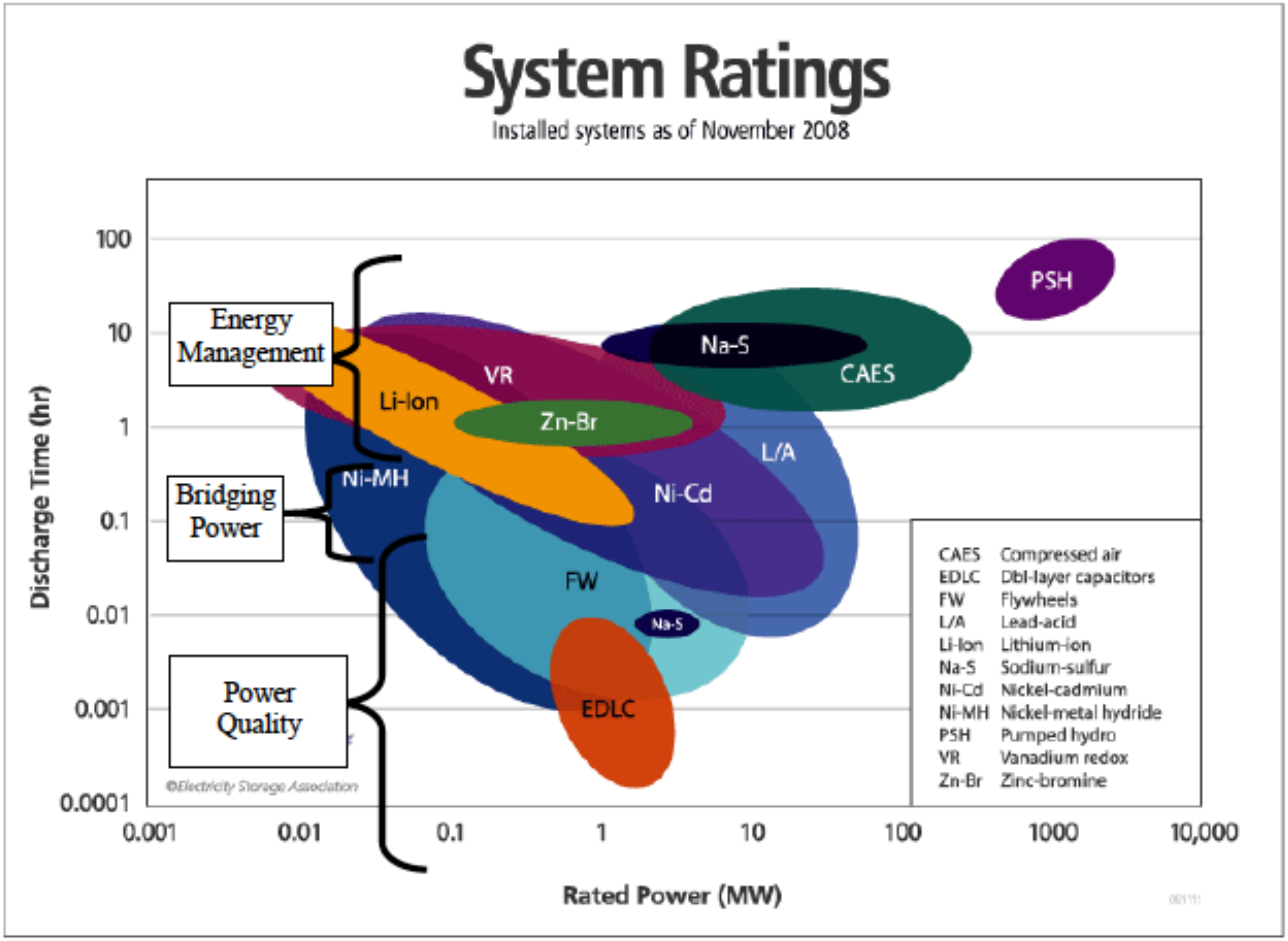

Figure 5.2. Energy storage applications and technologies[71]

Denholm, NREL 2010

Key Elements of Storage Technologies

- Peak power
- Total Energy/Operable Time
- Response time
- Round-trip efficiency
- Cost
- Technology readiness

Storage Technologies

- Capacitors
- Superconducting Coils
- Compressed Air

Storage Technologies

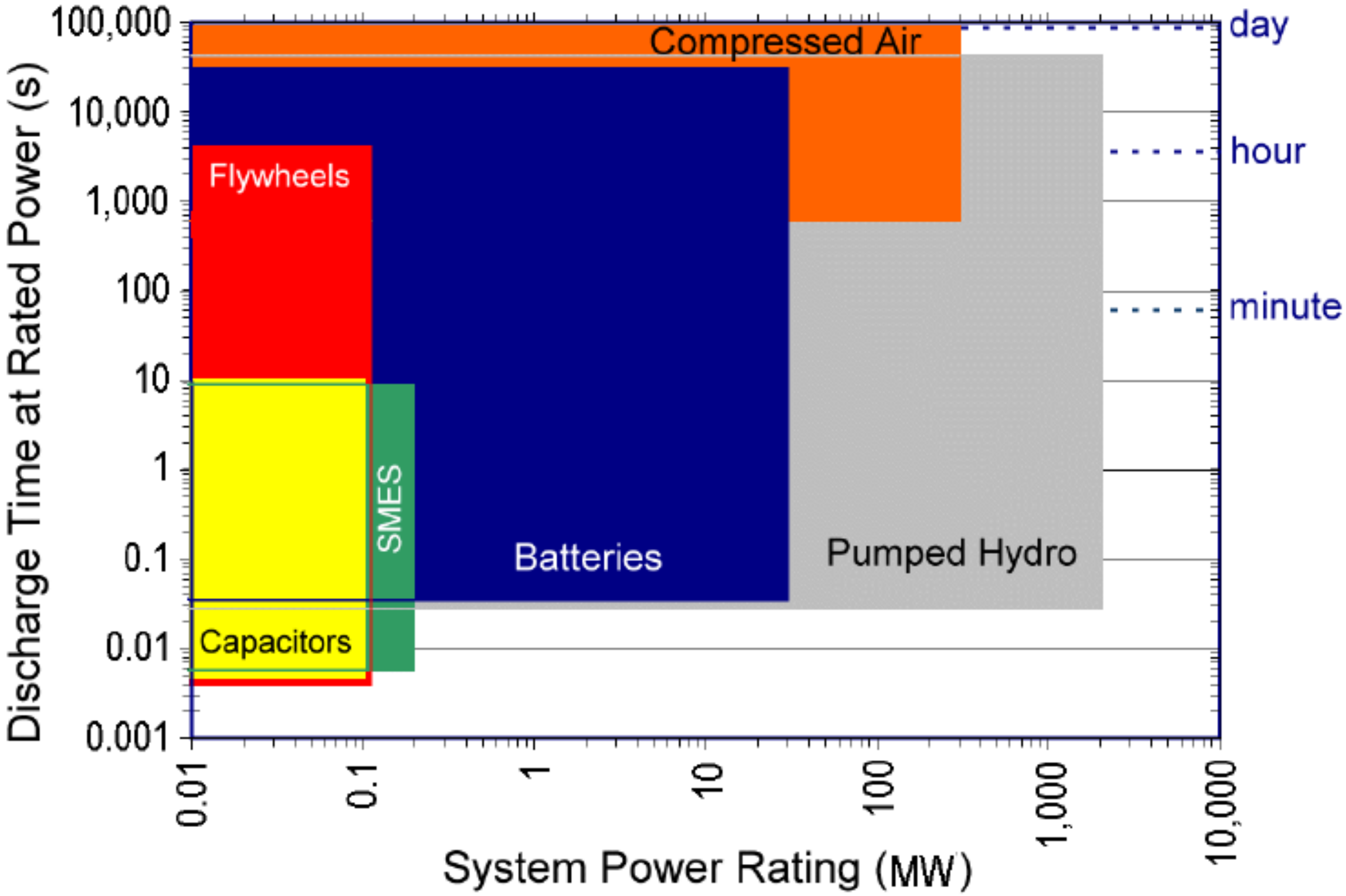

Fig. 1. Capabilities of Existing Electricity Storage Technologies.

Energy Storage Report, APS 2007