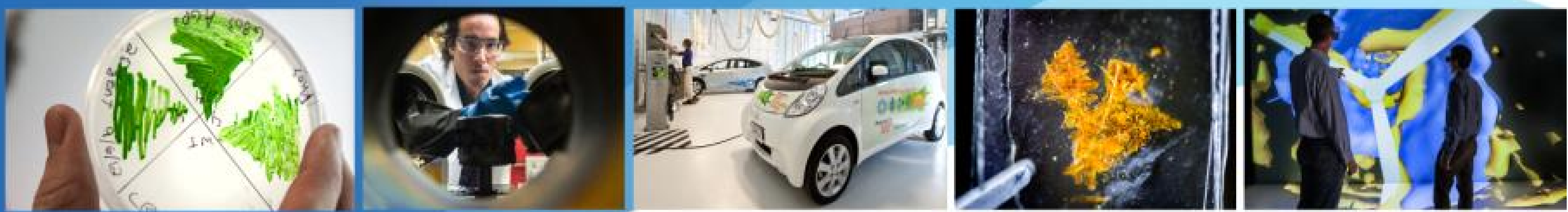


Timescales of Energy Storage Needed to Reduce Renewable Energy Curtailment: Report Summary

Paul Denholm and Trieu Mai

October, 2017

NREL/PR-6A20-70238

P. Denholm and T. Mai, “Timescales of energy storage needed for reducing renewable energy curtailment,” NREL/TP-6A20-68960, 23 pp. (Sept 2017).

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Introduction

Our goal

- Integrate large amounts of variable generation (VG) from wind and solar into a region’s power grid,
- Minimize significant VG curtailment, and
- Preserve VG’s environmental and economic value.

Reaching this goal

This goal will likely require an increase in system flexibility by a combination of

- Changing grid operations, and
- Deploying enabling technologies.

Energy storage as an enabler

Energy storage is of increasing interest because actual and projected prices of storage have declined.

But questions remain:

- What **amount and configuration** of storage is needed to reduce VG curtailment?
- How do we **value the multiple benefits** that storage offers VG integration and grid operations?

Focus of our report

What we analyzed:

- The **storage duration** required to reduce VG curtailment under high-penetration (55%) VG scenarios.
- The **storage value** under varying storage durations.

Some overarching remarks

- Our initial valuation approach can provide storage developers with insight on optimal storage sizing.
- We consider a 55% VG penetration, but are not implying that energy storage is required to reach this level.
- Multiple options exist for integrating VG, and their effectiveness should be evaluated with and without the use of storage.

Timescales of Energy Storage

What is energy storage size?

The size of energy storage is defined by

- **Power capacity**—rate of charge or discharge (in kilowatts or megawatts), and
- **Energy capacity**—amount of stored energy (in kilowatt-hours or megawatt-hours).

Storage duration links these two capacities

Storage duration—amount of time that storage can discharge at its *power capacity* before depleting its *energy capacity*

- Consider a battery with
  - 1 MW of power capacity, and
  - 4 MWh of usable energy capacity

  => Its *storage duration* is 4 hours

Energy-storage timescales and their applications

- Seconds to minutes
    - Operating reserves, including frequency regulation
- Several hours
    - Peaking capacity
    - Shifting energy from off-peak to peak periods
    - Ramp events
    - Daily mismatch of renewable supply and electricity demand
- 10 hours or more
    - Arbitrage between weekday and weekend price differences
    - Seasonal mismatches

Methods and Scenarios

Our approach/methodology

- NREL's Renewable Energy Flexibility (REFlex) model
  - To dispatch the power system under each scenario
  - To analyze use of energy storage to avoid curtailment
- Assumptions
  - New transmission construction avoids significant transmission-related curtailment
  - All curtailment results from system-generation constraints.

REFlex simulations

- REFlex perform chronological dispatch of
  - Aggregated thermal and hydro units
  - Energy storage
- Simulations performed using 6 years (2007–2012) of
  - Historical load patterns
  - Corresponding wind and solar generation data
- Dispatch of increasing levels of VG to examine curtailment patterns and ability to avoid curtailment using energy storage.

Our scenarios

- They are based on DOE's Wind Vision study, which examined the potential for wind to provide a large fraction of the nation's electricity supply.
- We examine a scenario where VG provides 55% of the electricity demand in the Electricity Reliability Council of Texas (ERCOT) grid system in 2050.
  - In 2016, ERCOT used wind generation to meet ~15% of its annual electricity demand.

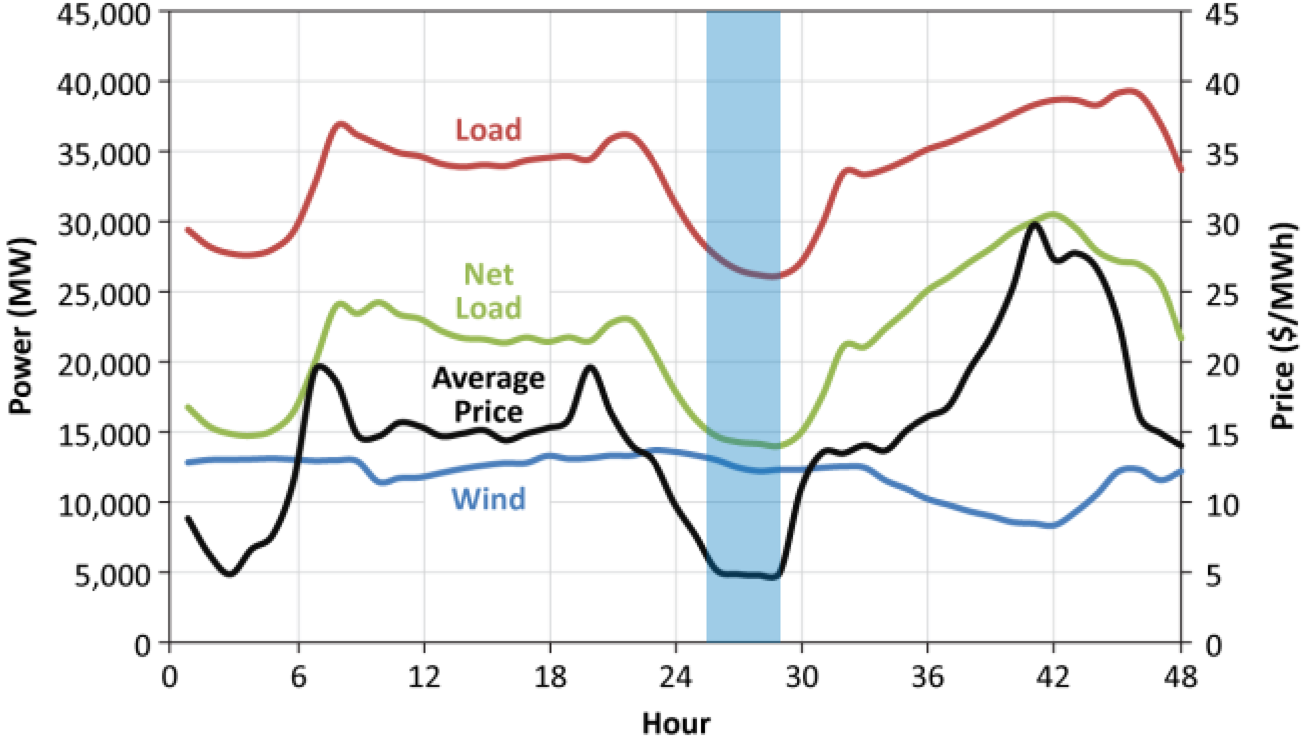
Three primary scenarios of 55% VG

Scenario	% Wind	% PV
Wind Vision	44	11
Minimum Curtailment	37	18
Equal Mix	27.5	27.5

Adding wind and PV to our scenarios

- Adding wind
  - Calculate energy value
  - Estimate capacity credit
  - Estimate capacity value (= capacity credit x assumed annualized value of new capacity value in ERCOT)
- Adding PV
  - Select PV sites generated for SunShot 2030 study
  - Simulate PV at each site using SAM to generate hourly profiles for the 6 years of data.

Calibrate aggregated minimum generation (1 of 2)



- Actual load, winds, and average price conditions in ERCOT on March 22–23, 1026.

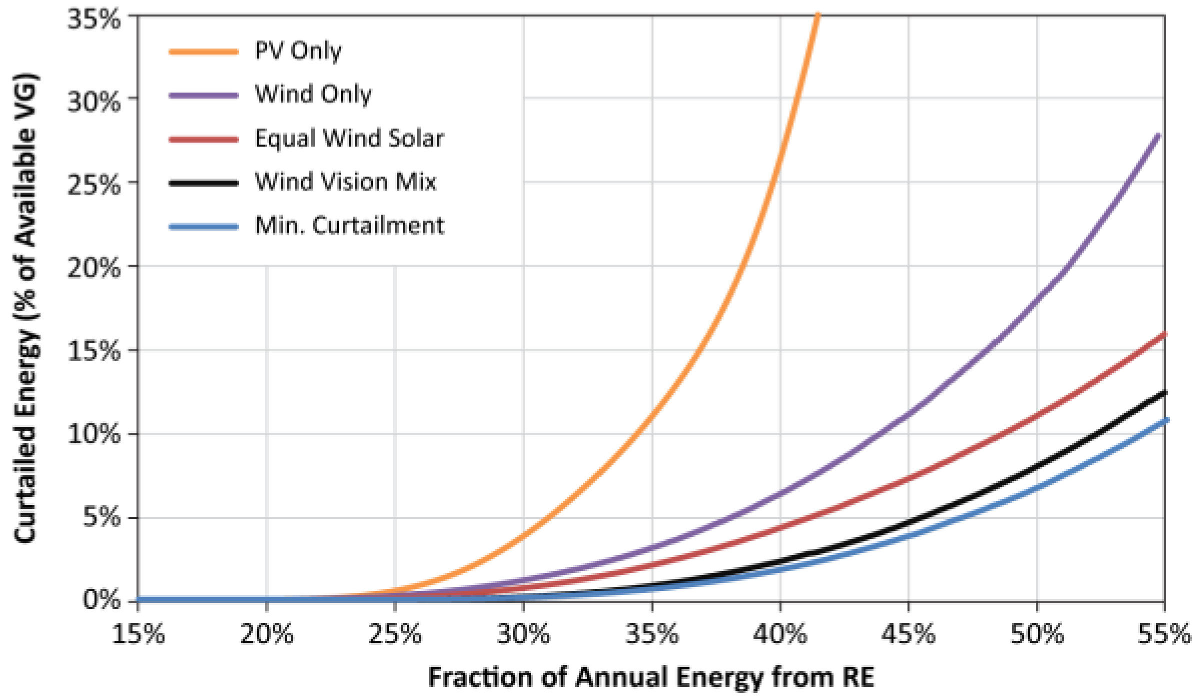
Calibrate aggregated minimum generation (2 of 2)

- 2016 minimum output was ~ 14,000 MW from 2 to 4 a.m. on March 23 (see blue band on previous chart)
  - Relatively low load and high wind output
  - Day-ahead price for energy fell to $9/MWh
  - Assumed only modest increase in grid flexibility from now to 2050
  - Assumed all existing nuclear capacity receives license extension and operates at least until 2050.

Results:
Curtailment in No-Storage Scenarios

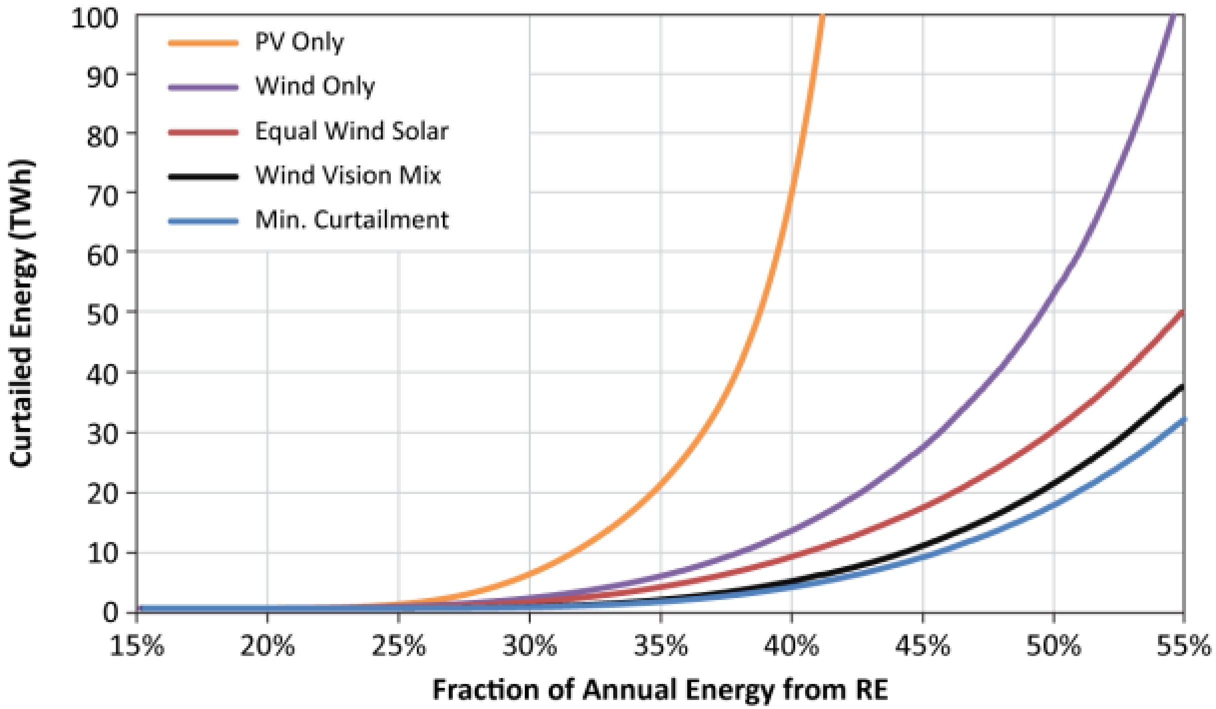
- *Base Curtailment Levels*
- *Curtailment Patterns*

Base curtailment levels (1 of 3)



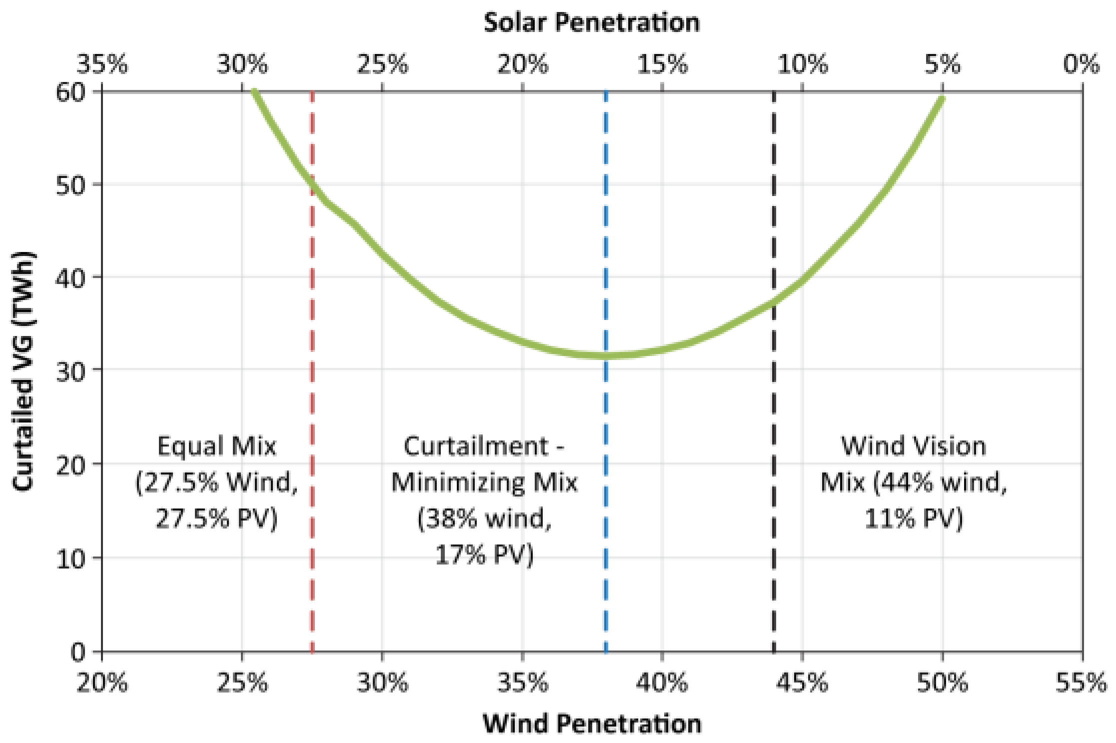
- **Total VG curtailment rate** under increasing VG penetrations, with different mixes of wind and solar and no energy storage.

Base curtailment levels (2 of 3)



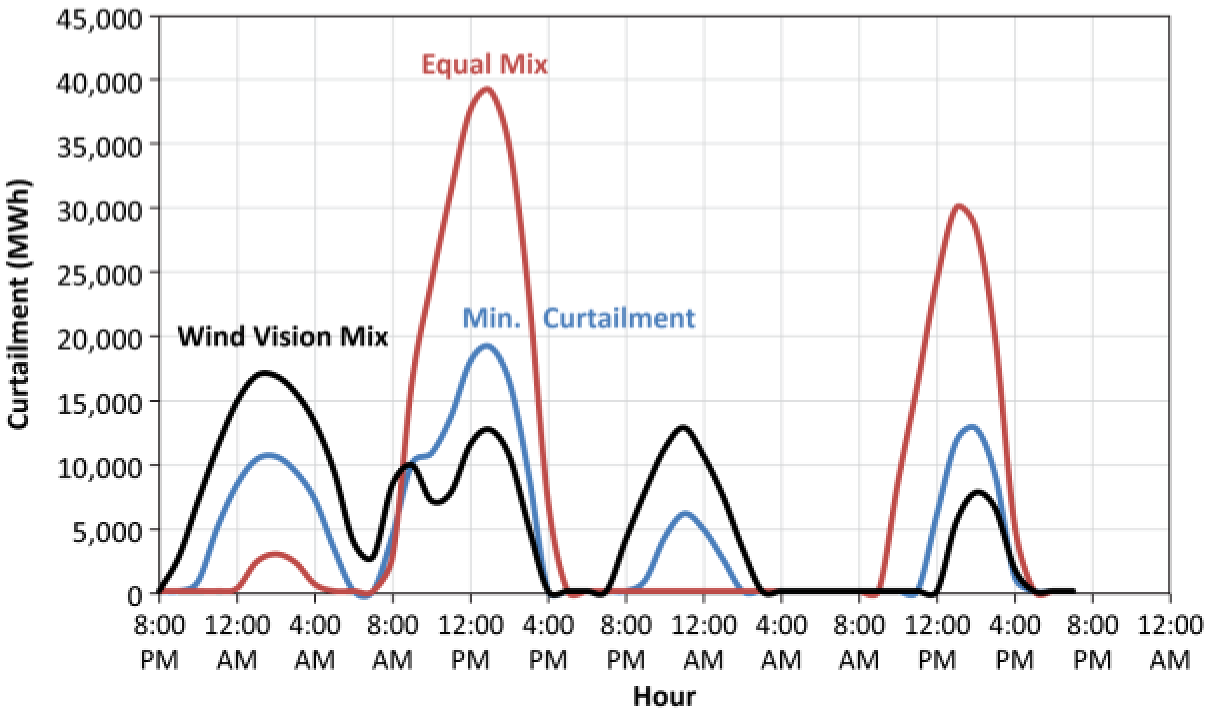
- **Total VG energy curtailed** under increasing VG penetrations, with different mixes of wind and solar and no energy storage.

Base curtailment levels (3 of 3)



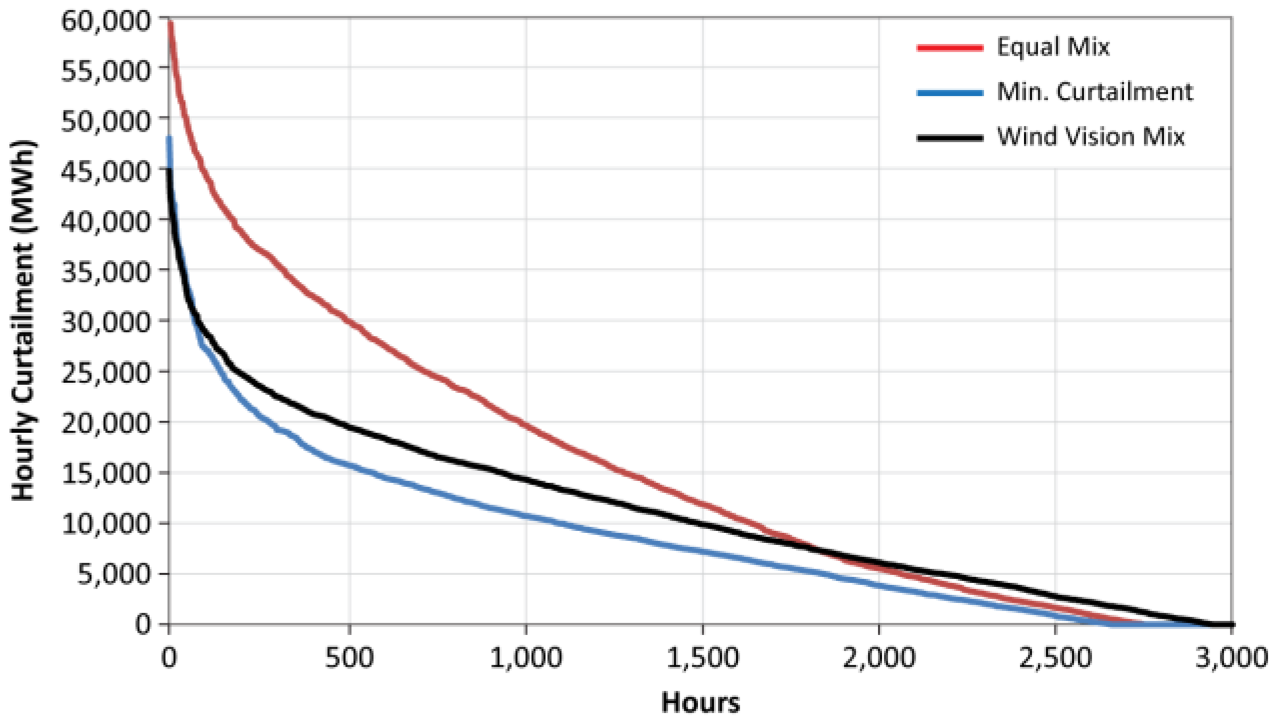
- Total VG curtailed at an annual VG penetration of 55% as a function of wind/solar mix, with no energy storage.
- Wind/solar ratio that minimizes curtailment is 38% wind/17% solar (2.2:1)

Curtailment patterns (1 of 4)



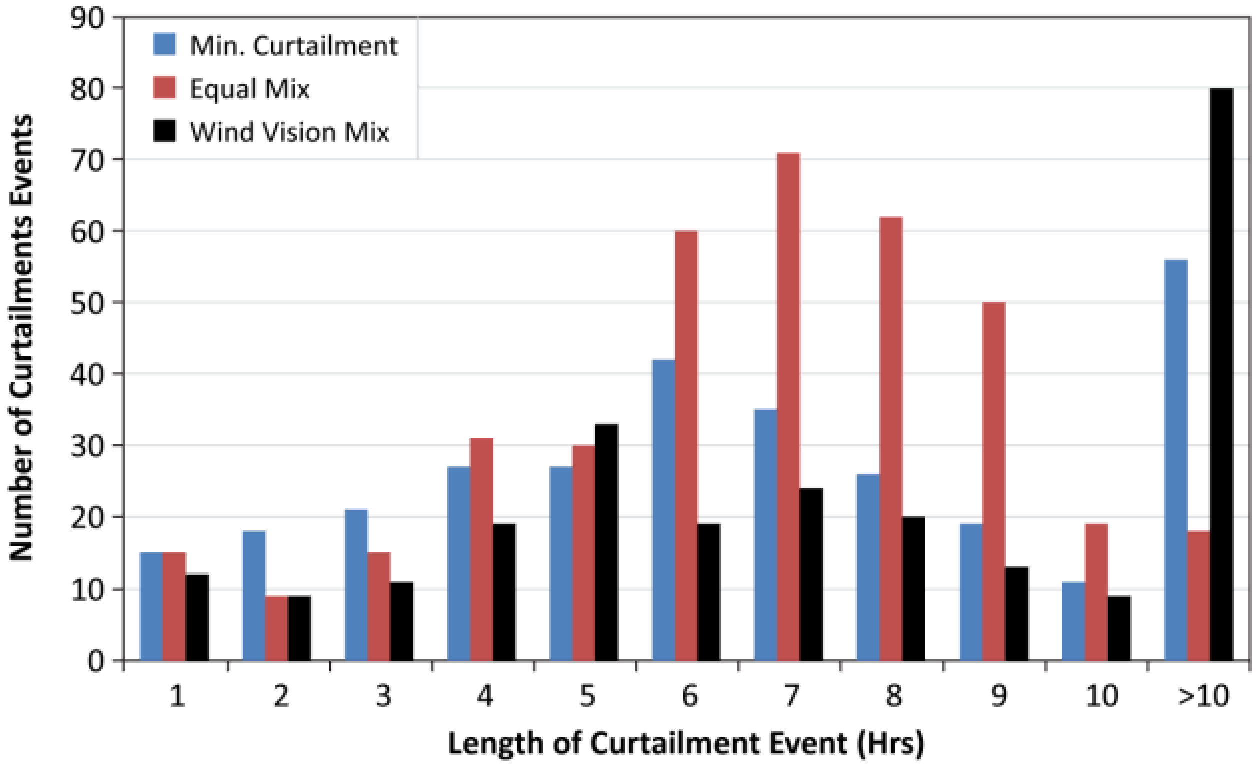
- **Simulated curtailment** during January 20–21 in ERCOT with no storage using 2012 wind, solar, and load patterns.
- Wind and solar have different diurnal and seasonal production patterns that impact duration of curtailment events and required storage duration.

Curtailment patterns (2 of 4)



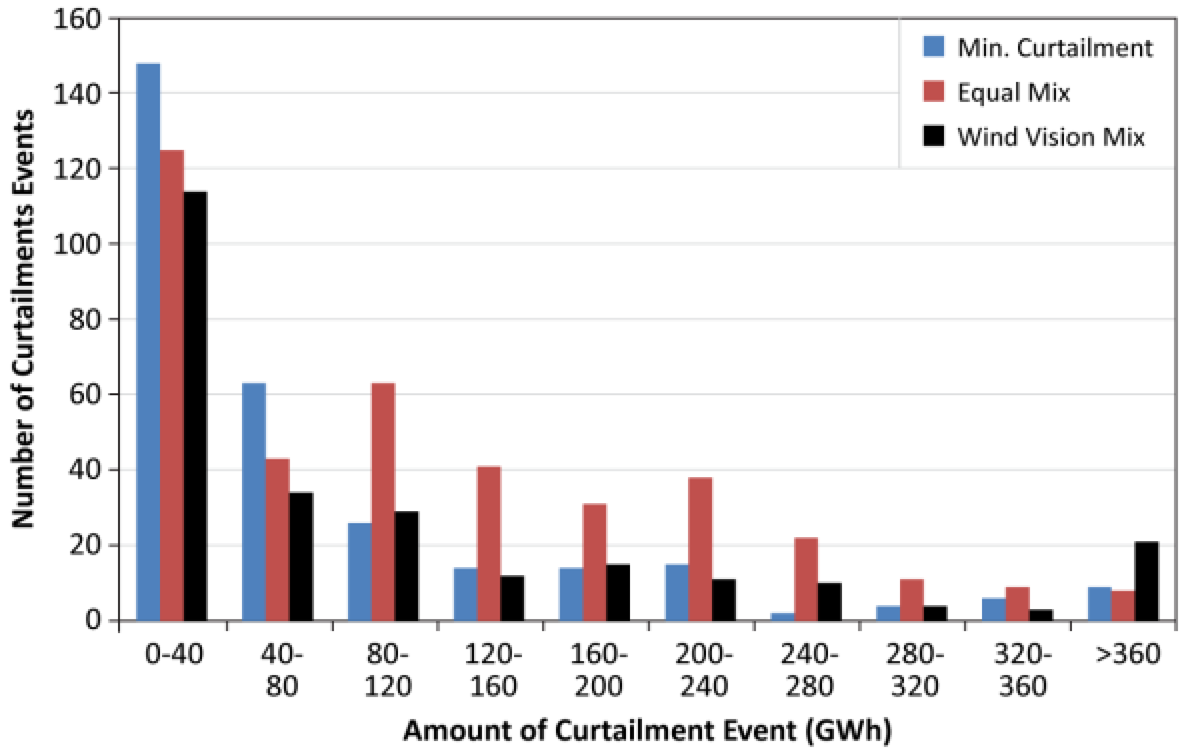
- **Duration curve of curtailment** at 55% VG in ERCOT with no storage using 2012 wind, solar, and load patterns.
- The scenarios have a large range in both instantaneous curtailment and length of curtailment events.

Curtailment patterns (3 of 4)



- Distributions of **durations** of curtailment events with no storage using 2012 wind, solar, and load patterns.

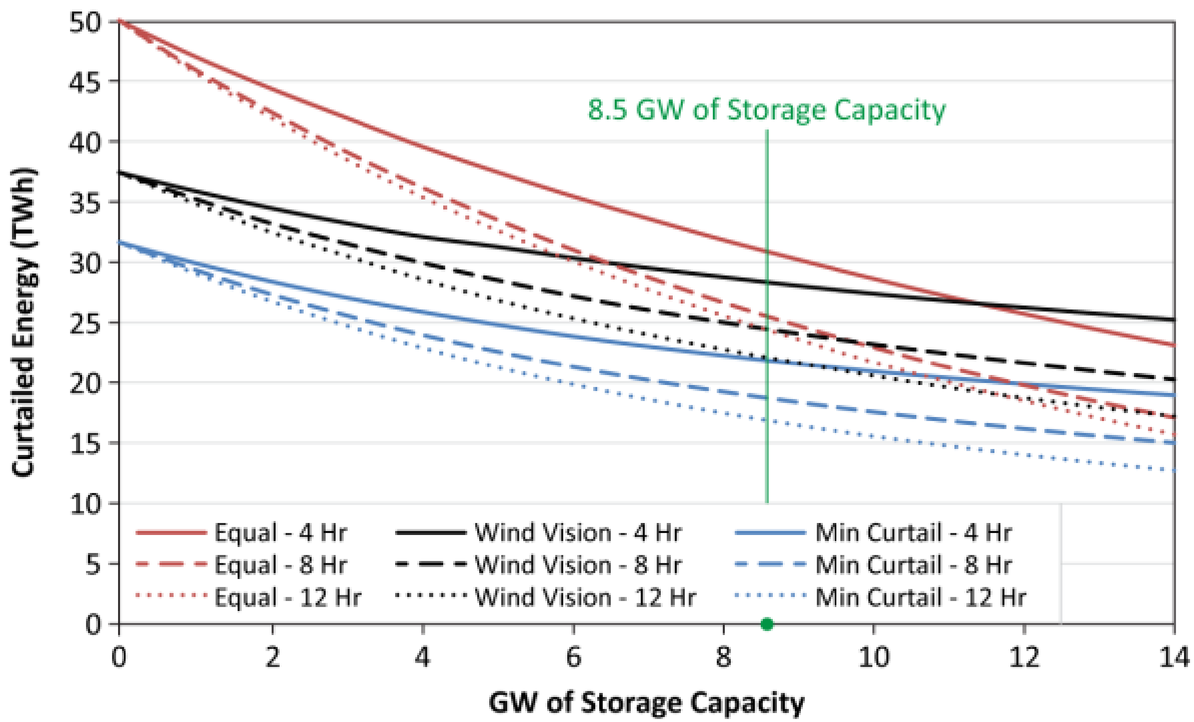
Curtailment patterns (4 of 4)



- Distributions of **energy** of curtailment events with no storage using 2012 wind, solar, and load patterns.

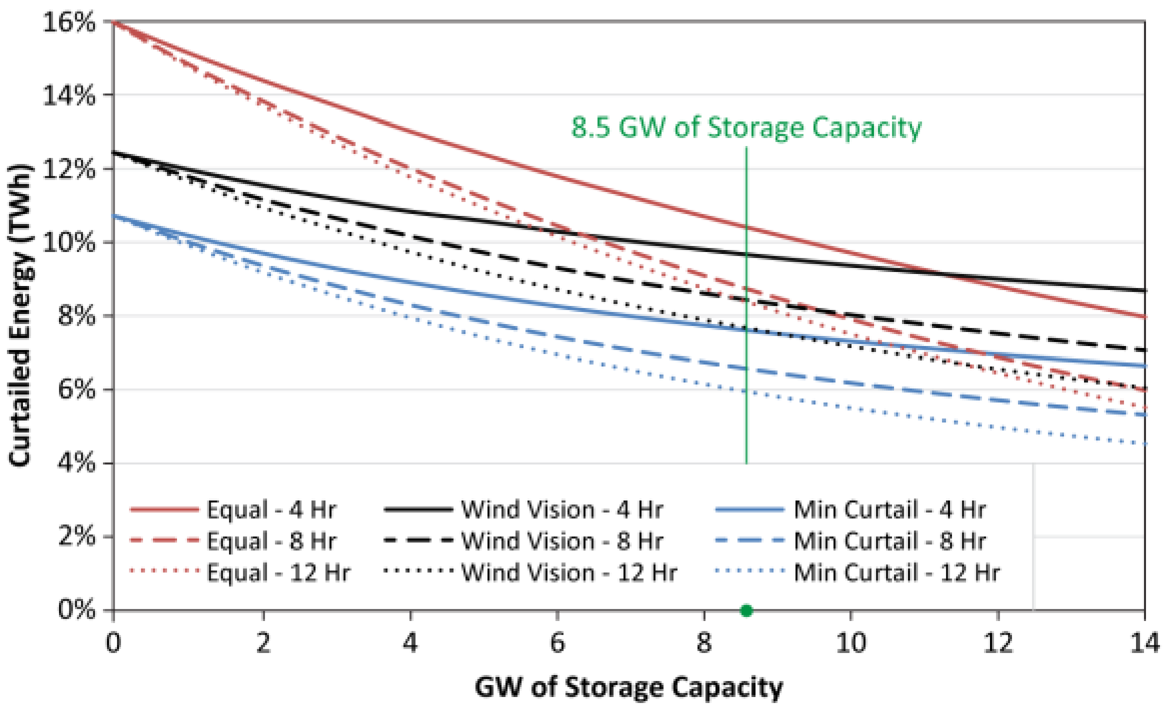
Results:
Impact of Storage Capacity on Curtailment

Impact of Storage on Curtailment (1 of 2)



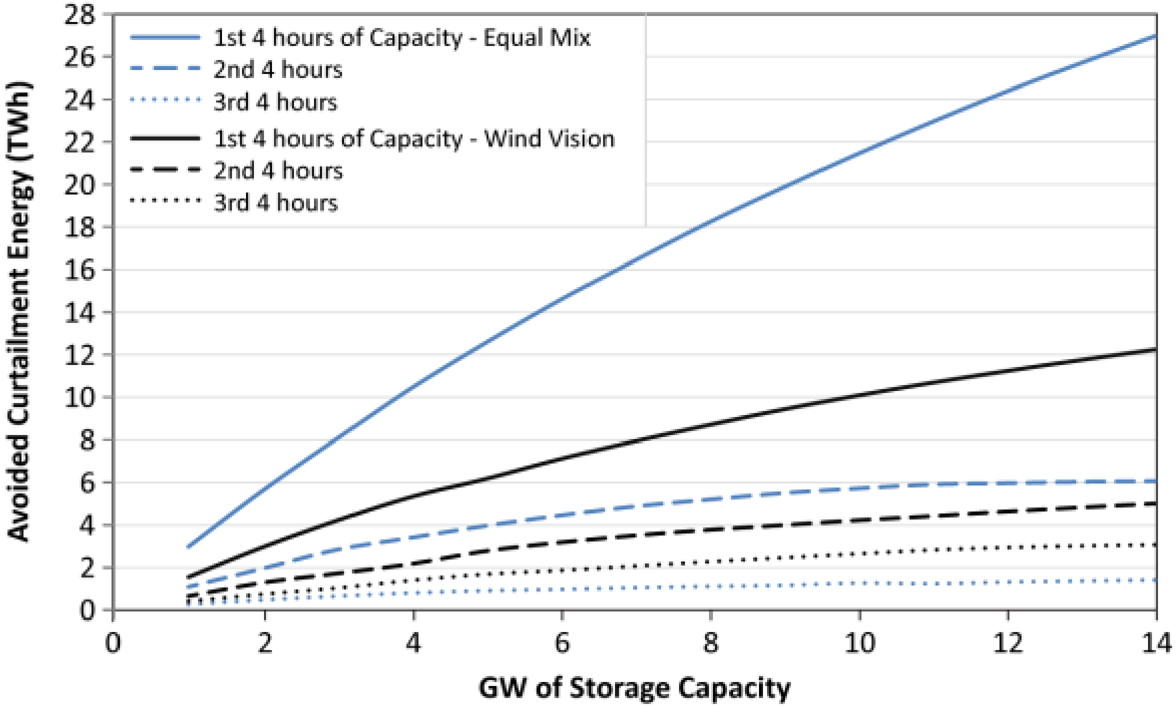
- **Total curtailment** at 55% VG as a function of **storage power capacity** for the three study scenarios at varying storage durations.

Impact of Storage on Curtailment (2 of 2)



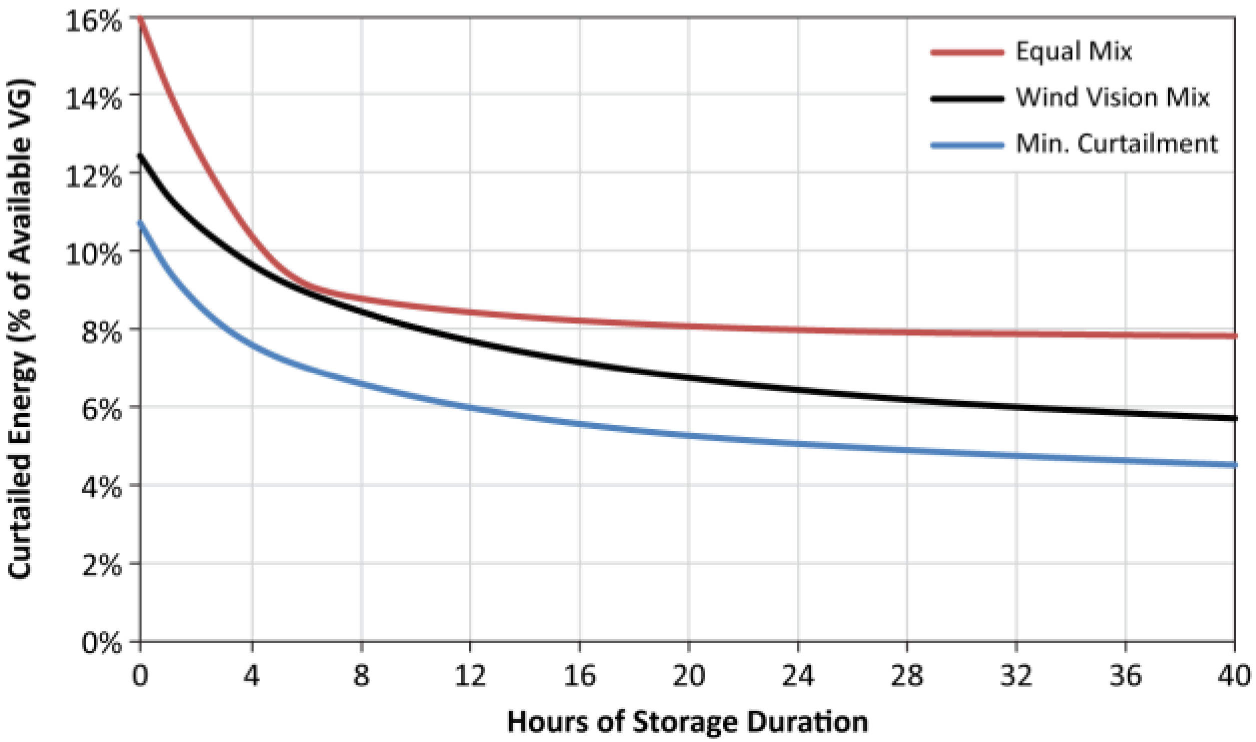
- **Curtailment rate** at 55% VG as a function of **storage power capacity** for the three study scenarios at varying storage durations.
- With no storage: ~11%–16% of VG energy is curtailed
- With 8.5 GW storage capacity (using Wind Vision Mix):
  - VG curtailment is ~8%–10%
  - Curtailment is thus reduced by ~24%–38%
- **Impact: 4 hours of storage can substantially reduce curtailment**

Diminishing returns with greater storage duration



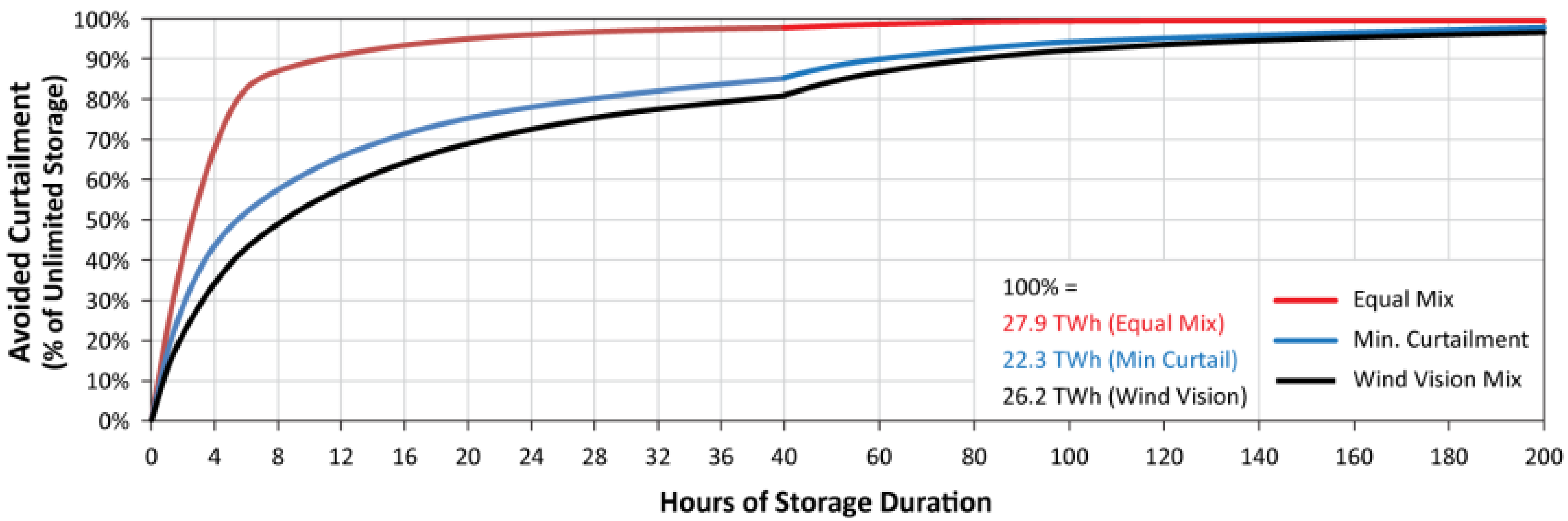
- **Avoided curtailment** at 55% VG as a function of **storage power capacity** for the Equal-Mix and Wind Vision scenarios with varying amounts of additional storage duration.
- Additional storage duration and power capacity provides diminishing avoided-curtailment returns.

Fixed storage capacity (8.5 GW)



- **Total curtailment** at 55% VG as a function of **storage duration** assuming 8.5 GW of storage power capacity for the three study scenarios.
- Storage capacity of 8.5 GW is equivalent to about one-third of ERCOT's projected peaking capacity in 2050.
- **Impact: Additional storage duration (beyond 8 hours) and power capacity yield diminishing returns with respect to avoided curtailment.**

Avoided curtailment



- **Avoided curtailment** at 55% VG as a function of **storage duration** assuming 8.5 GW of storage power capacity for the three study scenarios.

Further results

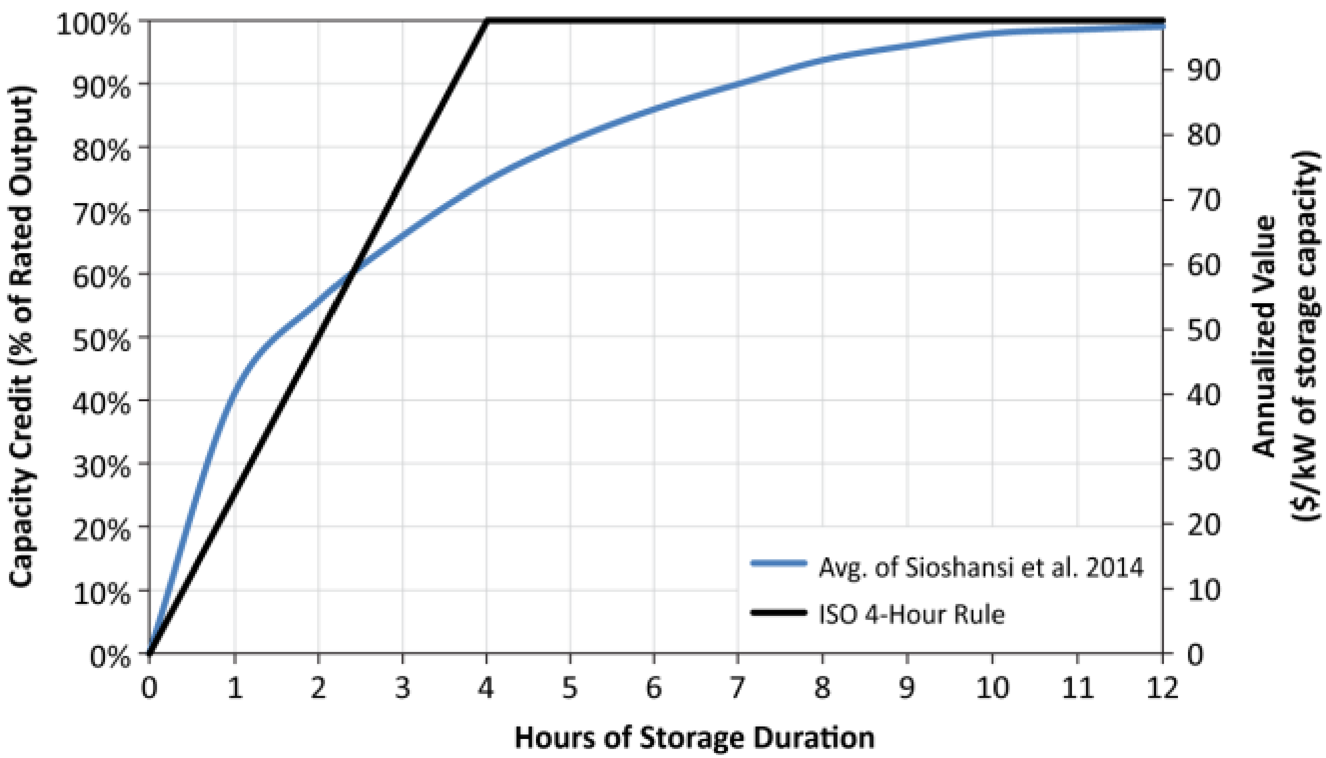
- Storage duration of 4 hours in the Wind Vision scenario avoids 35% of the curtailment that could be avoided with an 8.5-GW storage device of unlimited duration and about 70% in the Equal-Mix scenario.
- Storage duration of 8 hours would reduce curtailment by 49% (in Wind Vision scenario) and 88% (in Equal-Mix scenario), relative to an unlimited duration device.
- The incremental amount of avoided curtailment falls off rapidly when increasing storage duration beyond these levels, especially with greater amounts of PV.

Results:
Impact of Storage Duration on Value

Value—more of the storage story

- **Capacity value**—the ability of storage to replace conventional peaking capacity.
  - Several U.S. markets award full capacity credit to devices with 4 hours of capacity, further decreasing the need for longer-duration storage.
- **Energy value**—stored, otherwise-curtailed energy that benefits from energy price arbitrage/time-shifting.
- There are many other values provided by energy storage that are not considered here.

Annual capacity value



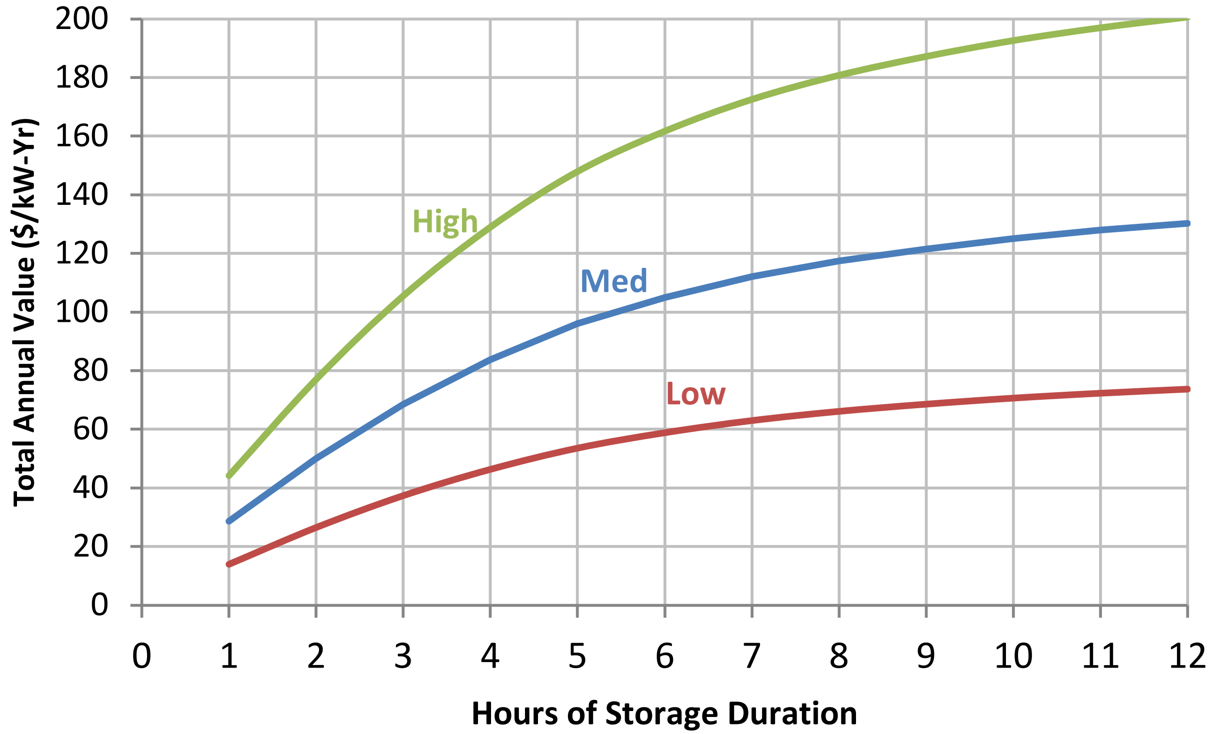
- **Capacity credit** and **annualized capacity value of storage** (value assumes avoided $97/kW of firm capacity).

Annual energy value (1 of 4)

Name	VG Penetration (%)	Wind/Solar Ratio	Natural Gas Price ($/MMBtu)	CO_2 Cost ($/ton)
Low Value	35	2.2:1	4	0
Medium Value	45	4:1	5	20
High Value	55	1:1	6	40

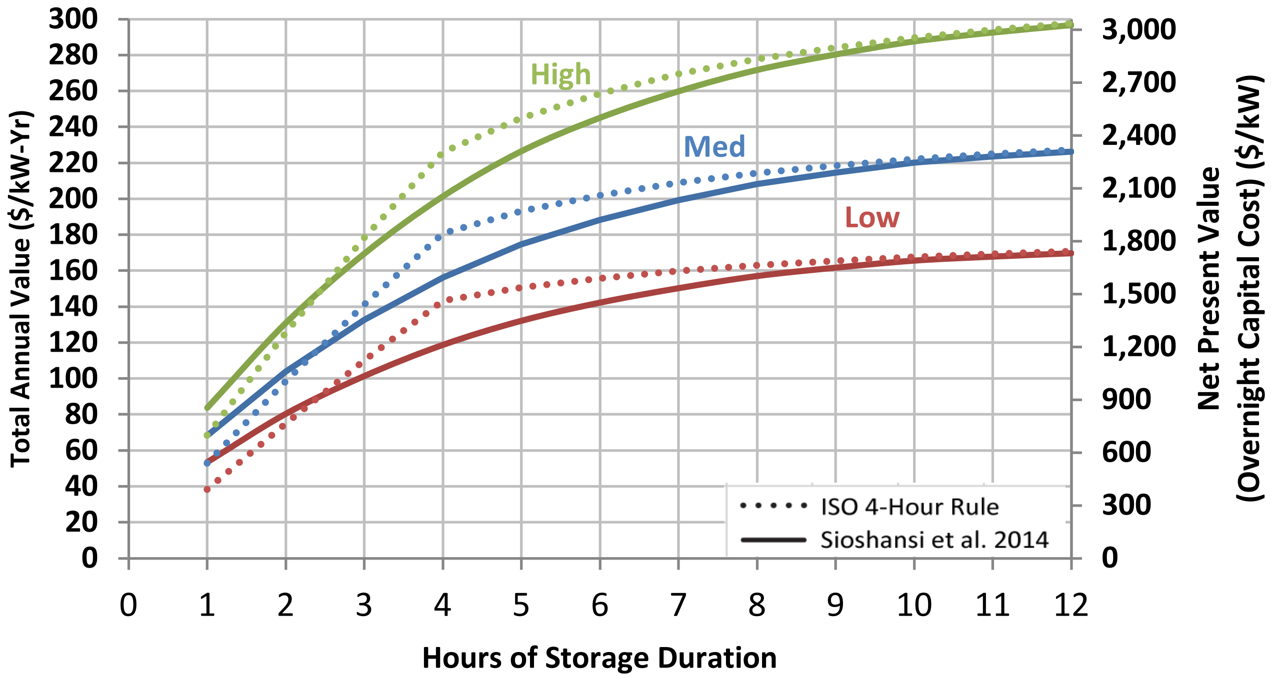
- Three cases evaluated

Annual energy value (2 of 4)



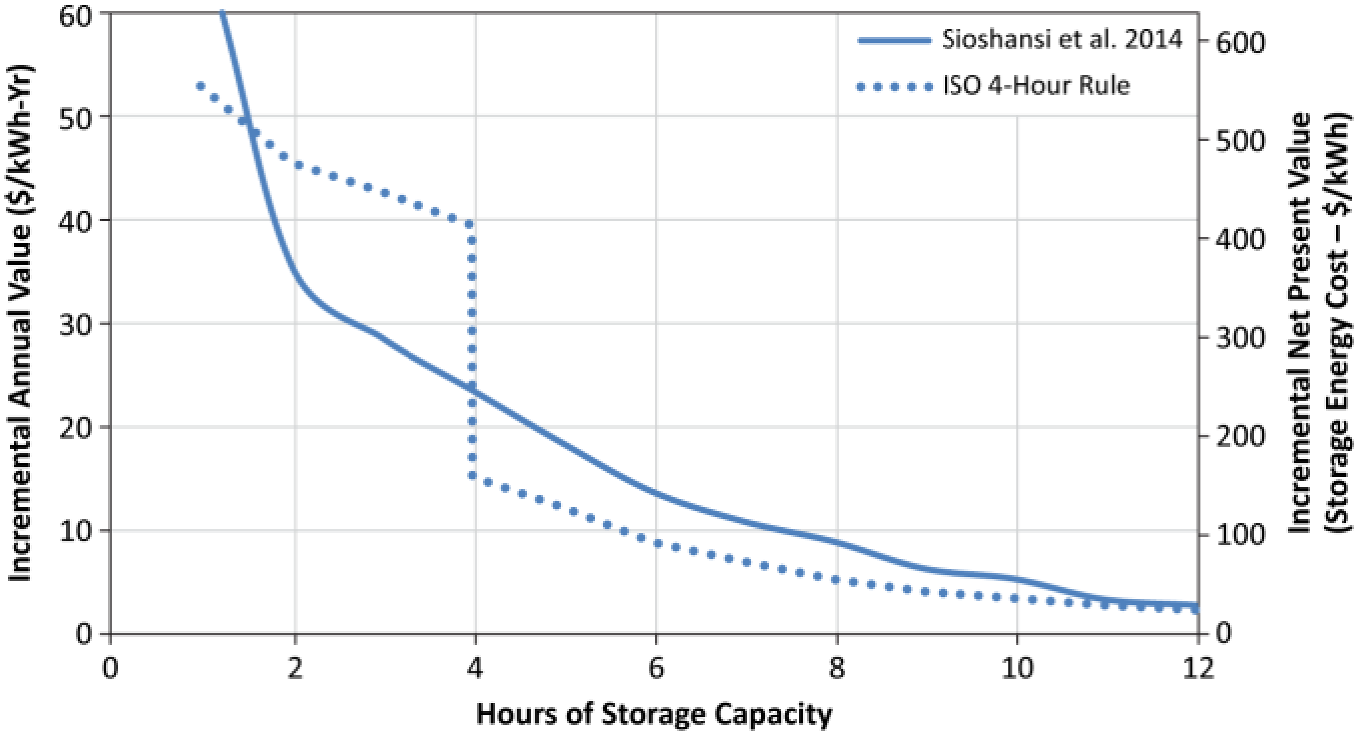
- **Energy value** of energy storage under different cases.

Annual energy value (3 of 4)



- **Total value of storage** as a function of storage duration.

Annual energy value (4 of 4)



- **Incremental value** of energy storage, medium-value case.
- Once a storage device achieves the bulk of its value from the first few hours, the incremental value of additional energy is relatively low under a range of scenarios.

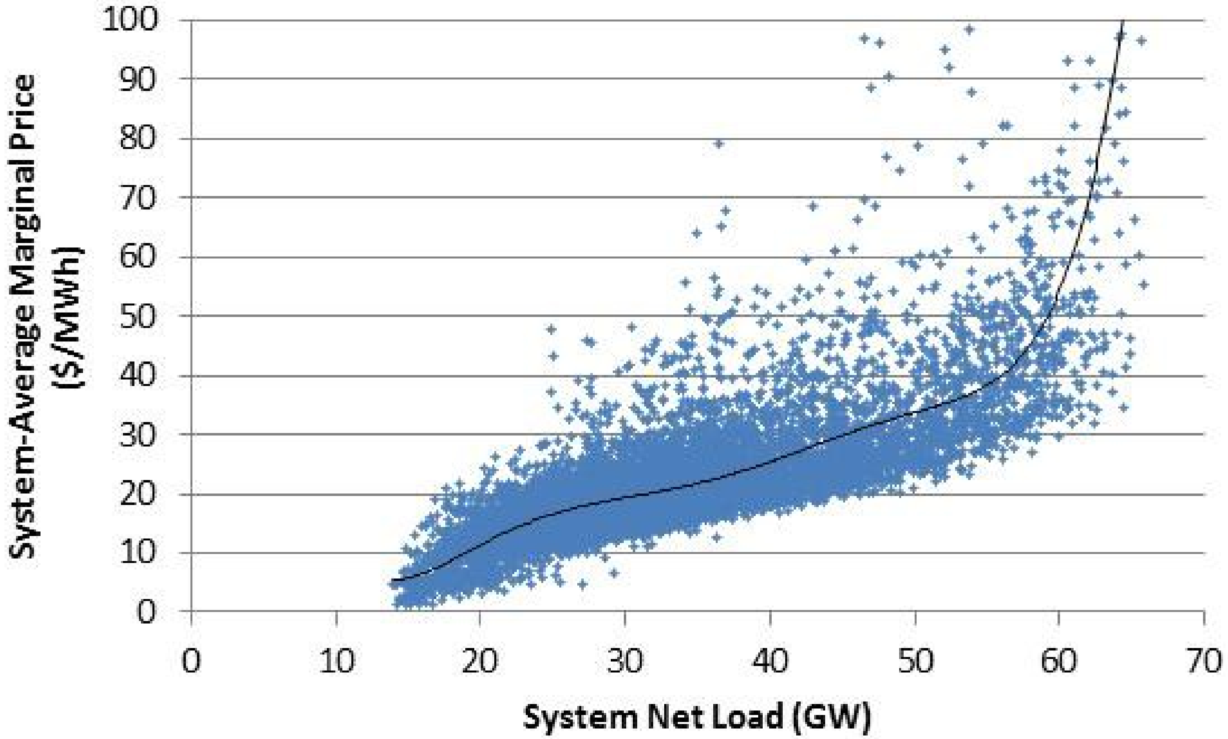
Conclusions

Overall conclusions

- Relatively short-duration energy storage may be an effective path to reduce VG curtailments at penetrations up to 55%.
- Across all mixes of wind and solar resources analyzed, at least half the potential avoided-curtailment benefits are realized with 8 hours of storage—and the first 4 hours provide the largest benefit.
- At VG penetrations up to 55%, very-long-duration or seasonal storage appears to provide little incremental benefit.

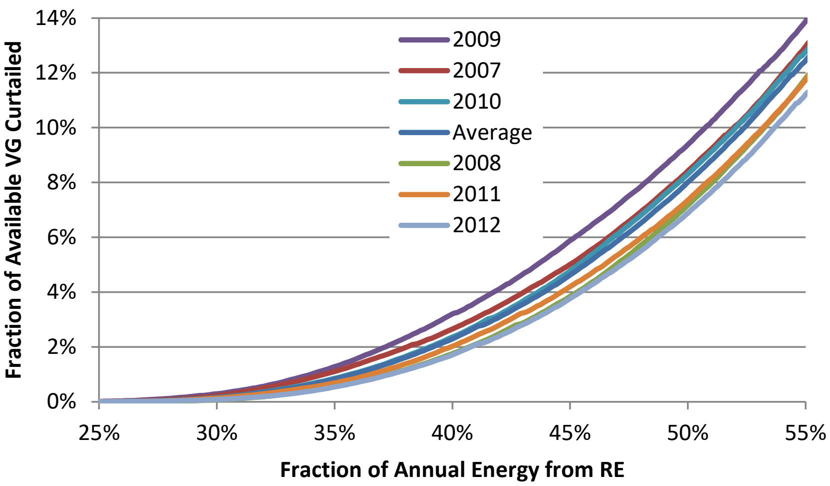
Additional slides

Price-load data used in REFlex model

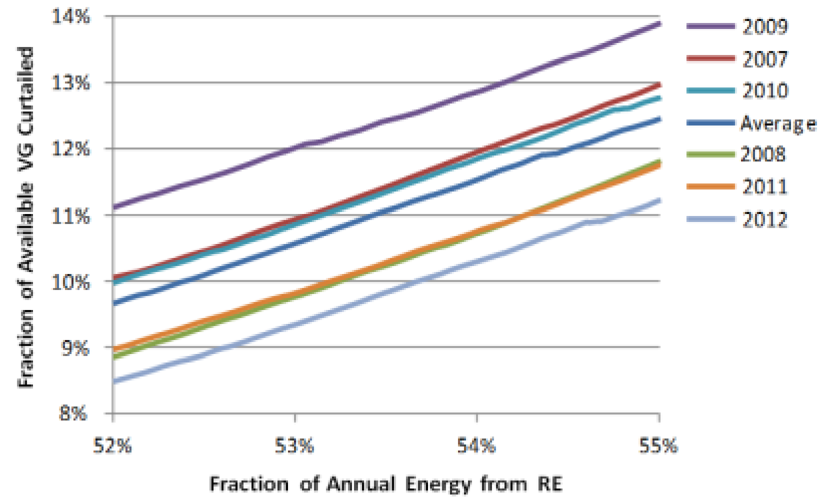


- Price and net load relationship in ERCOT in 2016.
- Graph used to determine marginal energy value of wind to site each wind cluster.

Variation in curtailment



a) Full Range



b) At highest penetration levels

- Variation in curtailment across all six years of data in Wind Vision scenario, without storage.

www.nrel.gov