National Renewable Energy Laboratory
Innovation for Our Energy Future

# Role of Electricity Storage in enabling Renewable Energy Integration
# 可再生能源并网技术中储能的作用


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## Do Renewables Need Electricity Storage?
## 可再生能源需要储能吗？

Common claims:

主要结论：

- **Wind and solar generation is variable and unreliable, and requires backup generation and firm output to be useful in a utility system**
- 风力发电与太阳能发电具有可变性和不稳定性，需要备用机组。在实际系统中固定出力是很重要的
- **Wind and solar energy should be smoothed or shifted times to times when the wind is not blowing or sun is not shining to better match electricity demand.**
- 当无风或太阳照射强度不够时，为了能更好地与电力需求匹配，风能与太阳能出力曲线需要随时进行平滑或者平移。

Insights from Renewable Energy Integration studies:

可再生能源接入研究表明：

- **Electricity storage is largely an economic decision, not a technical requirement**
- 储能更多的是个经济选择，而不是技术需求
  - **Invest in additional transmission and distribution resources**
  - 减少了附加的输电或配电方面的投资
  - **Balance energy markets over larger geographic regions**
  - 在大的地理区域平衡能量市场
  - **Curtail variable renewable energy**
  - 减少可再生能源的变化
  - **Run conventional units non-optimally**
  - 常规机组运行时是不优化的
  - **Ramp and cycle conventional units more frequently**
  - 常规机组的功率调节更频繁

## Talk Outline
## 目录

- Current status of storage
- 储能的现状
- Impacts of renewables on the grid and results from previous U.S. grid integration studies
- 可再生能源对电网的影响和美国可再生能源并网的研究结果
- How storage can help achieve high renewable energy targets and ease transmission constraints
- 储能怎样提高可再生能源的比例、减轻输电压力
- Overview of storage technologies for different utility and distributed applications
- 用于不同场合的储能技术概述



## Global status of Utility Scale Storage
## 效用率存储的国际现状

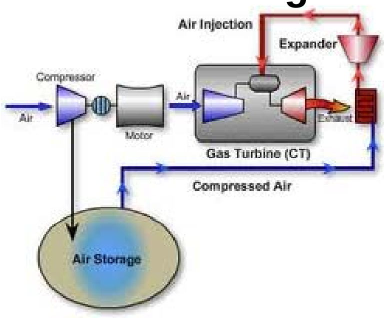
- 127 GW of pumped hydroelectric storage (PHS) worldwide
- 世界共有127GW的抽水蓄能电站(PHS)
    - 20 GW in U.S.
    - 美国有20 GW
- 400 MW Compressed Air Energy Storage (CAES) worldwide
- 世界有400 MW的压缩空气储能(CAES)
    - 110 MW unit in U.S., 290 MW unit in Germany
    - 美国有110MW，德国有290MW
- About 270 MW of Sodium–Sulfur Batteries (mostly Japan)
- 约有270MW的纳硫电池(主要在日本)
- 30 MW of flywheel energy storage plants
- 30MW的飞轮存储
    - Three U.S. demonstration projects
    - 美国有3个示范工程
- Few hundred MW of CSP with thermal storage
- 少量具有储热功能的聚焦式太阳能热发电

**PHS storage**

**Flywheel storage**

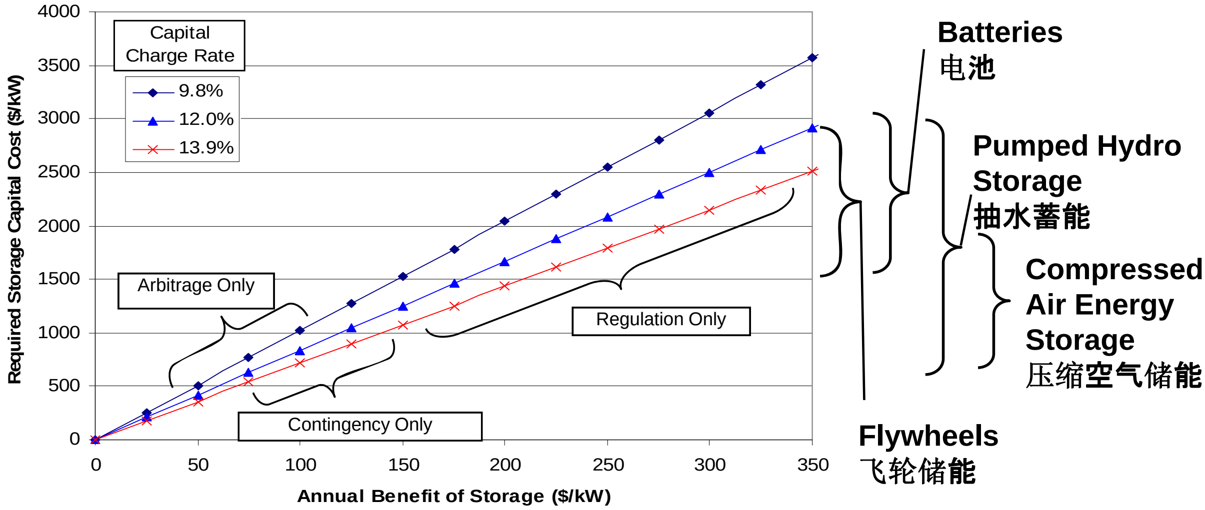
**CSP thermal storage**

**CAES storage**



# Value of Energy Storage in U.S. Markets
# 美国市场的能源存储价格

### Relationship between storage Net Revenues and Capital Costs*
### 资金成本与储能收益的关系

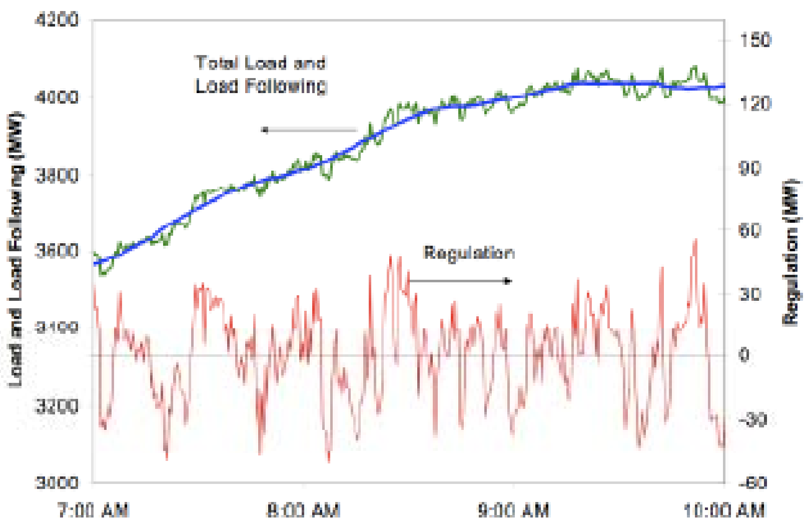



- **Storage technologies provide several value streams (energy and capacity)**
- **储能技术提供一些价值流(能量和容量)**
- **Arbitrage revenues alone are generally insufficient to support most storage technologies, which are generally >$1,000/kW**
- **套利收益不足以支撑储能技术，储能技术一般超过 1000美元/kW**
- **Regulation can be the highest value stream**
- **最高价值流是监管**

*Revenues derived from: Figueiredo et al. 2006, Denholm and Letendre 2007, Walawalker et al. 2007, Sioshansi et al. 2009, Eyer et al. 2010, Drury et al. *in prep*
Costs from Nourai 2007, Rastler 2009, EPRI 2003, EPRI 2007,



# Ramping in Conventional Power Systems
# 常规机组的爬坡率




[Kirby 2004]

**Daily variations in load met by ramping conventional generators; Up to 100% in summer**

**常规机组可调节负荷的日变动,夏季会上升至100%**

**Variability in load met with frequency regulation resources;**

**1-2% of total load**

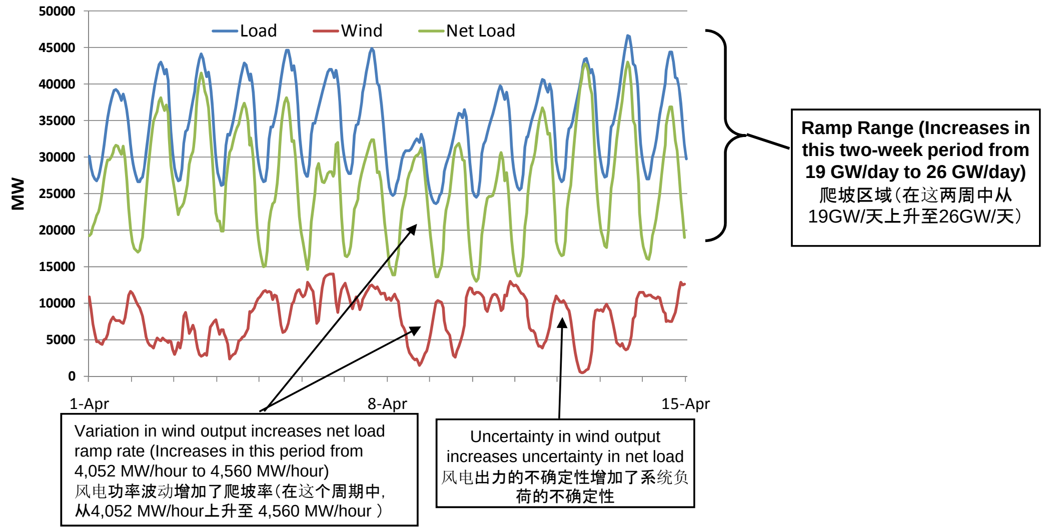
**调频电源可调节负荷变动**

**负荷总量的1-2%**

**Current variations in load and contingency events are met using conventional resources**

**使用常规能源可调节负荷的常规波动和紧急情况**

## Renewables increase daily ramping requirements
## 可再生能源增加每日需求变化



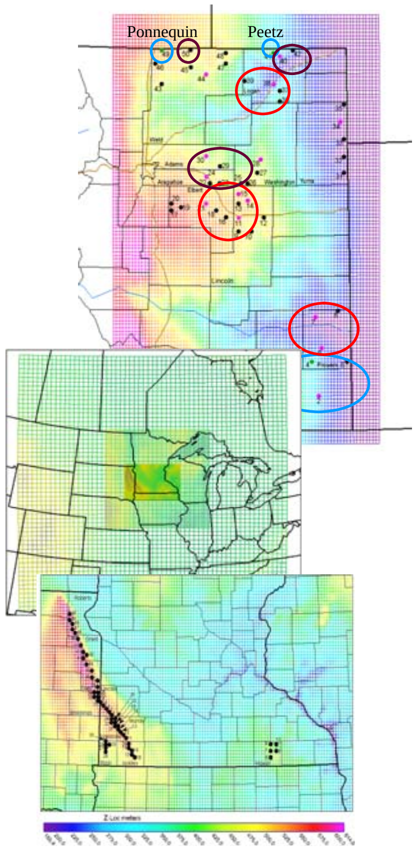

**Major impacts of variable generation (VG) on the grid:**

**出力变化的机组对电网 的主要影响**

1) Increases the need for frequency regulation resources
1) 调频需求 加大
2) Increases hourly ramp rates and total depth of ramping
2) 增加了每小时爬坡率和爬坡深度
3) Forecast uncertainties reduce the efficiency of scheduling and dispatching generation resources
3) 预测的不确定性降低了调度的效率



## RE (Mostly Wind) Integration Studies
## 可再生能源(主要是风电)接入研究




Simulate system with and without solar and wind

带有和不带风电/太阳能的仿真系统

- Use unit commitment and dispatch software that includes the existing generation and transmission resources
- 使用机组开机方式和调度软件，该软件包括已有的发电机和传输线路模型
- Use spatially diverse wind and solar simulations
- 仿真风能和太阳能的空间多样化
- May involve substantial costs
- 可能包括实体成本

Evaluate costs of additional regulation, ramping, and less efficient scheduling and dispatch due to RE forecast errors

需要增加可再生能源的预测误差造成的调节、爬坡和低效开机方式和调度的评估成本

# Variable RE Integration Costs

| Date | Study | Wind Capacity Penetration (%) | Regulation Cost ($/MWh) | Load Following Cost ($/MWh) | Unit Commitment Cost ($/MWh) | **Tot Oper. Cost Impact ($/MWh)** |
|---|---|---|---|---|---|---|
| 2003 | Xcel-UWIG | 3.5 | 0 | 0.41 | 1.44 | **1.85** |
| 2003 | WE Energies | 29 | 1.02 | 0.15 | 1.75 | **2.92** |
| 2004 | Xcel-MNDOC | 15 | 0.23 | na | 4.37 | **4.6** |
| 2005 | PacifiCorp-2004 | 11 | 0 | 1.48 | 3.16 | **4.64** |
| 2006 | Calif. (multi-year)[a] | 4 | 0.45 | trace | trace | **0.45** |
| 2006 | Xcel-PSCo[b] | 15 | 0.2 | na | 3.32 | **4.97** |
| 2006 | MN-MISO[c] | 36 | na | na | na | **4.41** |
| 2007 | Puget Sound Energy | 12 | na | na | na | **6.94** |
| 2007 | Arizona Pub. Service | 15 | 0.37 | 2.65 | 1.06 | **4.08** |
| 2007 | Avista Utilities[d] | 30 | 1.43 | 4.4 | 3 | **8.84** |
| 2007 | PacifiCorp-2007 | 18 | na | 1.1 | 4 | **5.1** |
| 2008 | Xcel-PSCo[e] | 20 | na | na | na | **8.56** |

[a] Regulation costs represent 3-year average.
[b] The Xcel/PSCO study also examine the cost of gas supply scheduling and found a cost of $1.45/MWh. [c] Highest over 3-year evaluation period. 30.7% capacity penetration corresponding to 25% energy penetration
[d] Unit commitment includes cost of wind forecast error.
[e] This integration cost reflects a $10/MMBtu natural gas scenario. This cost is much higher than the integration cost calculated for Xcel-PSCo in 2006, in large measure due to the higher natural gas price: had the gas price from the 2006 study been used in the 2008 study, the integration cost would drop from $8.56/MWh to $5.13/MWh.

- Most integration costs < $5/MWh; all < $10/MWh
- RE < 30% energy

# Variable RE Integration Costs
# 各种可再生能源并网成本

| 年份 | 名称 | 风电穿透功率(%) | 调度成本($/MWh) | 负荷追踪成本($/MWh) | 机组启停成本($/MWh) | **全部运行成本总和($/MWh)** |
|---|---|---|---|---|---|---|
| 2003 | Xcel-UWIG | 3.5 | 0 | 0.41 | 1.44 | **1.85** |
| 2003 | WE Energies | 29 | 1.02 | 0.15 | 1.75 | **2.92** |
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| 2008 | Xcel-PSCo[e] | 20 | na | na | na | **8.56** |

[A] 调度成本指三年的平均值.
[b] Xcel/PSCO的调研也包括燃气机组的成调度成本， $1.45/MWh，高达三年的评估期，并结合30.7%的传统容量和25%的穿透 能量
[d] 开机方式保罗风电预测误差成本.
[e] 这个并网成本反映了$10/MMBtu 的燃气机组情况。这个成本比Xcel-PSCo在2006年计算的并网成本高出很多。在一些计算中，已经考虑了昂贵的燃气：2006年研究的燃气价格已经应用到2008年的计算中。并网成本会从$8.56/MWh 降至 $5.13/MWh

- **大多数并网成本< $5/MWh; 所有成本 < $10/MWh**
- **可再生能源占总能源的比例< 30%**

## Conclusions of Wind Integration Studies (<30% Penetration)
## 风电并网研究总结（穿透功率比例<30%）

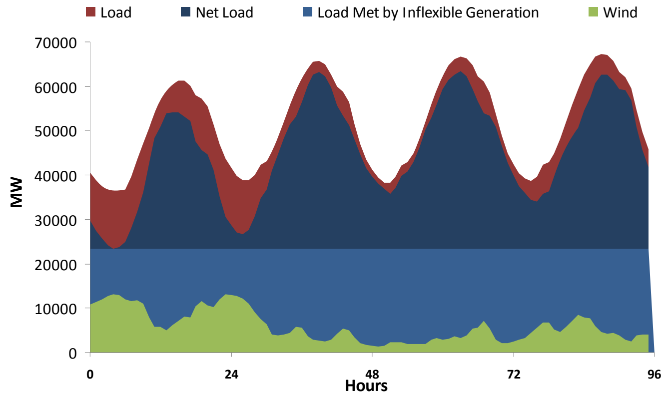
- Challenges are regulation, load following, and unit commitment
- 对调度、负荷追踪和机组开机方式的挑战
- Integration costs are modest (typically less than $5/MWh)
- 并网成本适中（一般小于$5/MWh）
- Increased variability can be accommodates by existing generator flexibility and other “low-cost” flexibility such as increased balancing area cooperation (balancing wind generation and load over larger areas to “share” the increased variability).
- 已有电机和其他“低成本”措施，比如增加区域间的调峰配合（在更大的区域平衡风电与负荷）的灵活使用可以调节风电的变化
- Spatial diversity smooths aggregated wind output reducing short-term fluctuations to hour time scales
- 空间多样性的平滑作用可以将风电总输出波动尺度降低到小时级
- Storage would “help” but is not needed, and the integration costs may not “pay” for expensive storage technologies.
- 储能是有用的但是不是必要的，综合成本可能不包括昂贵的储能技术成本



## When the grid will likely need storage
## 电网需要储能的情况

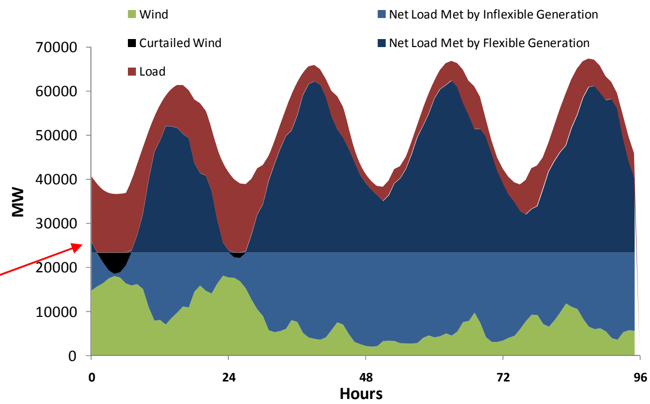
- High penetration of RE, where economic limits will be driven by increasing curtailment
- 在可再生能源穿透功率高的区域，增加的弃能会制约经济性
  - Limited coincidence of VG supply and normal demand
  - 变出力电源和正常需求的一致性有限
  - Minimum load constraints on thermal generators
  - 火电机组的负荷约束最小
  - Thermal generators kept online for operating reserves
  - 做为运行备用，火电机组保持联网
  - Mostly economic decision, technical constraint in some grids
  - 在一些电网，许多经济决策限制技术应用
- Transmission and distribution
- 输配电
  - Significant curtailment before high RE penetration reached
  - 在未达到可再生能源穿透功率之前就需要大幅度弃能
  - Economic decision, main challenge is siting new transmission resources
  - 选定新的传输线路对经济决策是个大挑战。

## High Penetration Limits
## 较高的穿透功率限制




Dispatch with low VG penetration (wind providing 8.5% of load)
VG穿透功率较低时的调度（将风电等效为负荷，占总负荷的8.5%）

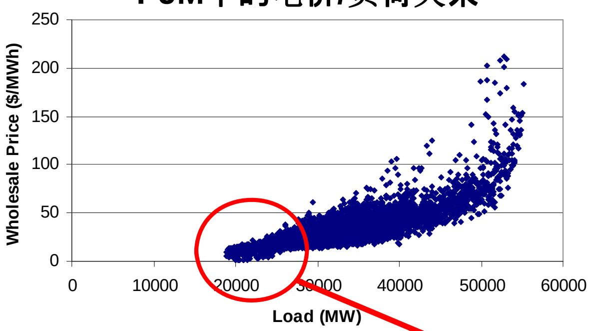
Dispatch with higher VG penetration (wind providing 16% of load)
VG穿透功率较高时的调度（将风电等效为负荷，占总负荷的16%）
Inflexible systems may be unable to accommodate large amounts of wind
非柔性系统可能无法接纳大规模风电接入



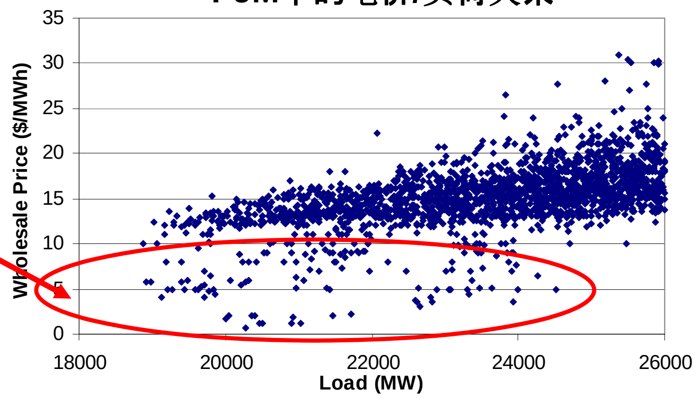



## System Flexibility Limited by Base load Generation Characteristics
## 基本负荷特性限制了系统的柔性

### Price/Load Relationship in PJM
### PJM中的电价/负荷关系




### Price/Load Relationship in PJM
### PJM中的电价/负荷关系

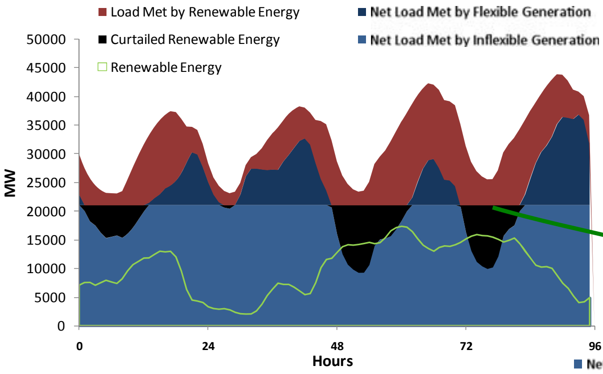



**Below Cost Bids**
**低于竞价**

**Plant operators would rather sell energy at a loss than incur a costly shutdown. Wind may be curtailed under these conditions**
**电厂业主宁可会降低电价而不会断网。风电在这种情况下会减少**

# Decreased Minimum Load
# 降低最小负荷

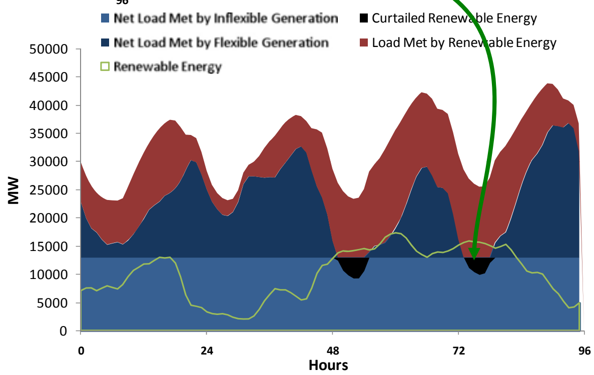
## Decreasing minimum load and adding system flexibility reduces curtailment
## 降低最小负荷，增加系统柔性以可以减少弃能




Inflexible System - Minimum Load of 21 GW (65% FF)
非柔性系统系统-最小负荷为21GW(固定负荷占65%)

Decreased curtailment

More Flexible System - Minimum Load of 13 GW (80% FF)
柔性系统-最小负荷为13GW（固定负荷占80%)

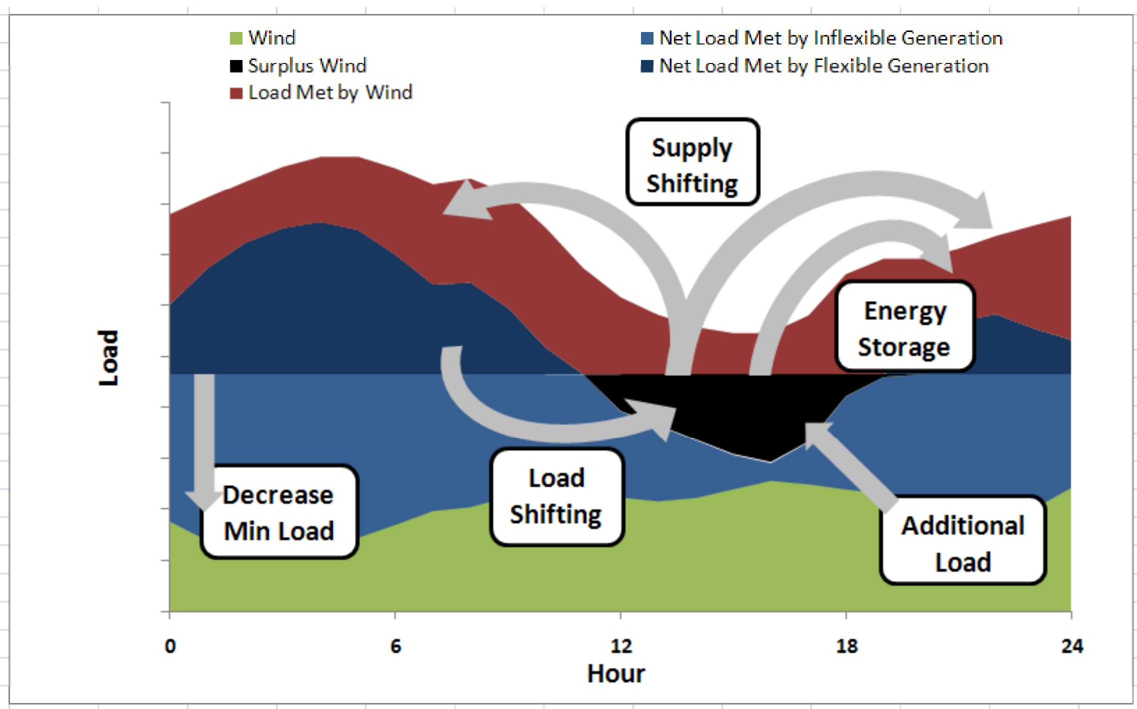



**Simulations based on 2005 load and weather**

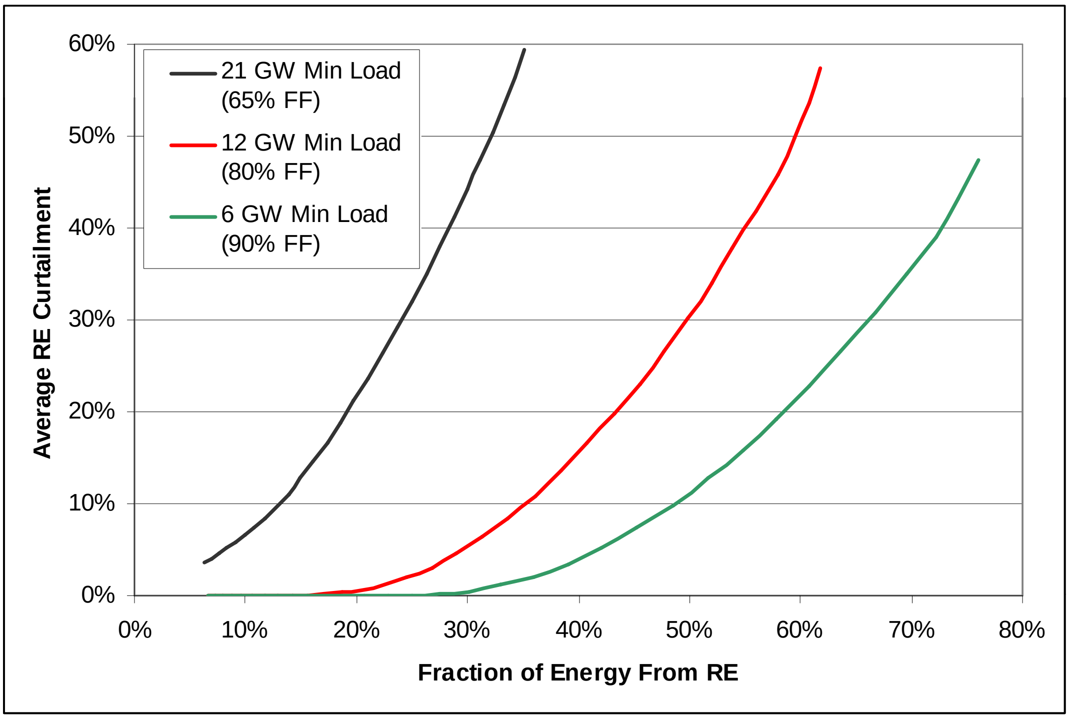
**仿真基于2005年的负荷与天气数据**



# Flexibility Options
# 灵活选择



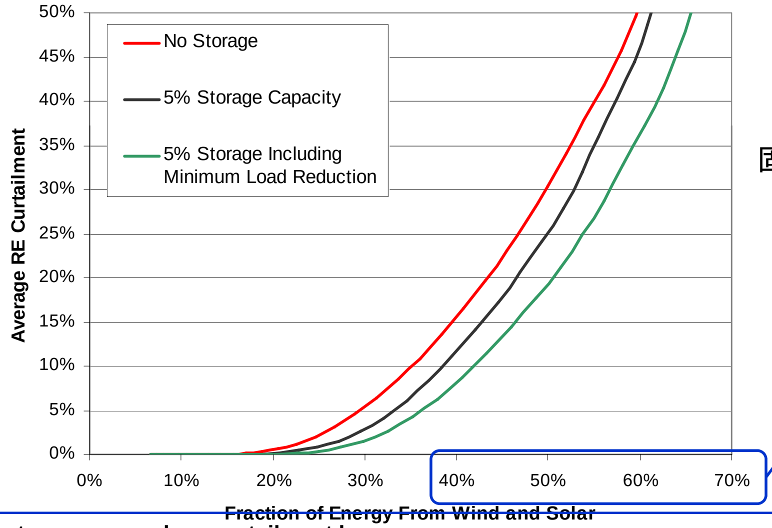
## Curtailment as a Function of Flexibility
## 以柔性为自变量的弃能量的函数




80% / 20% mix of wind and solar (on an energy basis) in Texas in 2005
2005年，在德克萨斯州的可再生能源中，风电占80%，太阳能占20%



## Energy Storage Can Reduce VG Curtailment
## 储能可以降低弃能




FF=80% (12 GW min load)

固定潮流=80%（最小负荷12GW）

U.S not likely to see this much RE for several decades

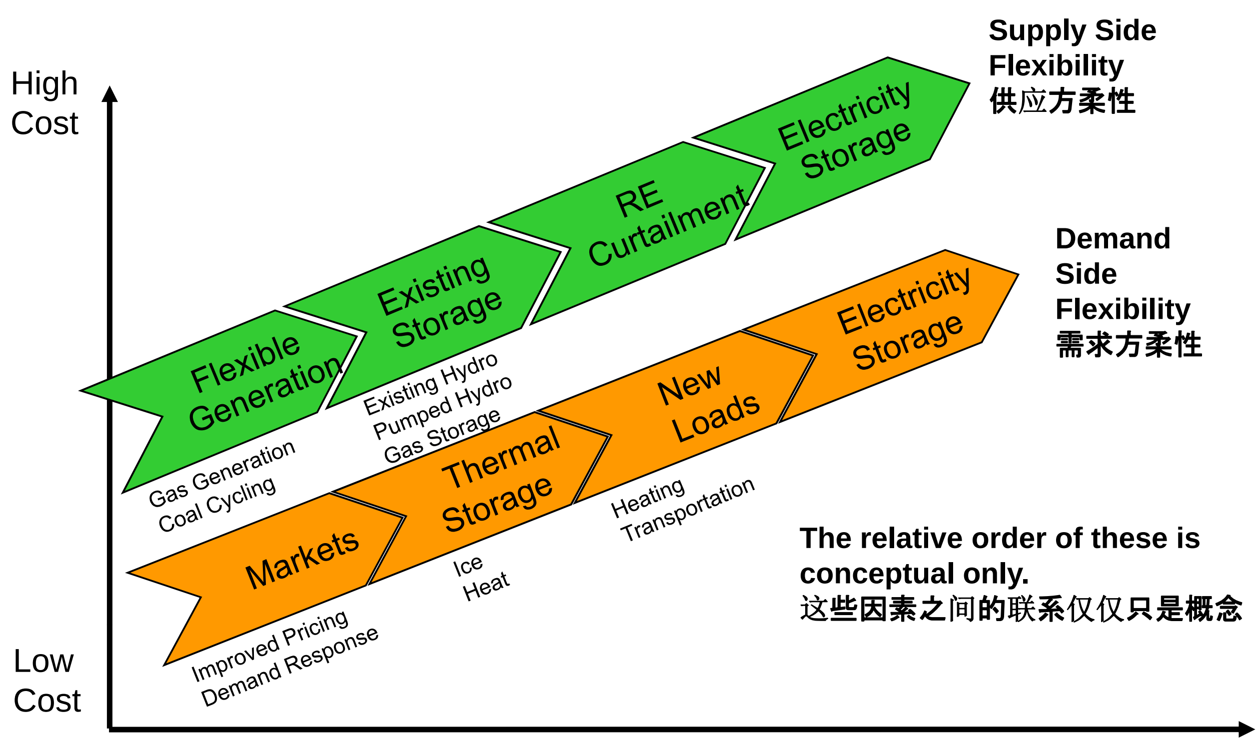
几十年之内美国可再生能源比例还达不到

**Energy storage can reduce curtailment by:**

**储能可以通过以下方法降低弃能：**

- **shifting otherwise unusable generation**
- **转移当时多余的能量**
- **increasing system flexibility by providing regulation and reserves (reducing the need for partially loaded thermal generators)**
- **通过调度和备用提高系统柔性（降低对部分热电厂的需求）**
- **improving transmission line loading, utilization**
- **提高线路负载率**

## Flexibility Supply Curve
## 柔性供应曲线

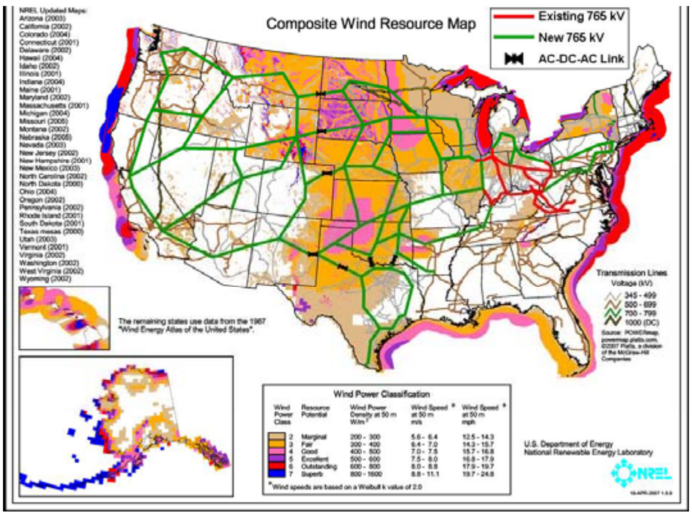





## Transmission Constraints
## 传输约束

**AEPs conceptual overlay of transmission expansion for the 20% wind study**

**AEPs的理念是为20%的风电扩展输电系统**

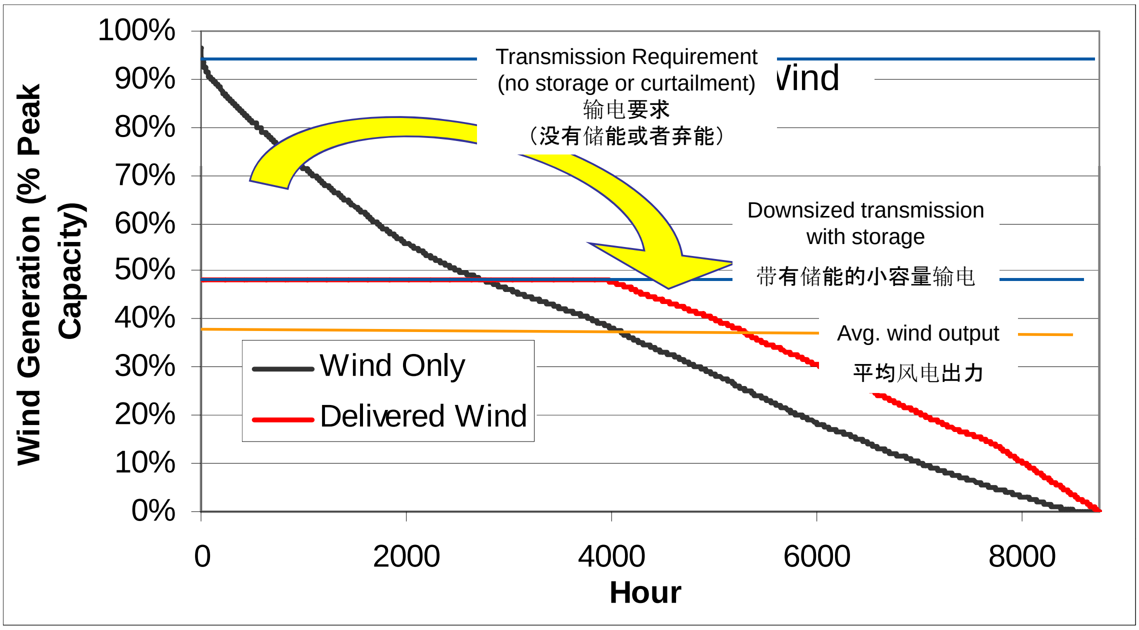



**Can we build this? If not, what are the alternatives?**

**我们可以建造这个吗？如果不行，有其他选择吗？**

- 16% of Texas wind curtailed in 2009, mostly because of transmission constraints (Rodgers et al. 2010)
- 2009年得克萨斯州削减16%的风电，主要是因为传输约束
- Long permitting and construction time for developing new transmission resources
- 新建传输线路需要较长的审批与建设时间

## Storage Can Increase Transmission Line Loading
## 储能可以提高线路负载率

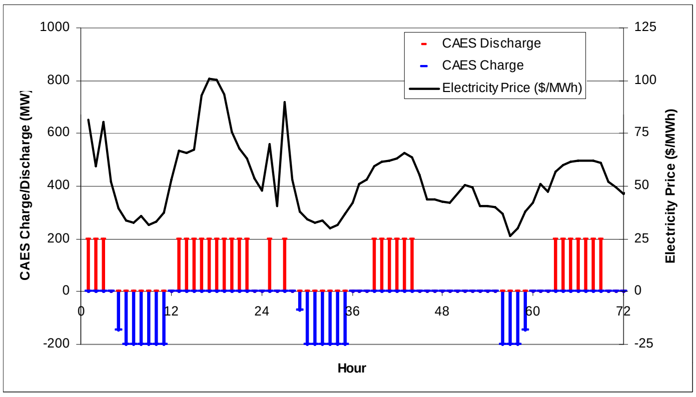





## Trade-offs in collocating storage with wind
## 带有风电的系统储能设备充放电设置

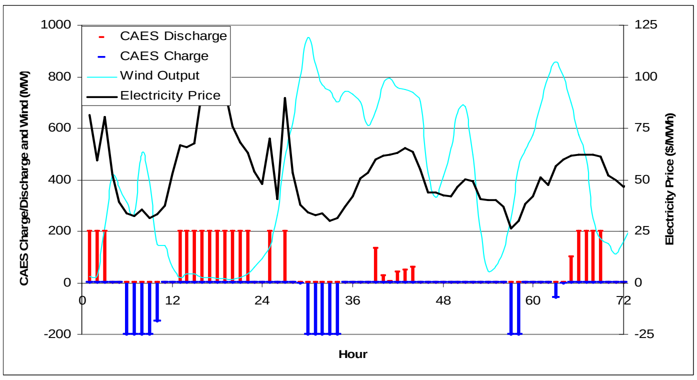
### Load-sited CAES Dispatch
### 负荷侧CAES调度

- no transmission constraints
- 没有输电约束
- dispatch determined by hourly electricity prices
- 基于每小时风电价格的调度



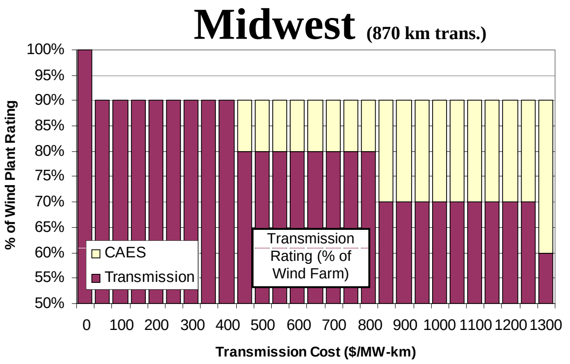

### Wind-sited CAES Dispatch
### 风电侧CAES调度

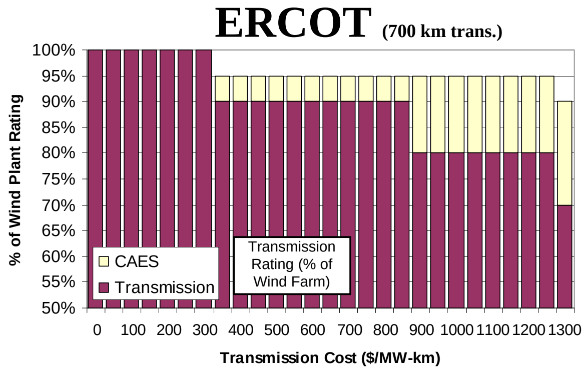
- transmission constraints for CAES and wind
- CAES和风电的输电约束
- dispatch is determined by hourly electricity prices and transmission capacity
- 基于每小时风电价格和传输容量的调度




Texas 2006

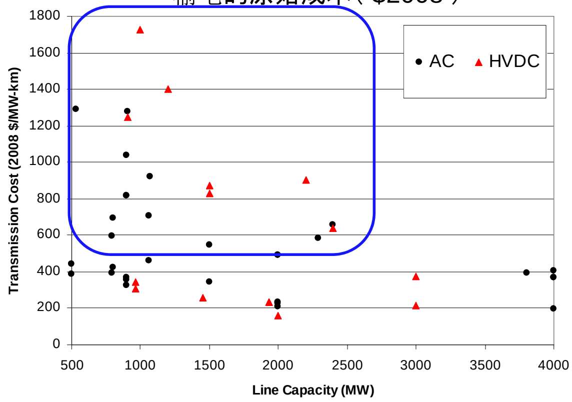
# Optimum Mix of CAES* and Transmission
# CAES*和输电的优化组合




- **Co-locating CAES with wind resources becomes economic if:**
- CAES和风资源的协调定位会使调度更具经济性，如果
  - **Transmission costs > $400/MW-km**
  - 传输成本>$400/MW-km
  - **New transmission is unavailable**
  - 没有其他传输渠道
- **Historical transmission costs suggest that several projects could be economic today**
- 原始输电成本显示，有些工程可以变得更具经济性。

Historical Transmission Costs ($2008)
输电的原始成本（ $2008 ）



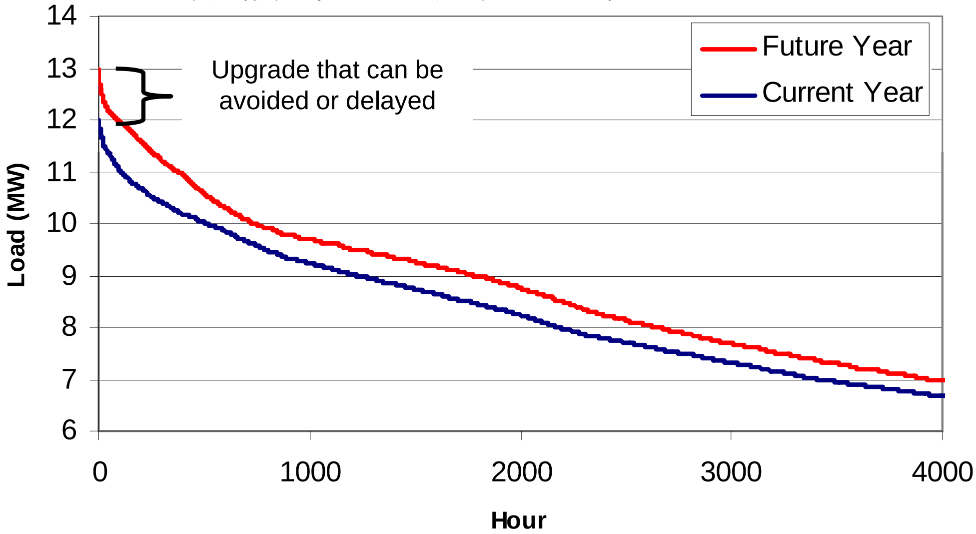

***Assuming $750/kW CAES w/ 20hrs storage, 0.72 energy ratio, 4,200 BTU/kWh**
**Denholm and Sioshansi, *Energy Policy,* 37, 3149-3158, 2009**



# Transmission and Distribution (T&D) Relief / Deferral
# 输配电系统（T&D） 减轻/延缓

Sample Load Duration Curve on a distribution feeder

在配电网馈线侧的负荷随时间变化曲线




- **T&D expansion can be deferred using storage**
- **使用储能可以延期对输配电系统的扩展**
- **Particularly promising for distributed storage resources (batteries) on distribution feeders**
- **馈线上采用分布储能（电池）更加值得期待**

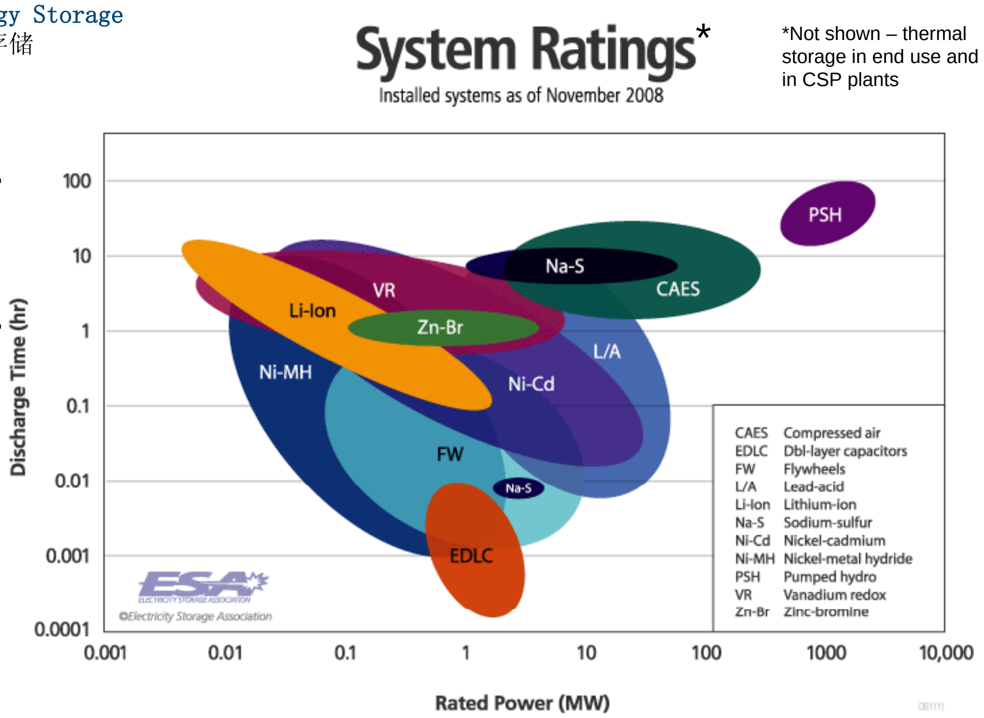
# Types of Storage Technologies
# 储能技术分类

Three Classes of Energy Storage
3种典型的能量存储

**Energy Management**
**能量管理**
**Load Leveling**
**负荷水平**
**Firm Capacity**
**固定容量**
**T&D deferral**
**输配电延期**

**Bridging Power**
**桥接功率**
**Contingency Reserves**
**事故备用**
**Ramping**
**爬坡率**

**Power Quality**
**电能质量**
**Transient Stability**
**暂态稳定**
**Frequency Regulation**
**调频**




*Not shown – thermal storage in end use and in CSP plants

**Wide variety of storage technologies fill variety of grid services**
**储能技术的多样性可适应电网服务的多样性**



# Storage for increased Regulation requirements
# 调度需求增加的储能

- Flywheels
- 飞轮储能
  - $2,000 - 3,500/kW for systems with 15 min discharge*
  - 放电时间是15分钟，价格是$2,000 - 3,500/kW
  - Long calendar life, hundreds of thousands of cycles without storage degradation
  - 寿命较长，如果储能设备不退化可以成千上百次的充放电
- Several battery chemistries
- 几种化学电池
  - $1,550 – 3,000/kW for systems with 4 hours storage**
  - 储能时间是4小时，价格是$1,550 – 3,000/kW
  - Modular and mobile
  - 模块化和可移动化
- CAES and PSH for new AS categories – bridging between regulation and ramping
- 新AS分类的CAES 和 PSH—调度与爬坡之间的支撑
  - $600 – 2,000/kW for CAES systems with 20 hrs discharge***
  - CAES 系统，放电时间是20小时，价格是$600 – 2,000/kW
  - $650 – 2,000/kW for PSH systems with 20+ hrs discharge****
  - CAES 系统，放电时间是20小时以，价格是$650 – 2,000/kW

***Beacon Power 2010; **Rastler 2009; ***EPRI 2007, ****projects completed 2003-2009 and proposed projects**

# Storage for Energy Management
# 能源管理储能

**Centralized bulk storage (several hours of storage)**

集中大容量储能（存储多个小时）

- CAES*
  - $600 – 2,000/kW for CAES systems with 20 hrs storage
  - 储能时间20小时，价格是$600 – 2,000/kW
  - Efficiencies 73-84% (4,200 BTU/kWh heat rate, 72% energy ratio)
  - 效率是73%-84%（4,200 BTU/kWh的热耗，72%的能量比值）
- PSH**
  - $650 – 2,000/kW for PSH systems with 20 hrs storage
  - 储能时间是20小时，价格是$650 – 2,000/kW
  - Efficiencies 68-82%
  - 效率是68-82%



# Storage for Energy Management
# 能源管理储能

- CSP with thermal storage***
  - $450-1,400/kW for 6 hrs thermal storage
  - 储能时间是6小时，价格是$450-1,400/kW
  - Efficiencies >90%
  - 效率>90
  - Cost could decrease with higher temperature heat transfer fluids
  - 如果采用高温度传热媒介会降低成本
- Emerging technologies (high energy batteries, thermal storage)
- 新兴技术（高能量电池、储热）
  - Emerging technologies have not demonstrated near-term pathways to < $2000/kW for 8+ hours of storage****
  - 新兴技术的储能时间是8小时，价格不低于 $2000/kW

Most important storage class to reduce RE curtailment
最重要的储能技术是降低可再生能源的弃能容量

***EPRI 2007, **projects completed 2003-2009 and proposed projects, ***Turchi 2010 personal communication, **** Rastler 2009**

## Distributed Storage
## 分布式储能

**Distributed storage (several hours)**

分布式储能(几个小时)

- Battery storage
- 电池储能
  - <$2,000/kW demonstrated by NaS
  - 钠硫电池的费用是小于$2,000/kW
  - PV + batteries in regions with demand based rates
  - 基于需求比例的光伏发电+电池
  - Electric vehicles
  - 电动汽车
- Thermal storage
- 储热
  - Water heating and space heating
  - 热水和采暖
  - Ice storage for cooling loads
  - 储冰冷却负荷

Market growth will be highly dependent on retail rate structures

市场增长很大程度上依赖于税率结构



## Conclusions
## 结论

- Storage is an economic decision, not a technical requirement
- 储能是经济性需求而不是技术性需求
- Renewed interest in storage technologies in the U.S., based on new electricity markets and growing RE deployment
- 基于新电力市场与可再生能源的调度需要，美国对储能技术重新感兴趣。
- Previous grid integration studies suggest that storage is valuable, but not necessary for RE up to 30% (energy)
- 之前的电网接入研究表明，当可再生能源比例高于30%，就需要储能技术。
- Storage can reduce curtailment at higher RE penetrations, and reduce transmission constraints
- 可再生能源穿透功率较高时，储能技术可以减少弃能，降低输电压力
- Several storage technologies available to fill different utility and distributed applications
- 几种储能技术可以用于不同场合并满足配电的要求

# Questions?



## Why So Little CAES? – Three Reasons
## 为什么CAES这么少？—3个理由

- At existing wind penetrations, wind does not drive LMPs
- 依据现在的风电穿透功率，风电不需要LMPs
  - Dispatch of CAES is currently driven by existing demand patterns and thermal generators
  - 现有的需求模式和火电机组推动C AES调度
  - As penetration increases, wind will begin setting the price
  - 随着风电穿透功率的增加，会给风电定价
  - The dispatch of load-sited CAES and wind-sited CAES will converge, decreasing opportunity cost of wind-sited CAES
  - 负荷侧与风电场侧CAES调度的融合可降低风电场侧 CAES的机会成本
- Configuration (expander/compressor ratio) not optimized for wind-sited CAES
- 风电场侧CAES采用组态（膨胀率/压缩率）是优没有经过有优化的
- Does not take advantage of long storage times that may be available in aquifers.
- 没有充分利用长时间储能的优点，长时间储能在抽水蓄能电站是可行