GE Energy

US/China Wind Integration Workshop
中美风电并网研讨会

Grid Integration of Wind/Solar Power
风电/太阳能发电并网

Baozhuang Shi 史保壮
GE Energy 通用电气能源集团

Beijing, China 中国 北京
December 7, 2010 2010.12.07

imagination at work

Agenda 议程

US Western Wind/Solar Integration Study

美国西部风电/太阳能发电并网研究

- Study Goal 研究目标
- Scenarios 方案
- Key Findings 关键成果

GE's China Integration Work

GE在中国的并网工作

- Inner Mongolia Wind Study 内蒙古风电研究
- Wind Modeling for Simulations 风电仿真建模

imagination at work

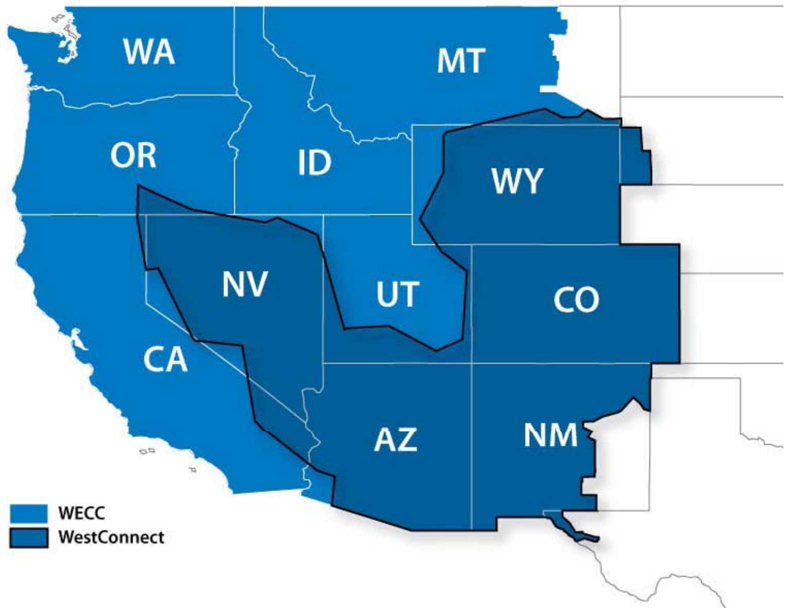
Western Wind and Solar Integration Study（WWSIS）
美国西部风电和太阳能发电并网研究（WWSIS）

"To help multiple utilities in the western U.S. understand the costs and operating impacts of the variability and uncertainty of wind and solar power on their grids and potential mitigation options for these impacts."

"为协调美国西部电网并网的风电和光伏的多变性和不确定性带来的费用和运行影响，以及针对这些影响的潜在的缓解措施。"

Can we Integrate 35% wind and solar in the West?

我们能够在西部并网35%的风电和太阳能吗？



imagination at work

The information about WWSIS in this document is from the report of "Western Wind and Solar Integration Study"

本文档中有关WWSIS的信息来自报告——"（美国）西部风电和光伏并网研究"。

Study Focus 研究重点

- What is the operating impact of up to 35% renewable energy penetration and how can this be accommodated?

  新能源发电比重达到35%时，对电网运行会有何影响？如何消纳如此多的新能源发电？

- How does geographic diversity help to mitigate variability?

  地理上的差异如何缓解多变性？

- How do local resources compare to remote, higher quality resources delivered by long distance transmission?

  如何将偏远的资源进行优质的长距离传输？

- Can balancing area cooperation mitigate variability?

  区域联合调峰措施能缓解多变性吗？

imagination at work

Study Focus 研究重点

- How should reserve requirements be modified to account for the variability in wind and solar?

  如何修正备用需求来应对风电和光伏的多变性?

- What is the impact of integrating wind and solar forecasting into grid operations?

  风电和光伏功率预测对电网运行的影响是什么?

- How can hydro generation help with integration of renewables?

  水电如何帮助可再生能源并网?

- What is renewables capacity value?

  可再生能源的容量是多少?

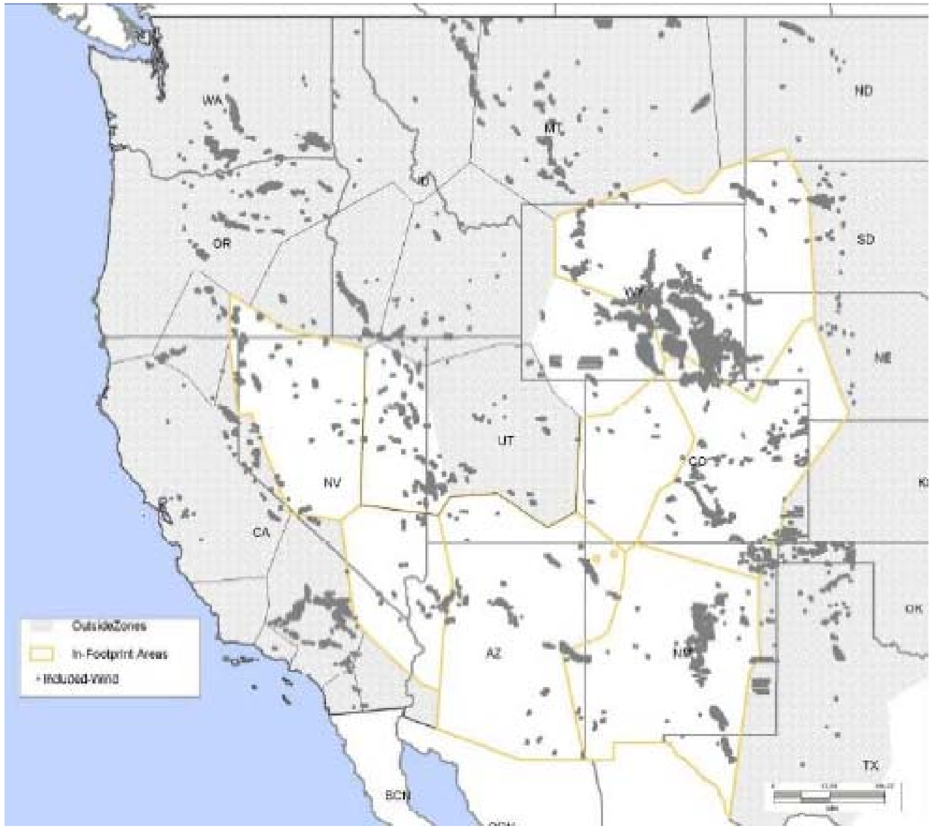
Wind Data 风数据

- 3TIER Group: 10 minute wind power output for 2004, 2005, and 2006 for 960 GW of wind sites in WECC (32000 sites of 30MW)

  3TIER公司：2004年、2005年和2006年，WECC（美国西部电力系统）中的风电场（960GW，32000个30MW风电场）每10分钟出力统计。

- Hourly day-ahead power output forecasts

  日前每小时功率预测



imagination at work

Scenarios 方案

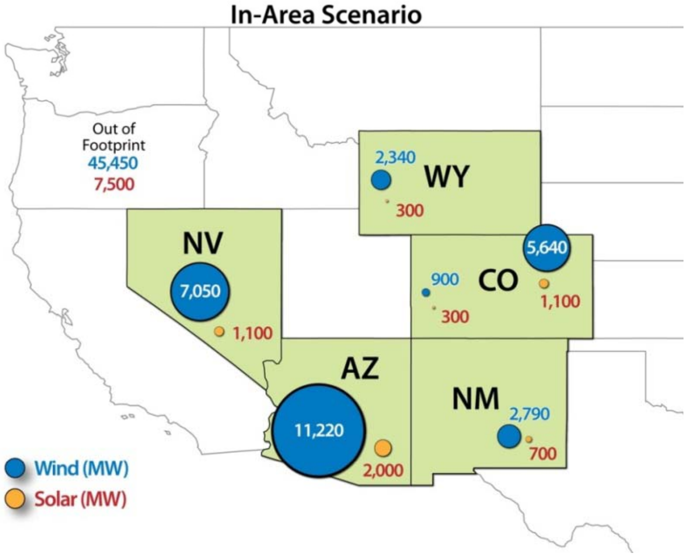
Name 名称	WestConnect 西部联网		Rest of WECC WECC其余部分	
	Wind 风电	Solar 太阳能	Wind 风电	Solar 太阳能
10%	10%	1%	10%	1%
20%	20%	3%	10%	1%
20/20%	20%	3%	20%	3%
30%	30%	5%	20%	3%

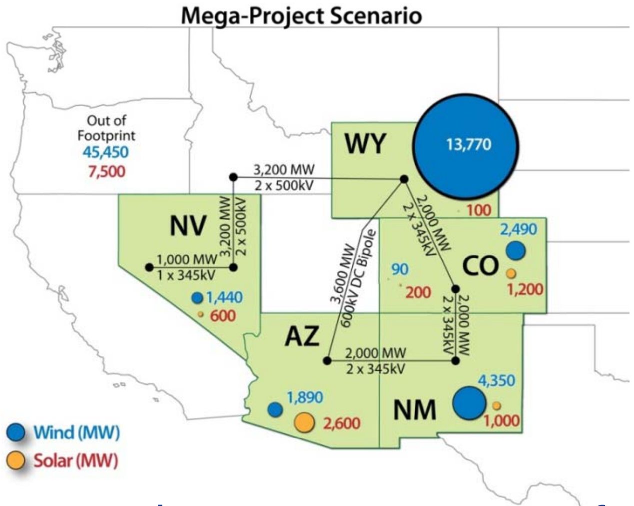
- Penetration levels are by energy, not capacity
  百分数是能量，而不是装机容量
- 70% concentrating solar plant with storage; 30% PV solar
  70%为光热发电，30%为光伏发电
- Modeled WECC power system for the year 2017
  2017水平年的美国西部电力系统模型
- 3 years of data 2004, 2005, 2006
  2004、2005、2006这3年的数据

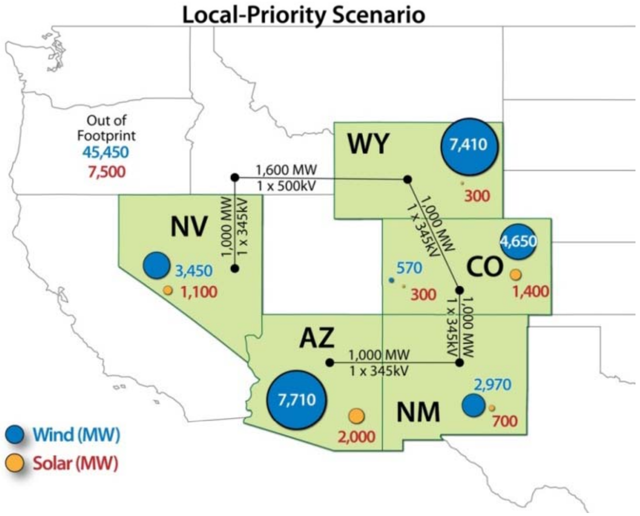
imagination at work

Scenarios 方案

-30% Wind/ 5% Solar Scenarios   30%风电，5%太阳能发电







In-Area - each state meets target from sources within that state
区域内–根据资源情况各州均有目标

Mega Project - concentrated projects in best resource areas
百万工程–在资源最好的地区集中开发

Local Priority - Balance of best resource and In-Area sites
局部优先–区域内电场和资源丰富地区的平衡

Analytical Methods 分析方法

- Statistical Analysis : Quantify the impact renewables' of variability on system operation performance

  统计分析：量化可再生能源的多变性对电力系统运行的影响
  - Multiple time frames (annual, seasonal, daily, hourly, 10-minute)

    多重时限（年，季，日，小时，10分钟）
  - Load following, regulation, unit commitment

    负荷跟踪，管理，机组开机方式
  - Forecast errors

    预测误差

Analytical Methods 分析方法

- Production simulation analysis: quantify the impact of

  生产模拟分析：量化如下影响
  - Maneuverable generation online

    实时调度
  - Changes of dispatch of conventional generation

    常规电源调度的变化
  - Changes in emissions

    废气排放的变化
  - Changes of cost grid operation

    电网运行成本的变化
  - Changes in hydro, and other resources

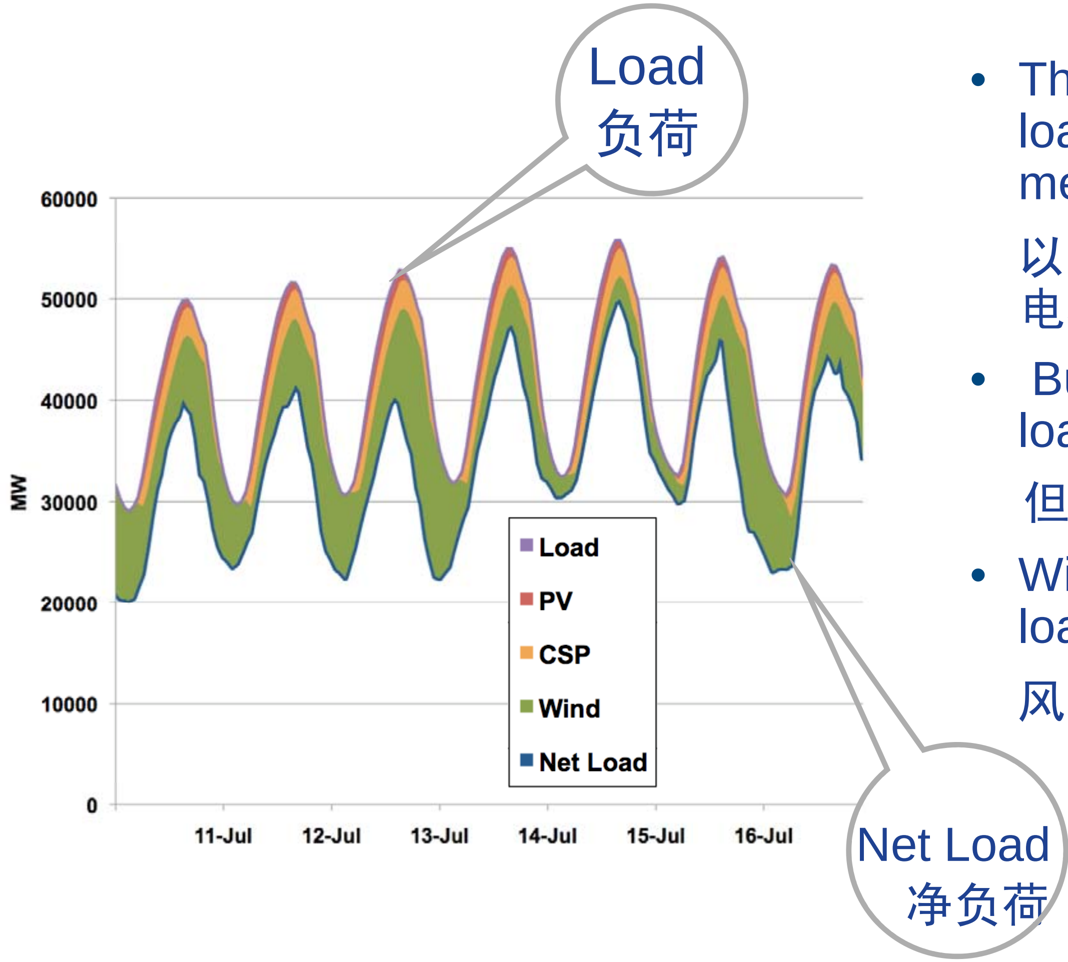
    水电和其他电源的变化

Analytical Methods 分析方法

- Quasi-steady simulation analysis: minute-to-minute time frame performance
  准稳态仿真分析：分钟级性能
- Reliability analysis: LOLE, capacity value
  可靠性分析：期望值，容量

imagination at work

How Does the System Operate With 35% Wind and Solar?
含有35%风电和太阳能的发电系统如何运行？



- The operator formerly managed to load (dispatch the generation to meet the load)

  以前，运营商专注于负荷（调度发电机以满足负荷）

- But now has to manage the net load

  但是现在须管理净负荷

- Wind adds the variability of the net load

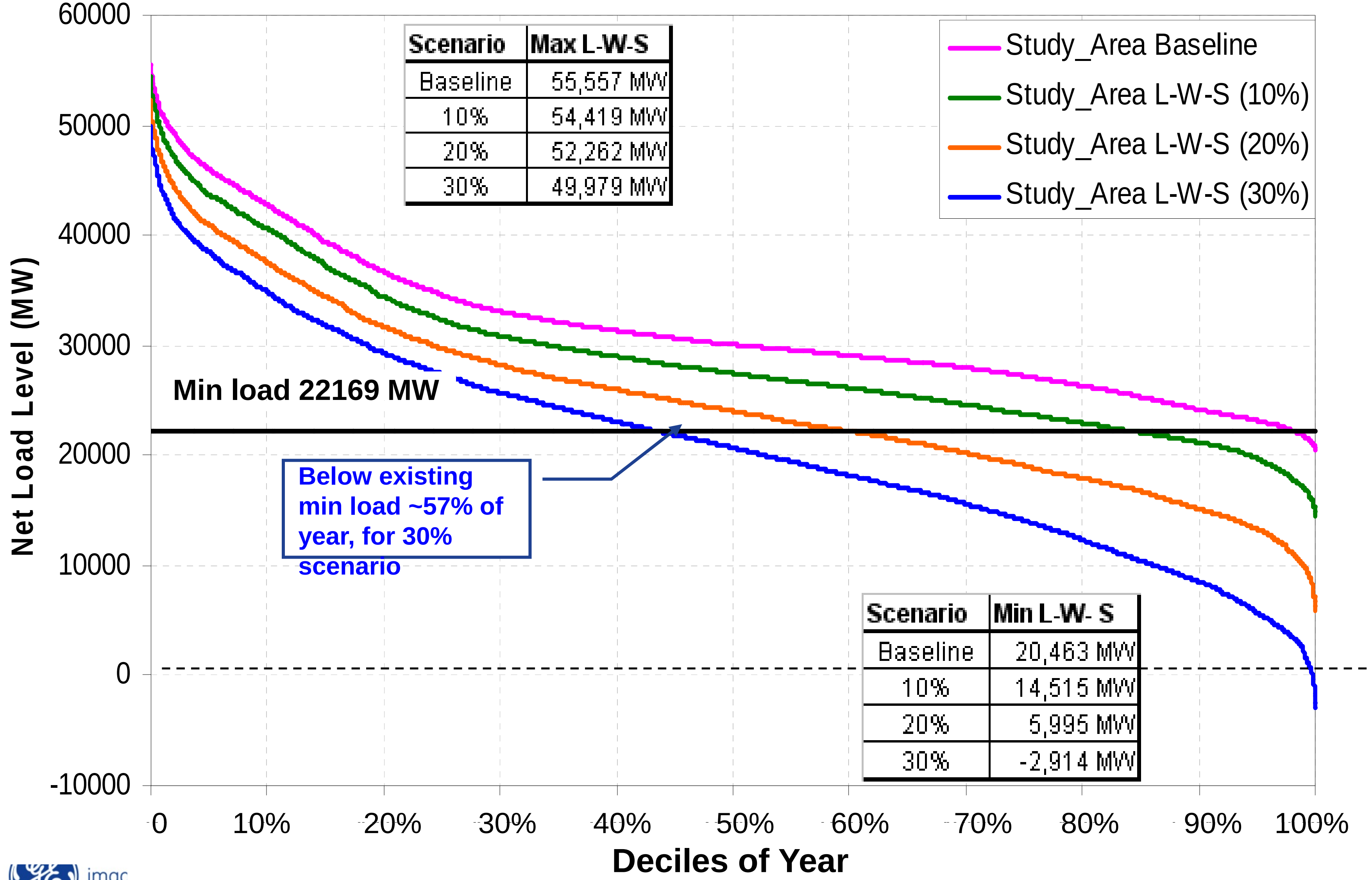
  风电增加了净负荷的波动性

Net Load = Load –Wind-Solar

净负荷 =负荷–风电–太阳能发电

imagination at work

Study Footprint 2006 Net Load Duration – In Area Scenario
对2006年净负荷的研究–某地区的方案

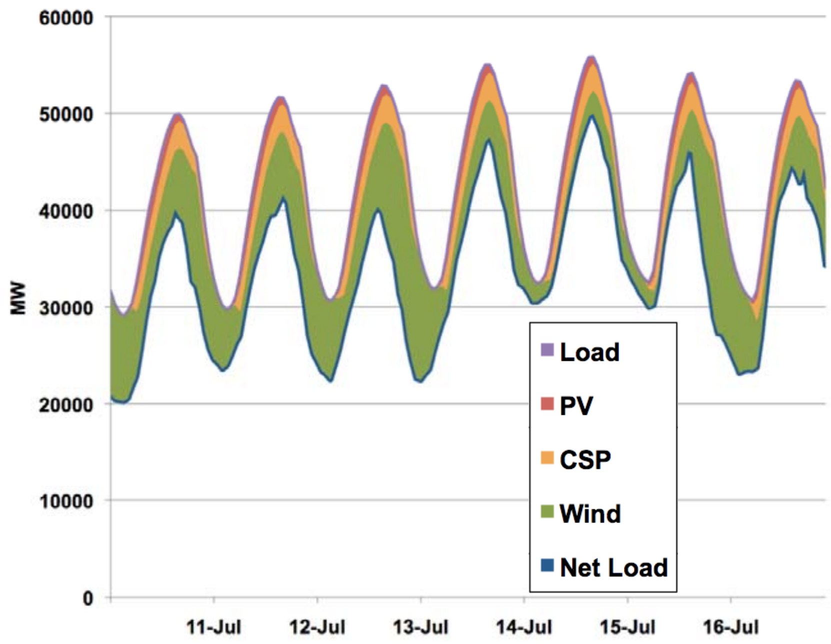


时间（一年十等分）

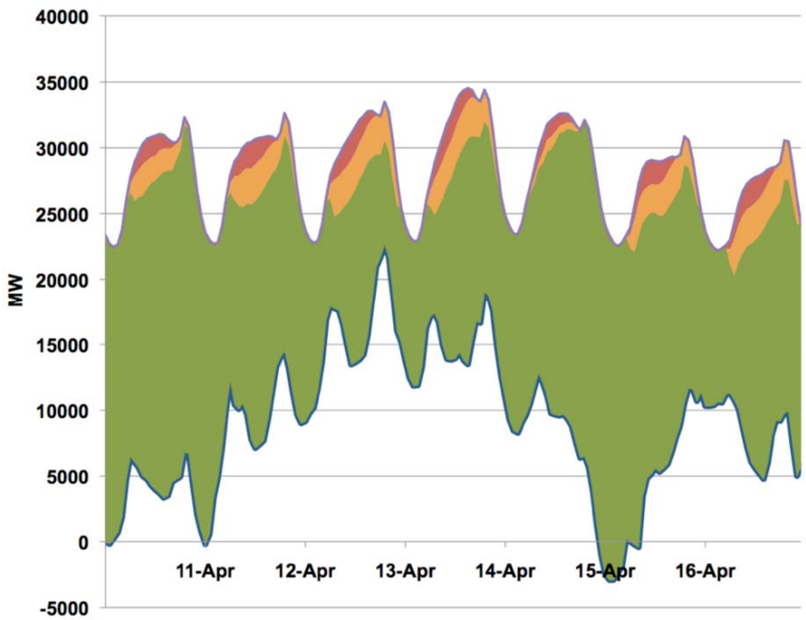
imag

How Does the System Operate With 35% Wind and Solar?
含有35%风电和太阳能发电系统如何运行？

Mid-July
七月中旬



Mid-April
四月中旬

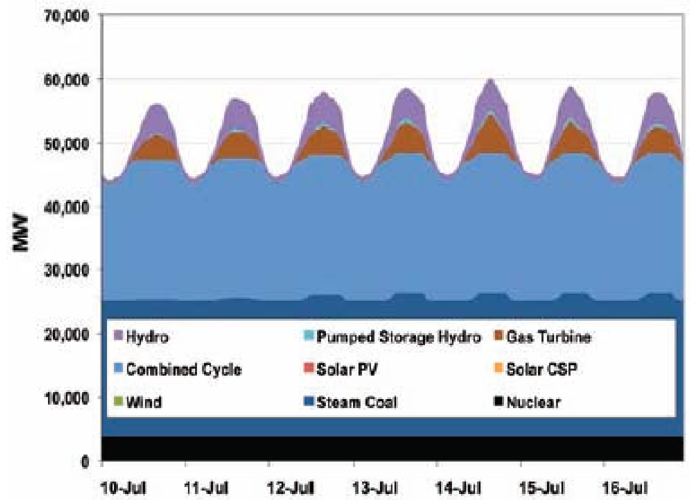


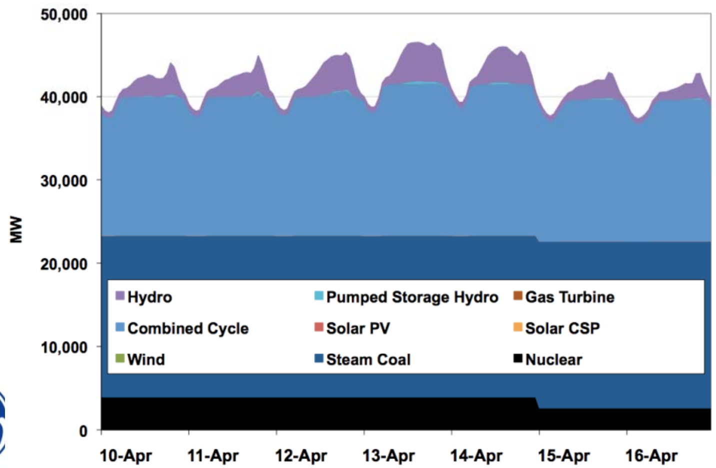
Mid-April shows the challenges of operating the grid with 35% wind and solar.
4月中旬的结果表明含有35%风电和太阳能的电网遇到了挑战。
This was the worst week of the 3 years studied.
这是3年研究中最严重的一周。

imagination at work

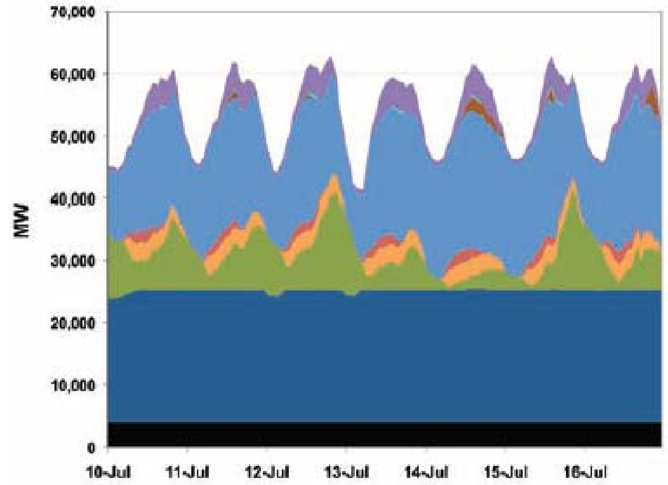
Operations During July and April
七月和四月的运行

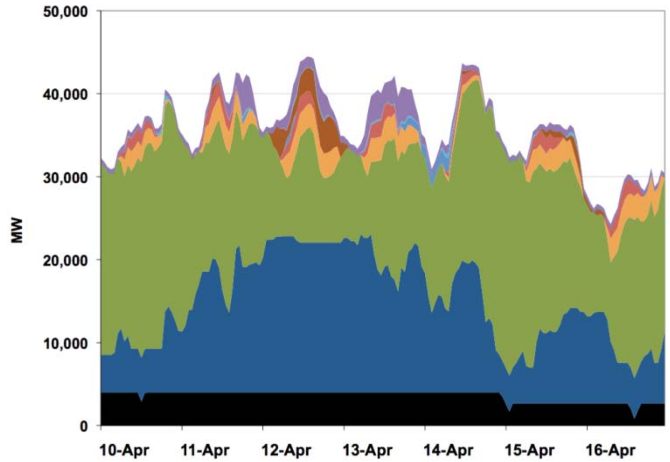
No Wind/Solar
无风电/太阳能发电





35% Wind/Solar
35%风电/太阳能发电





Key Findings
重要发现

It is operationally feasible for WestConnect to accommodate 30% wind and 5% solar IF:

满足以下条件，西部联网系统消纳30%的风电和5%的太阳能是可行的

- Substantially increase balancing area cooperation or consolidation, real or virtual

  充分利用调峰区域间的合作或合并，可以是现实的或虚拟的

- Increase the use of intra-hour scheduling of generation and interchanges

  加强利用发电联络线功率的小时内调度

- Increase utilization of transmission

  增加输电的利用率

- Enable coordinated commitment and economic dispatch of generation over wider regions

  实现大区域内的发电经济调度和协调组合

Key Findings
重要成果

- Use forecasts in operations

  运行中使用预测
- Increase flexibility of dispatchable generation

  增加发电可调度的灵活性
- Commit additional operating reserves as appropriate

  合理分配额外的运行备用
- Implement/expand demand response programs

  实现/扩展需求响应规划
- Require wind to provide down reserves

  要求风电提供下调备用

Summary of Key Findings
重要成果总结

- What are the biggest changes that make this possible?
  可能的最大变化是什么？
  - Extensive balancing area cooperation
    大范围的调峰区域合作
  - Sub-hourly economic dispatch
    小时内经济调度
- What are the benefits?
  有何收益？
  - Reductions of 40% in fuel/emissions costs
    减少40%的燃料/废气排放成本
  - Reductions of 25-45% CO2
    减少25%-45%的二氧化碳排放

imagination at work

Summary of Key Findings
重要成果总结

- What factors have a large impact on the operation economics of integrating wind/solar?

  影响风电/太阳能发电运行经济性的因素有哪些？
  - Use of forecasts in operations
    运行中预测的应用
  - Flexibility in the dispatchable fleet
    集群调度的灵活性
  - Wind/solar penetrations in the rest of WECC
    WECC其余地区的风电/太阳能所占比例
  - Different transmission/geographic scenarios do NOT have much impact
    不同的输送/地理方案之间没有相互影响
- Do we need long distance interstate transmission?

  是否需要州际间长距离输电？
  - We can start integrating lower penetrations of wind/solar before long distance transmission is commissioned
    在长距离输电授权之前，我们可以并网较低比例的风电/太阳能。

Summary of Key Findings
重要成果总结

- What often is wind curtailed?

  限制多少风电？
  - On the order of 1% or less of total wind energy
    大约不大于风能总量的1%
- Do we need more reserves or storage?

  是否需要更多的备用或者储能？
  - Load is always met but there are contingency reserve shortfalls that need to be addressed

    负荷需求总是可以满足的，但是有时需要应对紧急备用缺额
  - Demand response is a more cost-effective option than increasing operating reserves
    负荷需求响应是一个比增加运行备用更划算的选择

Summary of Key Findings
重要成果总结

- Reserve requirement for variability (load following) increases but the system naturally provides these increased reserves so more reserves is not needed
  应对负荷变化的备用需求（负荷跟踪）增加了，但是系统可以自行提供增加的备用，所以不需要附加备用
  Additional storage is not justified based on price arbitrage value alone.
  仅基于价格套利值的额外的储能是不合理的
- Increase the flexibility of dispatchable generation where appropriate could be an option
  增加合适地区的可调度机组的灵活性是不错的选择

• What capacity value do wind and solar provide?
  风电和太阳能风电的容量有多少？
  - Wind 10-15%, PV 25-30%, CSP 90-95%
    风电10-15%， 光伏25-30%， 传统电源90-95%

imagination at work

Impact of Uncertainty/Variability on Operations
对系统运行的不确定性/波动性的影响

- The net load variability increase with higher wind and solar penetration; however, the overall increase is not dramatic.

  净负荷波动性随着风电和太阳能发电比例的升高而增加，但是总体上不明显

- the number and size of extreme deltas at the footprint level (30%) is much more impressive than the increase in overall sigma.

  在特定区域（30%）内波动性的delta值（差值）要比增加的总体sigma值（总和）明显的多

Impact of Uncertainty/Variability on Operations
对系统运行的不确定性/波动性的影响

- Increasing the flexibility of dispatchable generation can be a measure to mitigate variability of the net load

  增加可调度机组的灵活性可能是减小净负荷波动的好方法

  - Shorter start time; faster ramp (up/down) rates

    缩短启动时间；加快向上/向下的爬坡率
  - Deeper turndown

    深度调峰
  - Cycling (lower start/stop costs)

    循环（启停成本低）

Scenario	Sigma (σ) of Net Load Deltas (MW/hr)	Max. Negative Net Load Delta (MW/hr)	Max. Positive Net Load Delta (MW/hr)	No. Deltas > 3 * (load σ) (-/+)	σ % Increase with Wind & Solar
Baseline	1,429	-4,282	3,793	0 / 0	--
10% LP Scenario	1,414	-4,195	4,178	0 / 0	-1.0%
20% LP Scenario	1,437	-4,359	4,777	1 / 2	0.6%
30% LP Scenario	1,523	-4,931	5,644	3 / 28	6.6%

imagin

Alternatives to Mitigate Extreme Forecast Errors and Contingency Reserve Shortfalls
替代减小极限预测误差和紧急备用缺额

- Severe under-forecasts can lead to curtailment or spilling of wind/solar

  预测量过少会导致风电/太阳能发电的少发
- Severe over-forecasts can result in inadequate contingency reserves Wind and solar double the variability reserve requirement (load following).

  与测量过多会导致紧急备用的不足，风电和太阳能发电加重波动备用需求（负荷跟踪）
- Increase spinning reserves 24/7 (8760 hours of the year)

  增加旋转备用 24/7 （一年按8760小时计）
- Add storage like pumped hydro or compressed air energy storage

  增加如抽水蓄能或者压缩空气储能

imagination at work

Alternatives to Mitigate Extreme Forecast Errors and Contingency Reserve Shortfalls 减小极限预测误差和紧急备用缺额

- We only have shortfalls for 89 hours of the year (1%), so these options can be expensive

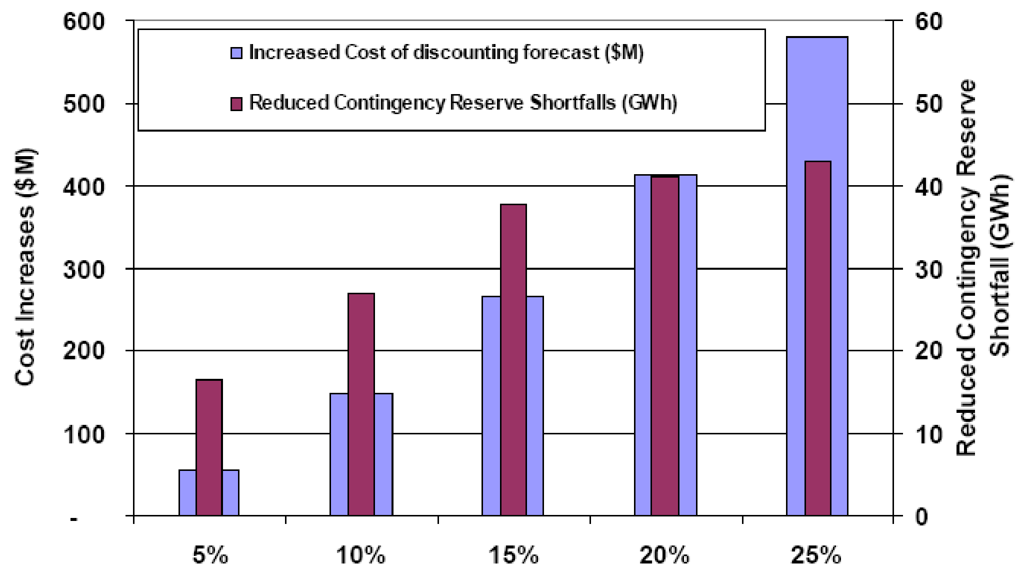
  我们一年只有89小时的缺额（1%），所以增加额外的紧急备用是不经济的

- Demand response (paying loads to turn off) was found to be effective and was less expensive

  需求响应（甩负荷）是有效的且花费较少

- Adding additional quick-start fast ramp rate peaking generation where needed can be an option

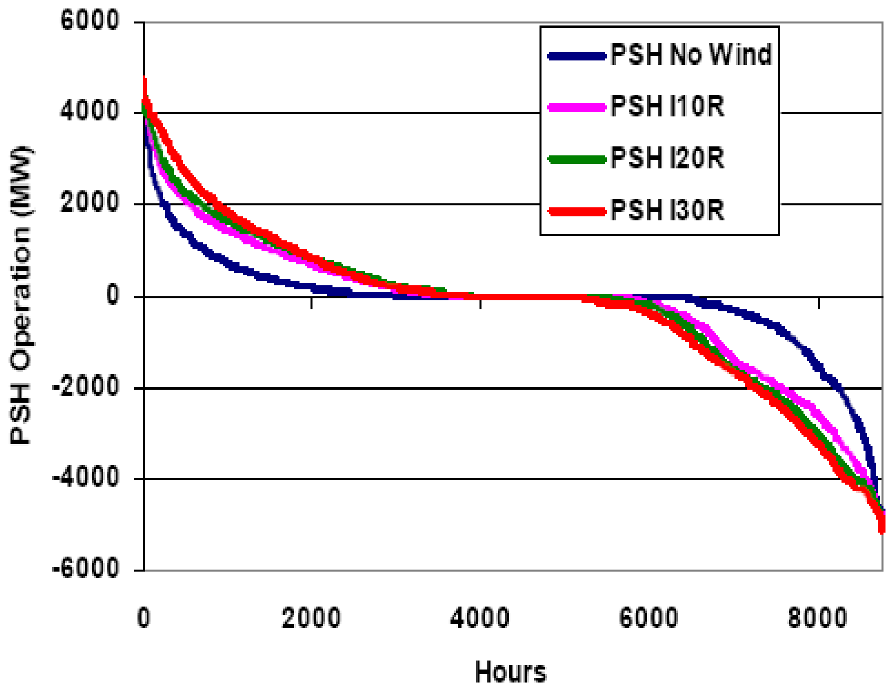
  在需要的地方增加额外的能快速启动具有快速爬坡率的调峰电源



imagination at work

Do We Need More Storage?
我们需要更多的储能吗？

- Storage was evaluated storage for price arbitrage, nor for ancillary services (reliability, regulation, etc)
. 储能可看做是价格套利，而不是辅助服务（可靠性、管理等）
- Wind and solar increased use of existing pumped hydro storage (PHS) slightly, but not to a point where more storage would be needed.
  增加的风电和太阳能可利用已建的抽水蓄能电站，而不需要增加更多的储能。
- We decreased pumping costs to increase use of PHS but overall production costs increased.
  我们减少抽水的成本而增加抽蓄的利用率，这使得总成本增加。



imagination at work

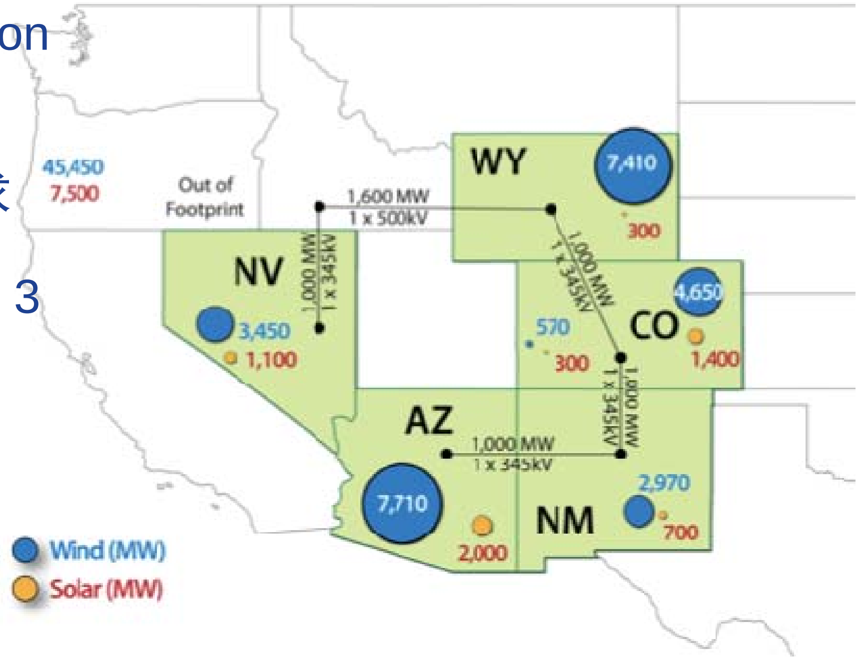
Doe We Need More Long Distance Interstate Transmission?
我们还需要更长距离的州际间输电吗？

- Absolutely need some ***intra***-state transmission to bring resources to load

  需要一些州内输电线路输送资源满足负荷需求

- Very little operational difference between the 3 geographic scenarios

  这3个区域中的运行差异是很小的



imagination at work

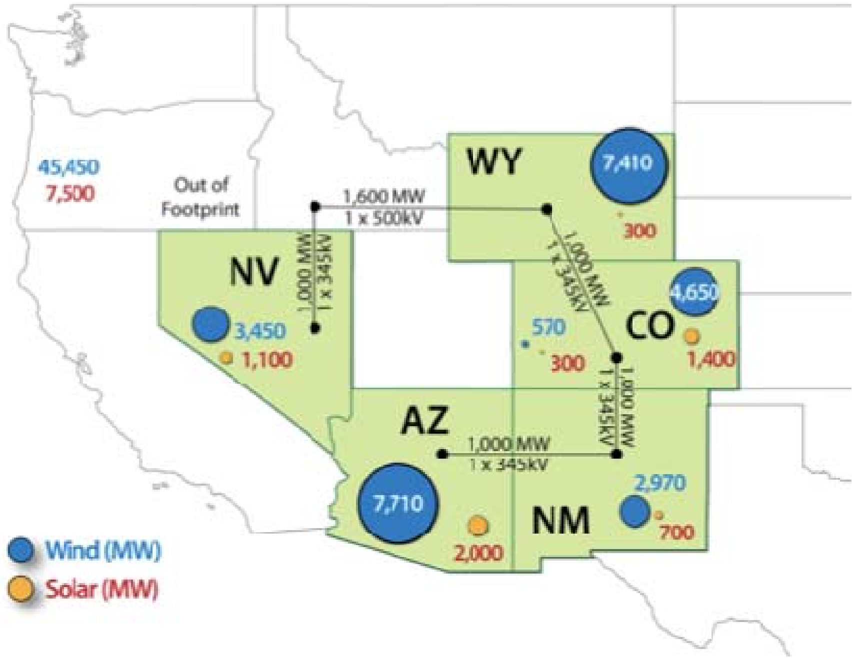
Doe We Need More Long Distance Interstate Transmission?
我们还需要更长距离的州际间输电吗？

- Wind/solar displace other generation, freeing transmission capacity. ***If*** this new capacity can be used for wind/solar, then less new transmission is needed.

  风电/太阳能发电取代了其他电源，释放了传输容量。如果这些新的容量用于传输风电/太阳能，将减少新建传输通道。

- We can start integrating up to 20% wind/3% solar before interstate transmission is commissioned, assuming better utilization of existing transmission

  假如充分利用现有的传输通道，在州际联络线建成前，我们可以并网20%的风电和3%的太阳能。



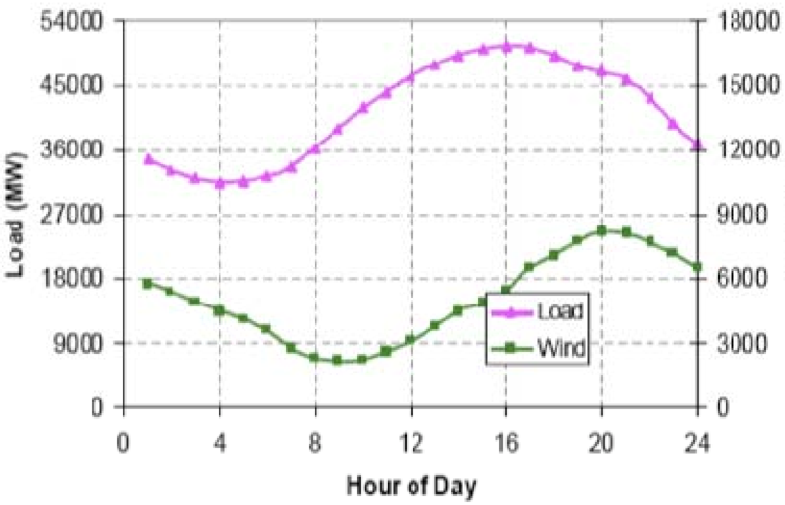
imagination at work

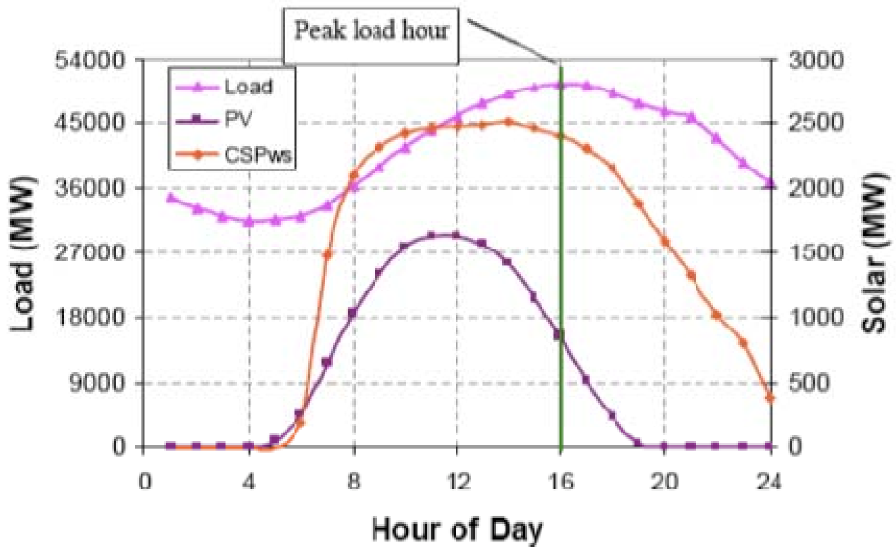
Do Wind and Solar Provide Capacity Value?
风电和太阳能容量?

Wind 风电: 10-15%

PV 光伏: 25-30%

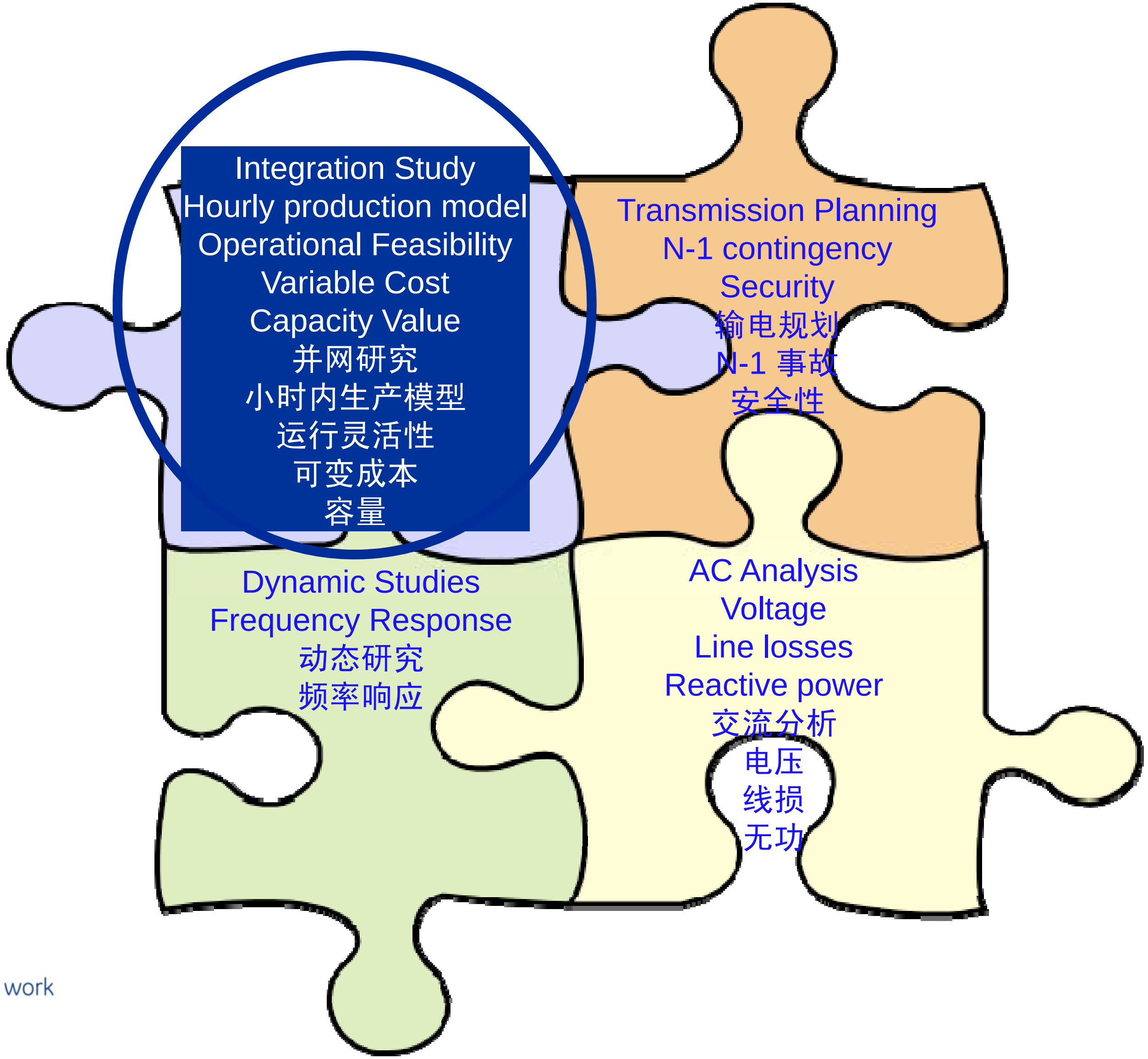
CSP with storage 带储能的传统电源: 90-95%





imagination at work

This Is but One Piece of the Puzzle
这只是一张拼图



imagination at work

大规模风电接入蒙西电网可行性研究

Feasibility Study on Large-scale Wind Power Connecting into WestInner Mongolia Power GridWind

1 研究背景和目的
Background and objectives

- 风电具有与常规电源完全不同的特性，且风资源丰富的地区通常都位于电网的末端，电网网架结构相对薄弱。Wind is non-dispatchable and good resources are usually located where the grid is relatively weak

- 如果在规划阶段没有对电网如何接纳风电和风电对电网的影响进行全面的研究，对可能发生的问题没有足够的认识并提前采取合理的技术措施，这些大型风电场建成后可能面临难以正常运行，且并网后会对电网运行产生严重影响，造成重大的经济损失。If the impact of wind generation on the grid is not studied and necessary mitigations are not prepared during the planning period, there could be severe operational problems and economic loss when the wind generation is in operation.

- 对内蒙古风电发展规划进行研究，分析风电如何与电网和其它电源进行协调，并提出提高电网和风电场安全运行的措施、规划和运行建议，为制定风电与其它电源及电网的协调规划提供参考依据。The study will explore how to accommodate the targeted wind generation and propose necessary mitigation and recommendation for the coordination of wind and grid planning.

2 合作方式 Cooperation Mechanism

- 中国电力科学研究院牵头完成可行性研究报告，内蒙古电力（集团）有限责任公司、内蒙古绿能新能源有限责任公司为参加单位。
- 内蒙古电力（集团）有限责任公司、内蒙古绿能新能源有限责任公司协助提供了所需的电网资料及风电规划资料。
- 中国电力科学研究院具体承担项目研究工作，通用电气(GE)公司提供专家指导，共同提交项目成果《大规模风电接入内蒙古电网可行性研究》。

Inner Mongolia LuNeng Renewable Energy Company provided the wind data; Inner Mongolia Power Grid provided the grid data.

CEPRI performed the study and GE provided expert guidance and support. CEPRI and GE jointly prepared the final report.

3 风电和电网概况

Overview of the WIM grid and planed wind generation

附图1： 内蒙古西部地区电网2010年规划

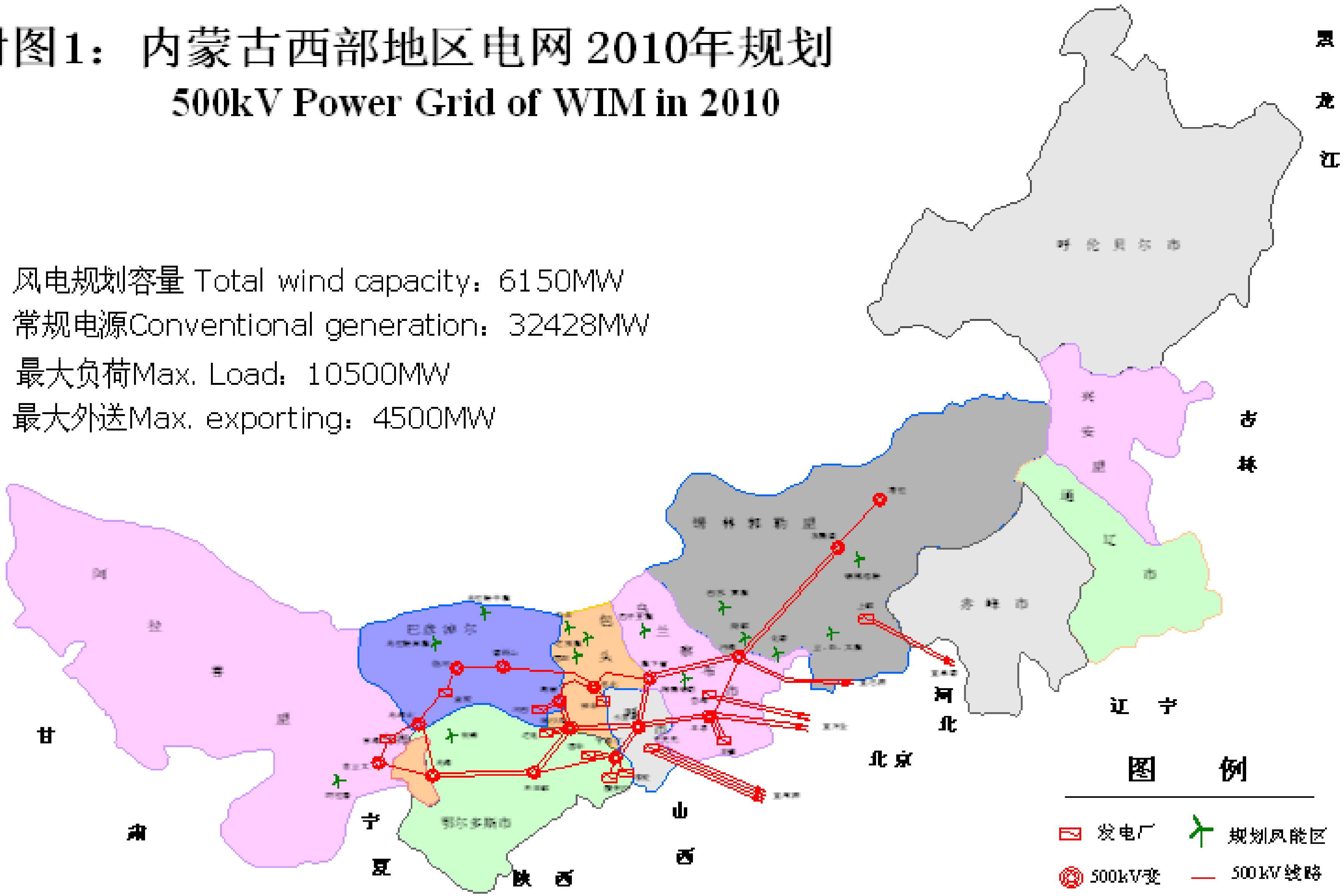
500kV Power Grid of WIM in 2010

风电规划容量 Total wind capacity：6150MW

常规电源Conventional generation：32428MW

最大负荷Max. Load：10500MW

最大外送Max. exporting：4500MW



3　风电和电网概况

Overview of the WIM grid and planed wind generation

2015年500kV蒙西电网结构示意图

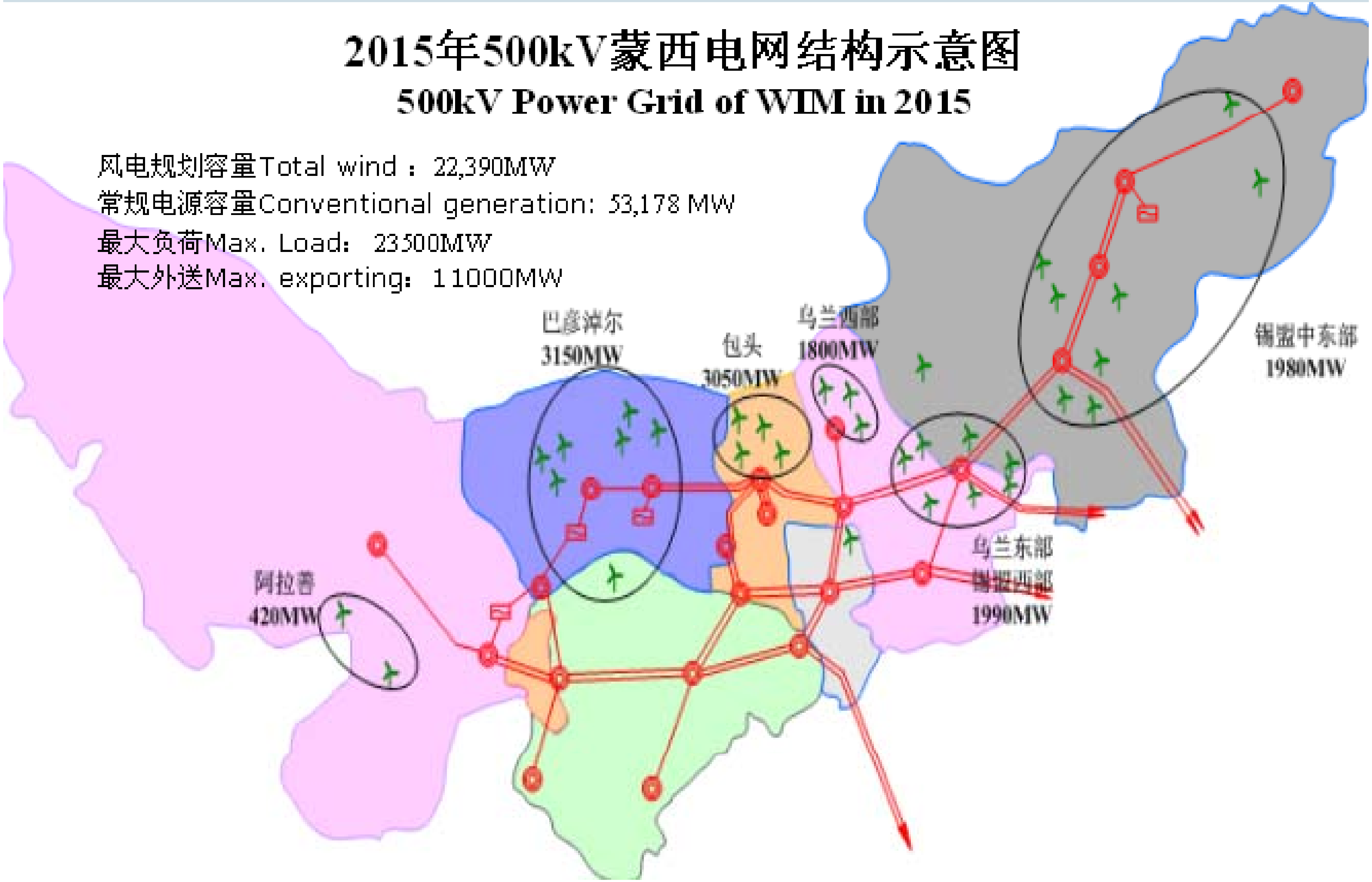
500kV Power Grid of WIM in 2015

风电规划容量Total wind：22,390MW

常规电源容量Conventional generation: 53,178 MW

最大负荷Max. Load: 23500MW

最大外送Max. exporting: 11000MW



4、主要研究内容
Main contents

1. **大规模风电并网对内蒙古电网调峰的影响**
   Impact of wind power on peak-load regulation of WIM power system.

   - 内蒙古电网中火电机组占绝大部分，水电和燃气机组所占比例很小。火电机组调整速度慢、调整容量有限，无法满足风电功率大幅波动情况下的电网调峰、调频需要。Most of the generation in WIM is coal-fired generation and its flexible capability is limited for high wind penetration

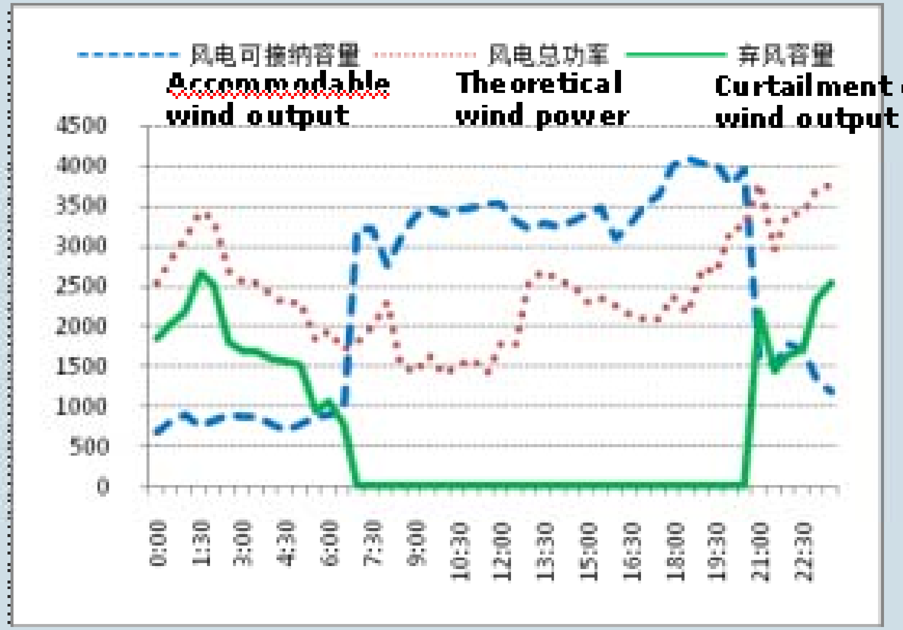
   - 部分火电机组承担供热任务，机组调峰能力非常有限，特别是在冬季夜间低负荷、大风时段，风电出力快速增加。The peaking capability is even less in Winter because part of the coal fired generation has to provide heat (less minimum operation level)

   - 系统调峰困难是制约风电并网的关键因素之一。Limited down-ramp capacity is the major constrain to accommodate wind in WIM

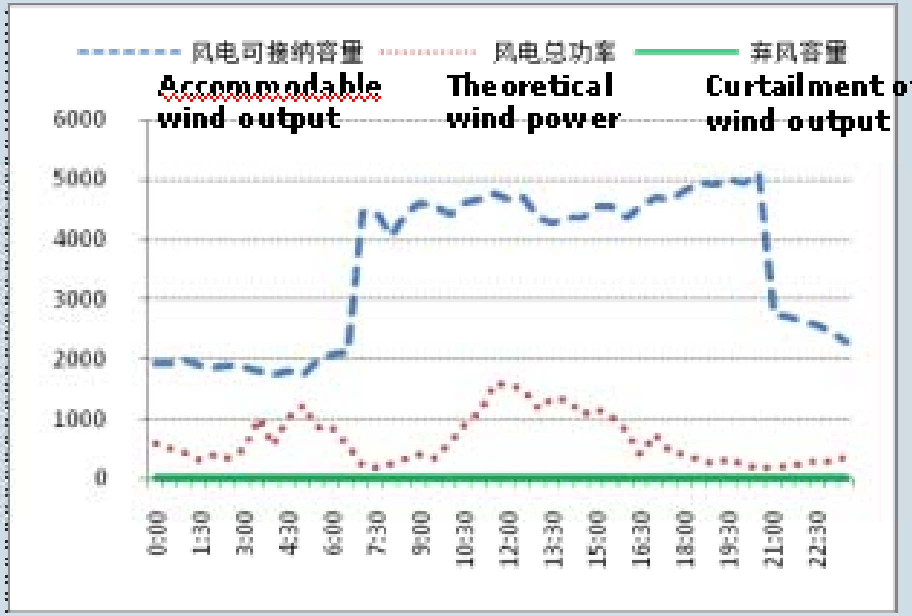
4 主要研究内容 Main contents

1. 大规模风电并网对内蒙古电网调峰的影响

Impact of wind power on peak-load regulation of WIM power system.



2010.1.6



2010.8.11

- 冬季部分火电机组承担供热任务，机组调峰能力非常有限，系统的风电消纳能力不足，导致出现大量弃风。
- Power balancing capability is insufficient due to the operation of CHP plants with limit operation range, which will lead to large curtailment of wind power.

4、主要研究内容

Main contents

2. 风电场并网运行对系统稳态特性的影响
   Impact of wind power on voltage and power flow of WIM power system

   - 规划风电场大多位于偏远地区，接入点基本都处于电网末端，地区电网结构薄弱，且距离负荷中心较远。Most planned wind generation is located in weak grid and far away from load centers.

   - 风电出力较小时，由于线路负载率低、线路充电功率大，导致地区电网电压偏高；而风电处于大出力状态时，大规模、长距离的电力传输将导致无功损耗增加、电网电压水平偏低。Voltage is a problem during high and low wind output.

   - 风电大规模接入后，电网可能面临无功功率分布不均、调压困难等问题。因此需要对风电并网后的系统潮流和无功电压进行分析，并提出风电场和电网应采取的技术措施。

   Load flow analysis is needed for necessary mitigations to address voltage problem.

4、主要研究内容
Main concerned contents

3. 风电场并网运行后的系统暂态稳定性

Transient stability analysis with the grid connection of wind power

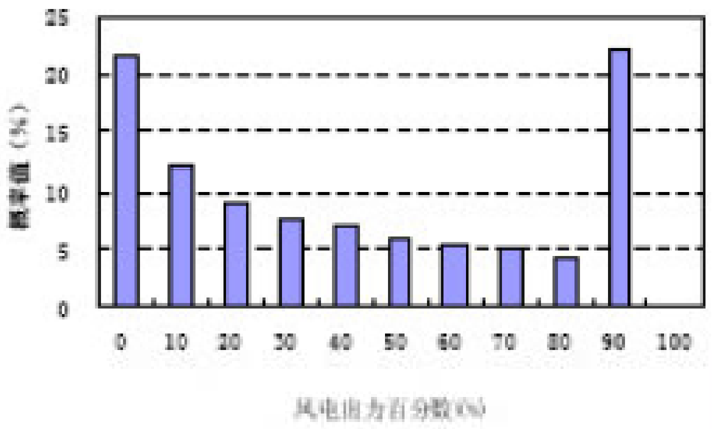
- 风电机组的暂态特性不同于常规电源，且目前国内风电场大多都不具备有功功率控制能力和低电压穿越能力。

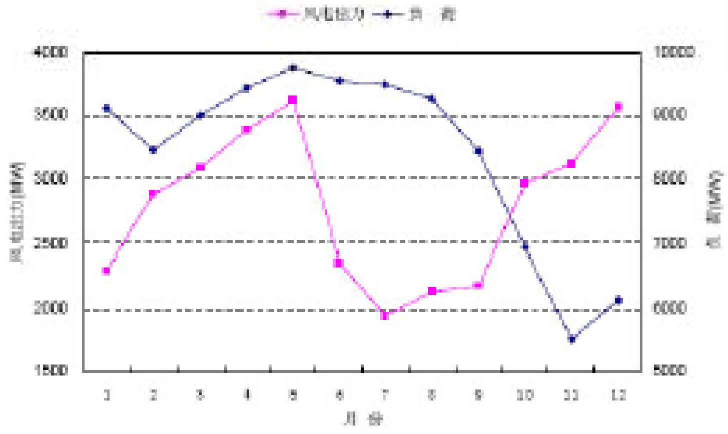
- 各类系统故障方式下，仿真分析风电场和电力系统的暂态稳定性，提出相应的提高系统稳定性的技术措施。

Wind generation has different transient stability characteristics. It needs to analyze the impact of the planned wind generation on the transient stability of WIM and propose mitigating measures if necessary.

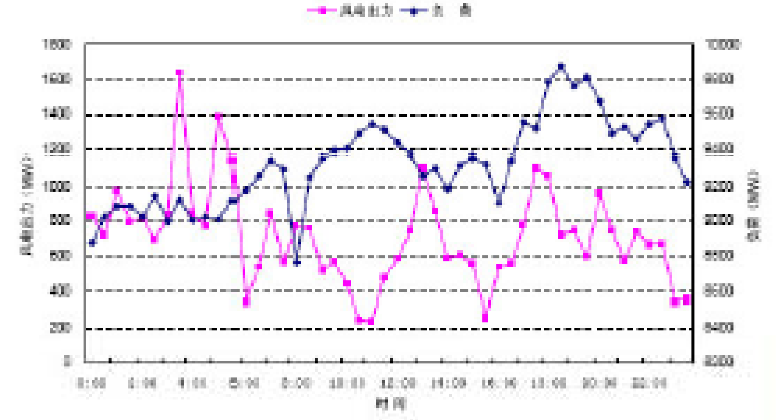
5、主要结论 Conclusions

风电出力和负荷曲线 Wind output and load profile





2010年内蒙古电网月平均负荷与风电综合出力比较图



(1) 1月10日

(2) 5月23日

5、主要结论 Conclusions

imagination at work

2015年不同风电规划容量和不同外送水平下的风电年平均等效弃风小时数
Equivalent cut-off hours with different planning capacity of wind power and exporting power in 2015

风电规划容量 Planning capacity (MW)	峰谷时段外送容量为不同值 Tie-line power flow is different in peak and valley time period		外送容量全天都为定值 Tie-line power flow is fixed	
	4000-8000MW	5500-11000MW	8000MW	11000MW
10000MW	98	80	2	0
11000MW	131	110	6	0
12090MW	169	144	18	4
13000MW	204	173	31	10
14000MW	243	207	55	20

5、结论 Conclusion

- 经过电网加强后，各风电场并网后的系统潮流和无功电压可满足系统要求。With recommended grid reinforcement, the system load flow and voltage can meet the requirement with the planned wind capacity

- 当全部风电场均满发且网内输电线路发生三相短路故障时，系统仍能够维持暂态稳定，各风电场均能维持并网运行。If a three-phase short-circuit fault happens at any transmission lines and all wind turbines operate in full capacity, the system can keep transiently stable, and all wind turbines can maintain operating.

- 当全部风电场均满发且网内任意一台常规机组跳闸时，系统仍能够维持暂态稳定，各风电场均能维持并网运行。When any conventional generator trips, the system can remain transiently stable, and all wind farms can maintain operating.

- 风电场并网运行过程中, 部分谐波超出了标准规定的允许值；建议在风电场投运初期进行电能质量测试，以准确评估风电场对电网电能质量的影响。Some harmonic components exceed the specified limit. It's suggested to perform harmonic test to further evaluate its impact on the power quality of WIM grid.

5、建议 Recommendations

- 加强电网 Grid reinforcement
- 增加系统的调峰能力（快速启停和爬坡率，可考虑抽水蓄能电站和燃气轮机电厂）
  Increase the maneuver capability of the system (quick start/stop and fast ramp rate, pumped storage and gas turbine generation as needed)
- 开展风电功率预测相关工作 Wind forecasting
- 提高风电场/风电机组的控制能力
  Requirement for the controllability of wind turbines
- 政策支持 Supporting policies

GE Energy
通用电气能源集团

Development of Wind Turbine-Generator Models for Power System Simulations

开发用于电力系统仿真的风力发电机组模型

imagination at work

Wind Model Development for Simulations
仿真用风电模型开发

- It is required by most grid codes globally

  世界上大部分并网导则的要求
- Generator models are necessary for power system studies (feasibility study, grid planning)

  发电机模型对于电力系统研究是必须的（可行性研究，电网规划）
- The characteristics of wind turbine generators are very different from conventional synchronous generators

  风电机组的特性与传统同步电机不同
- As wind generation grows big, it becomes critical to understand its impact on power grids

  随着风电增多，急需了解风电对电网的影响

imagination at work

Wind Model Development for Simulations
仿真用风电模型开发

- The need to have models to represent wind generation for power system simulations are urgent in China

  在中国，迫切需要用于电力系统仿真的能代表风电的模型

- GE worked with CEPRI to develop wind models (doubly fed WTGs and full conversion generators) in the power system simulation program PSD-BPA

  GE与中国电力科学研究院合作在电力系统仿真程序PSD-BPA中开发风电模型（包括双馈风电机组和直驱机组）

- These wind models developed in PSD-BPA was validated through a series of benchmark simulations against GE's PSLF

  在PSD-BPA中开发的风电模型，经过一系列的与GE公司PSLF软件的基准仿真，证明是有效的

imagination at work

Thank You!

谢谢！

imagination at work