Overview of Solar Integration
太阳能并网综述

Andrew Mills

December 5, 2011

Beijing, China

Overview
概览

- Distribution System Impacts of distributed PV

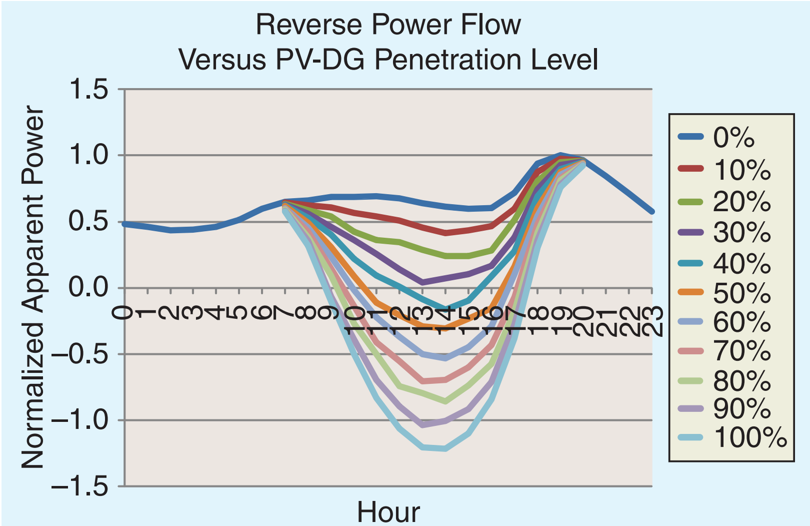
  分布式太阳能光伏对配电系统的影响

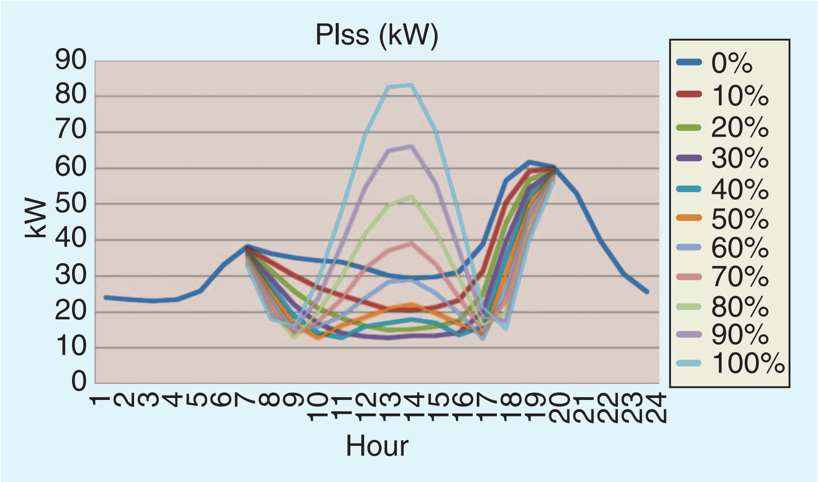
- Bulk Power System Impacts 对大电力系统影响
  - System stability 系统稳定性
  - Contribution to resource adequacy 增加电源充裕度Scheduling PV generation and forecasting 光伏发电计划和功率预测
  - Managing short-term variability 短期波动性管理

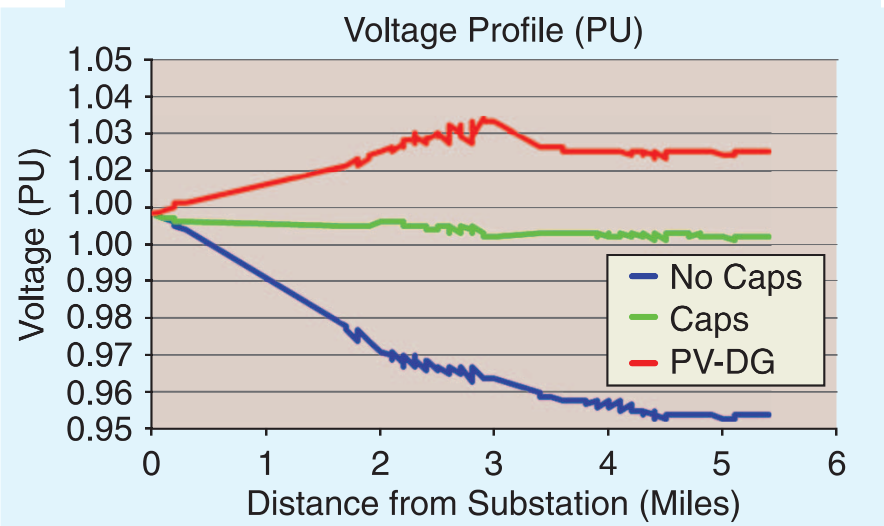
- Estimates solar integration costs

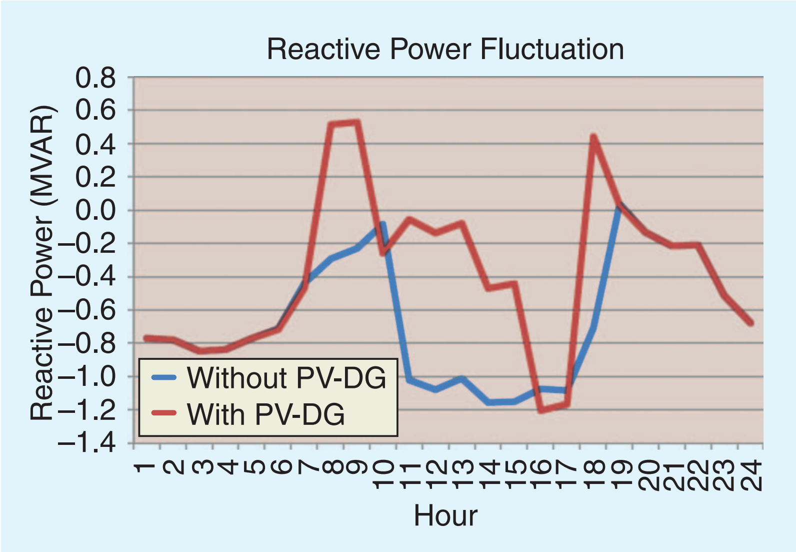
  估算太阳能并网成本

Distribution System Impacts
对配电系统的影响









Source: Katiraei and Agüero 2011

Bulk Power System Stability
大电力系统稳定性

- PV can impact frequency response (similar to wind) 光伏可以影响频率响应 （类似于风电）
  - PV interconnect with inverters 光伏与逆变器相联
  - Inverters have no mechanical inertia 逆变器没有机械惯性
  - System inertia and frequency regulation are reduced as conventional generation is de-committed. 常规能源发电被替代后，系统惯性和调频能力降低
  - Reduced inertia results larger frequency excursions from power imbalances 惯性减少导致系统不平横带来更大的频率波动
  - PV systems can add frequency control to maintain frequency performance 光伏系统可以增加频率控制来维持频率稳定
- PV IEEE 1547 standard requires inverters to trip during grid events PV IEEE 1547 标准要求逆变器在电网出现问题时跳闸
- If large portion trips at same time, reliability will be reduced 如果很多逆变器同时跳闸，将降低电网可靠性
  - Low voltage ride through (LVRT) standards needed for high PV 高比例光伏需要低电压穿越（LVRT）标准

Source: Achilles et al 2008

Contribution of Solar to Resource Adequacy
光电增加电源充裕性

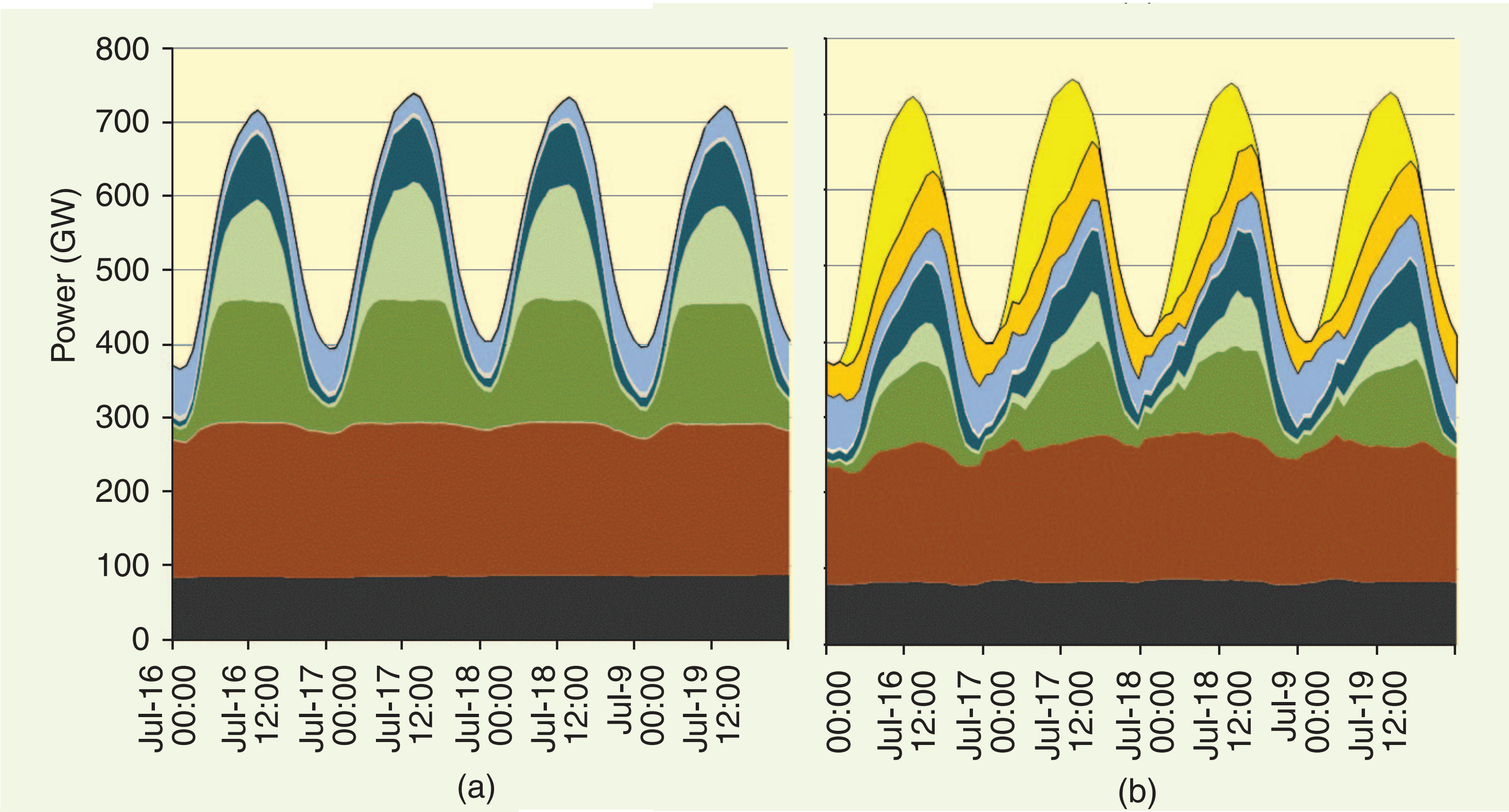
Penetration	Wind + CSP + PV	Wind only	CSP only	PV only
10% wind, 1% solar	17.1%	12.6%	90.8%	32.1%
20% wind, 3% solar	18.5%	11.5%	92.7%	30.3%
30% wind, 5% solar	18.9%	11.0%	92.6%	29.0%

Source: GE 2010

- Solar capacity credit can be higher than wind in places where peak loads are summer cooling loads 在峰值负荷为夏季制冷负荷的地区，光电容量置信度可以高于风能
  - Capacity credit will be low in systems with peak loads at night 峰值负荷处于夜间的系统，光电的容量置信度要低些
- Adding at least 4 hours of thermal storage can increase the capacity credit of CSP to the capacity credit of a conventional plant (Madaeni et al 2011)

增加4小时的储热系统可以将光电的容量置信度提高至和火电一样高

Scheduling Solar Resources and Operational Integration
太阳能资源发电计划与并网



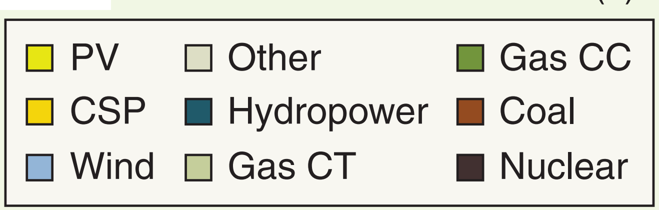


figure 3. (a) Nationwide dispatch, summer peak (reference case, no new solar); (b) nationwide dispatch, summer peak (20% solar case).

Source: Brinkman et al 2011

Sample of existing and ongoing studies of system operations with solar
对含太阳能发电的系统运行的现有研究

Author, Date	Region	PV (MW)	CSP (MW)	Notes
GE, 2007	CA, WECC	630 – 2,900	1,200 – 3,100	(1) CA Intermittency Analysis Project (2) DA forecast error based on the monthly average of the actual solar (3) 15-min PV data from 13 sites with synthesized 1-min data
Enernex, 2009	Xcel, CO	100	200 – 600	(1) Day-ahead forecast based on previous day production profile. (2) No within-hour variability or uncertainty (3) Estimated inefficiencies in system dispatch caused by uncertainties in DA solar forecast
GE, 2010	WestConnect, WECC	2,900 – 6,900	2,900 – 5,400	(1) Western Wind and Solar Integration Study (2) Hourly satellite derived solar data with synthesized 10-min variability (3) Day-ahead forecasts from meso-scale models
CAISO, 2010	CA	830	1,400	(1) 20% RPS case (2) DA forecasts from **[???]** (3) Evaluation of existing fleet capability (4) Quantification of regulation and load following need (5) Existing fleet can integrate renewables
Navigant, 2011	NVEnergy, NV only	150-1040	-	(1) Costs associated with PV wanting to connect to system (2) sub-hourly reserves (2) includes large plants (300MW)
CAISO, ongoing	CA, WECC	6,700	4,500	(1) 33% RPS cases (2) No day-ahead forecast error (3) Quantifies load-following and regulation needs (4) Adds CT’s to mitigate violations in model

Motion Vector Forecasts 运动矢量预测

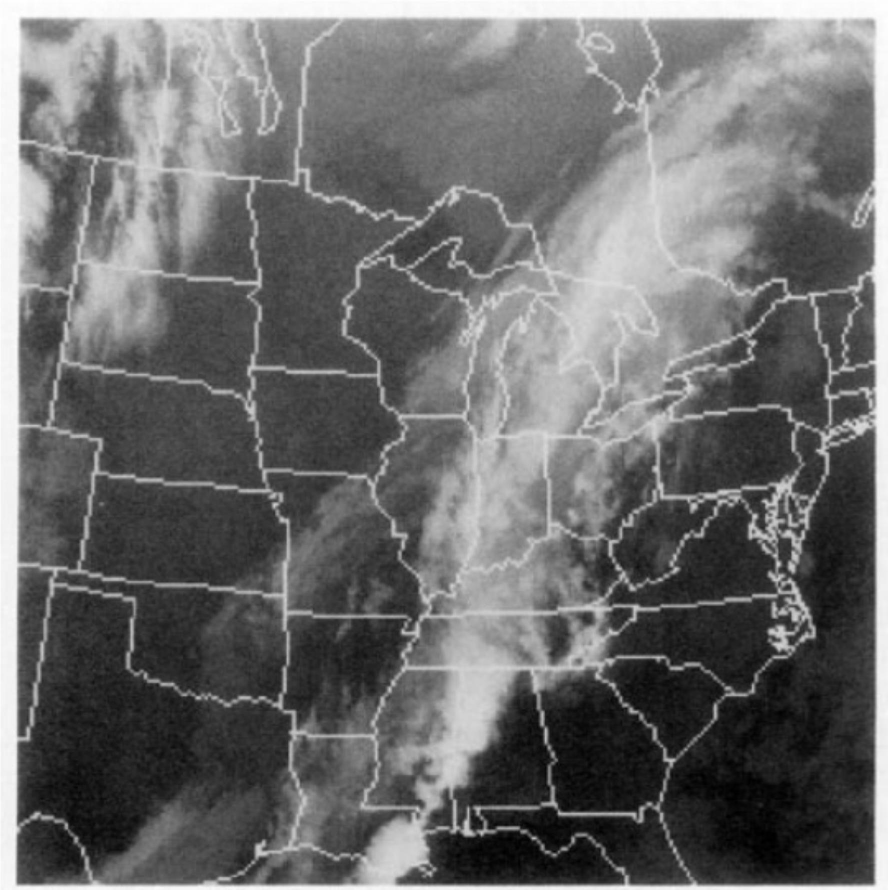


FIG. 3. A frame of the satellite imagery used in the demonstration correlation analysis. Data is over the central and eastern United States, valid at 1230 UTC 20 November 1991.

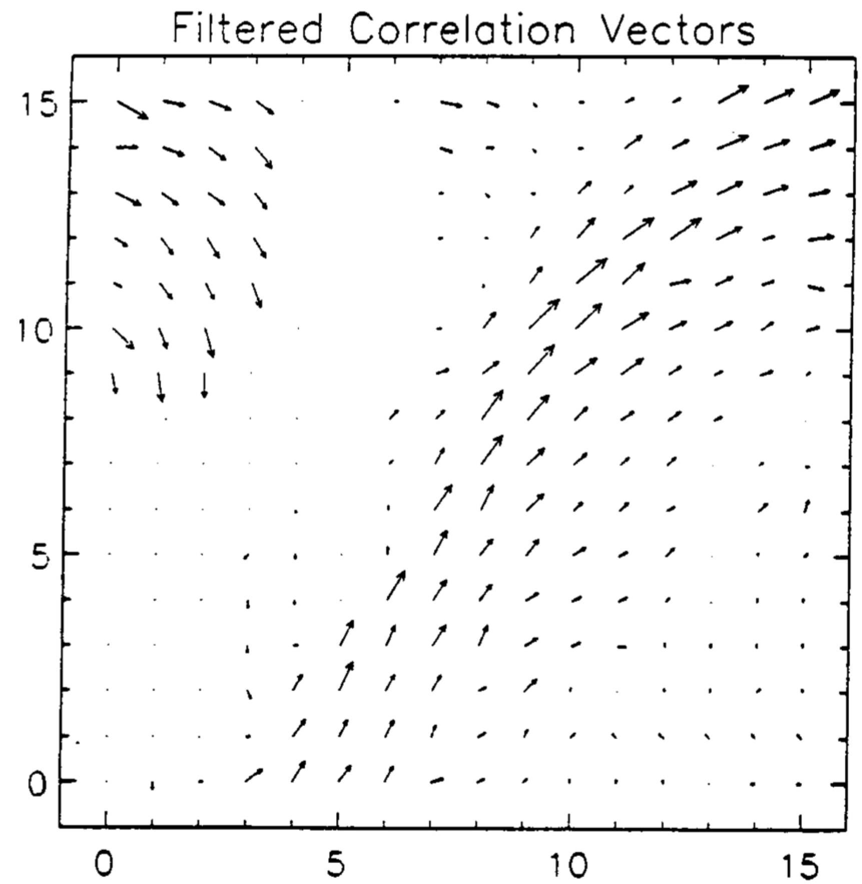
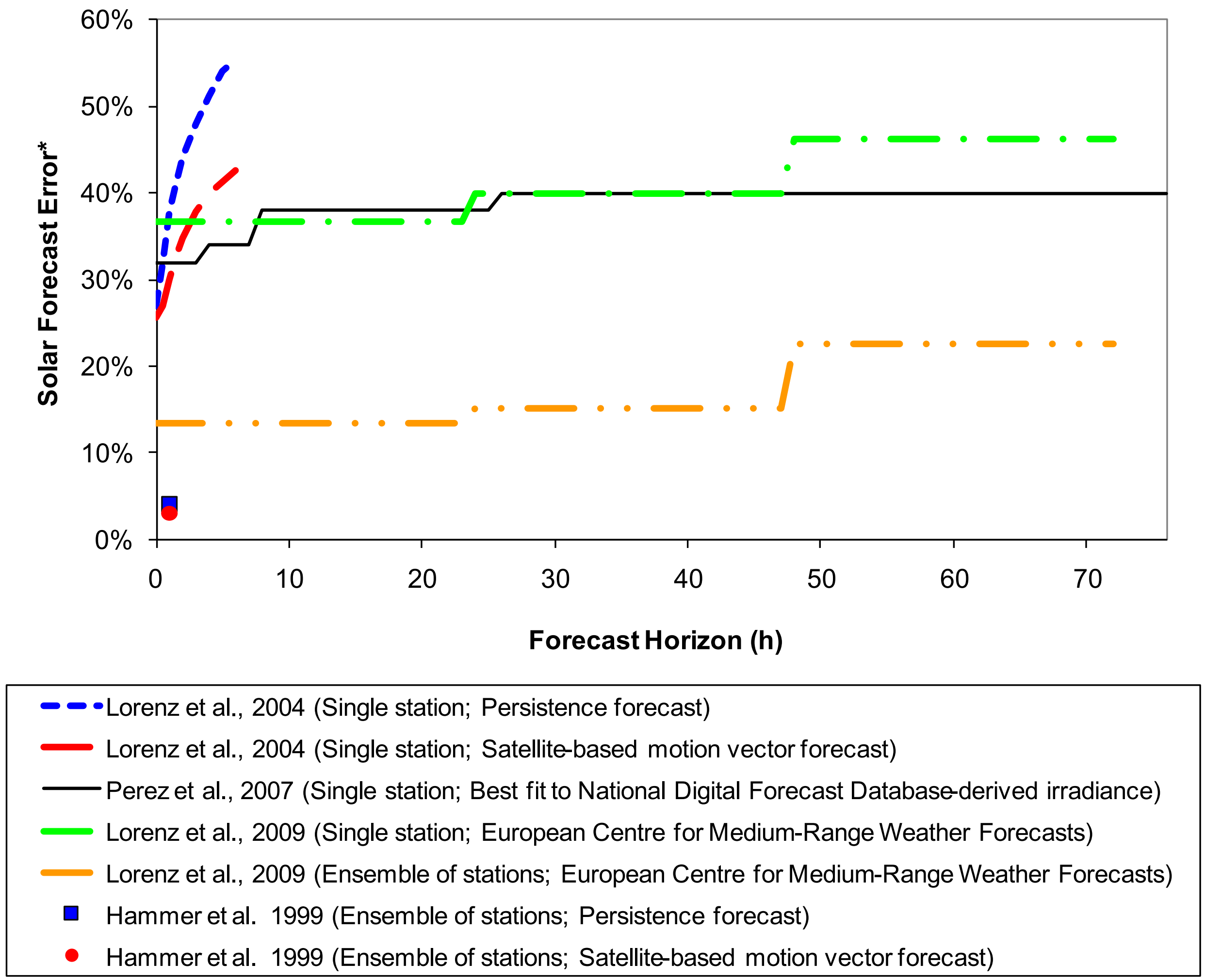


FIG. 6. Displacement vectors derived from images 0.5 h later (and processed through consistency check).

Source: Hamill and Nehrkorn (1993)

Sample of Solar Forecast Methods
几种太阳能预测方法



*Relative Root Sq. Mean Error of Global Solar Insolation Forecast

- Persistence and MVF are adequate for short-term (<4 hours) 持续性和运动矢量预测方法可以做短期 （小于4小时）预测

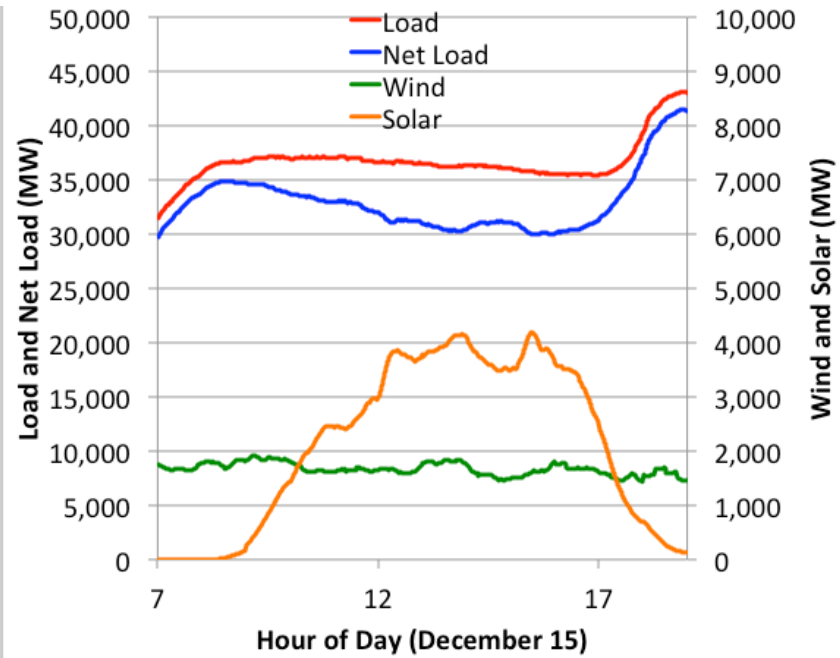
- Numerical weather models perform better for longer term forecasts 数值天气预报模型做长期预测效果更好

- Forecast errors for ensemble of solar plants will be lower than forecasts for individual plants 群体电站预测误差小于单个电站预测误差

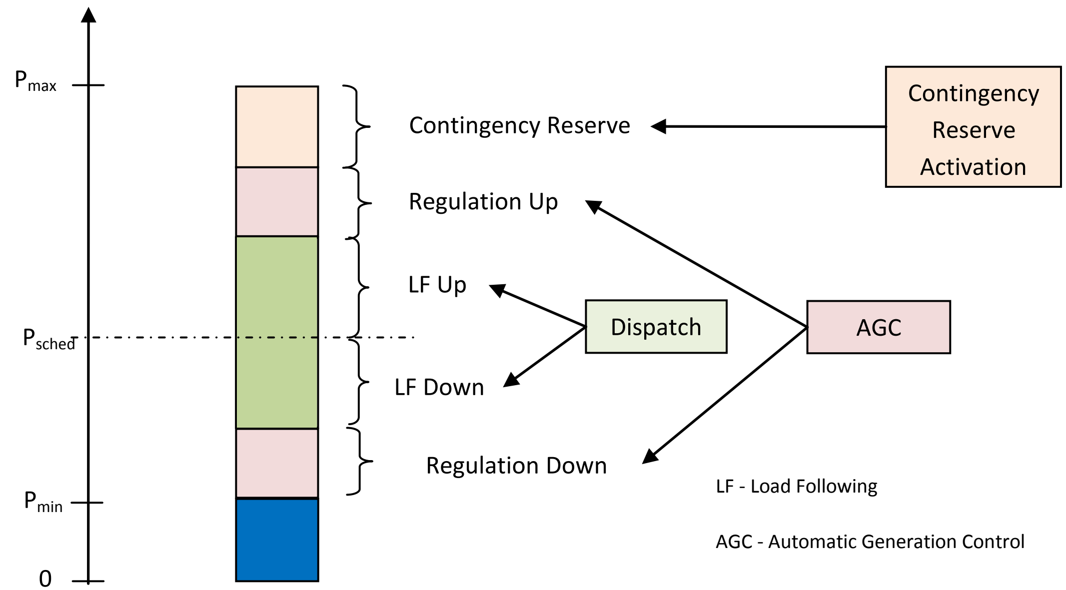
Many options available for generating solar forecasts
太阳能发电预测还有很多可行的办法

- Long-term (Multi-hour to multi-day horizon): 长期 （数小时或数天）
  - National Digital Forecast Database: 3-h basis for up to 3-days-ahead and on a 6-h basis up to 6-days-ahead 国家数字预报数据库：基于3小时数据的三天预测，基于6小时数据的六天预测
  - Meso-scale models: downscale Reanalysis weather data for relative humidity, convert into estimate of cloud cover (used in WWSIS) 中尺度模型：通过降尺度法用天气数据分析相对湿度，折算成云覆盖量 （应用在西部风能太阳能并网研究中）
- Short-term (Less than multiple hour forecast horizon):短期 （数小时之内的预测）
  - Persistence of cloudiness 云层持续性
  - Statistical methods using real-time output from multiple monitoring stations 基于多个观测站实时数据的统计方法
  - Motion vector forecasts (MVF) 运动矢量预测
  - On-site sky imaging 现场天空成像

Management of short-term variability
短期波动性管理



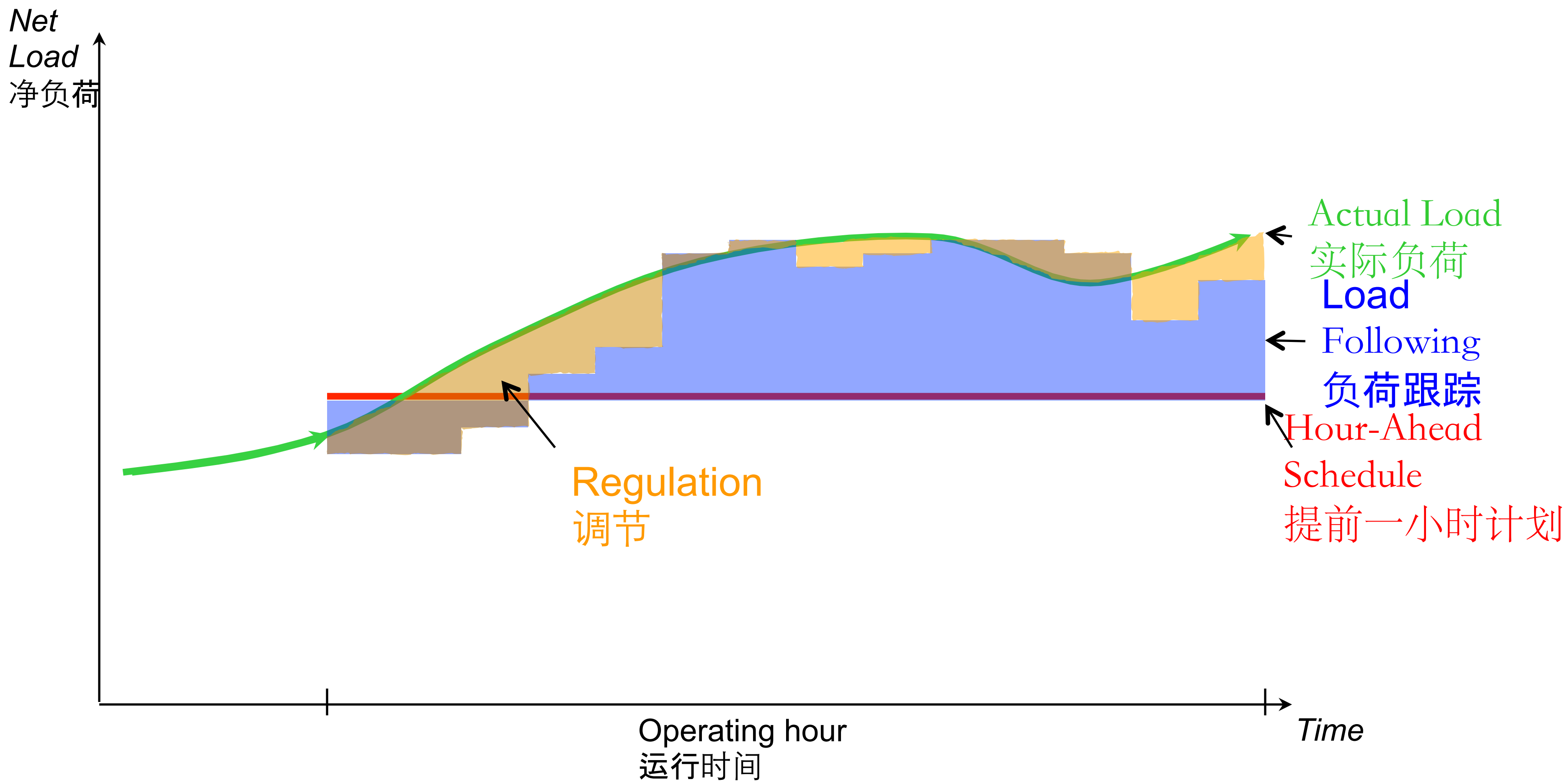
Source: Data from CAISO 33% Base



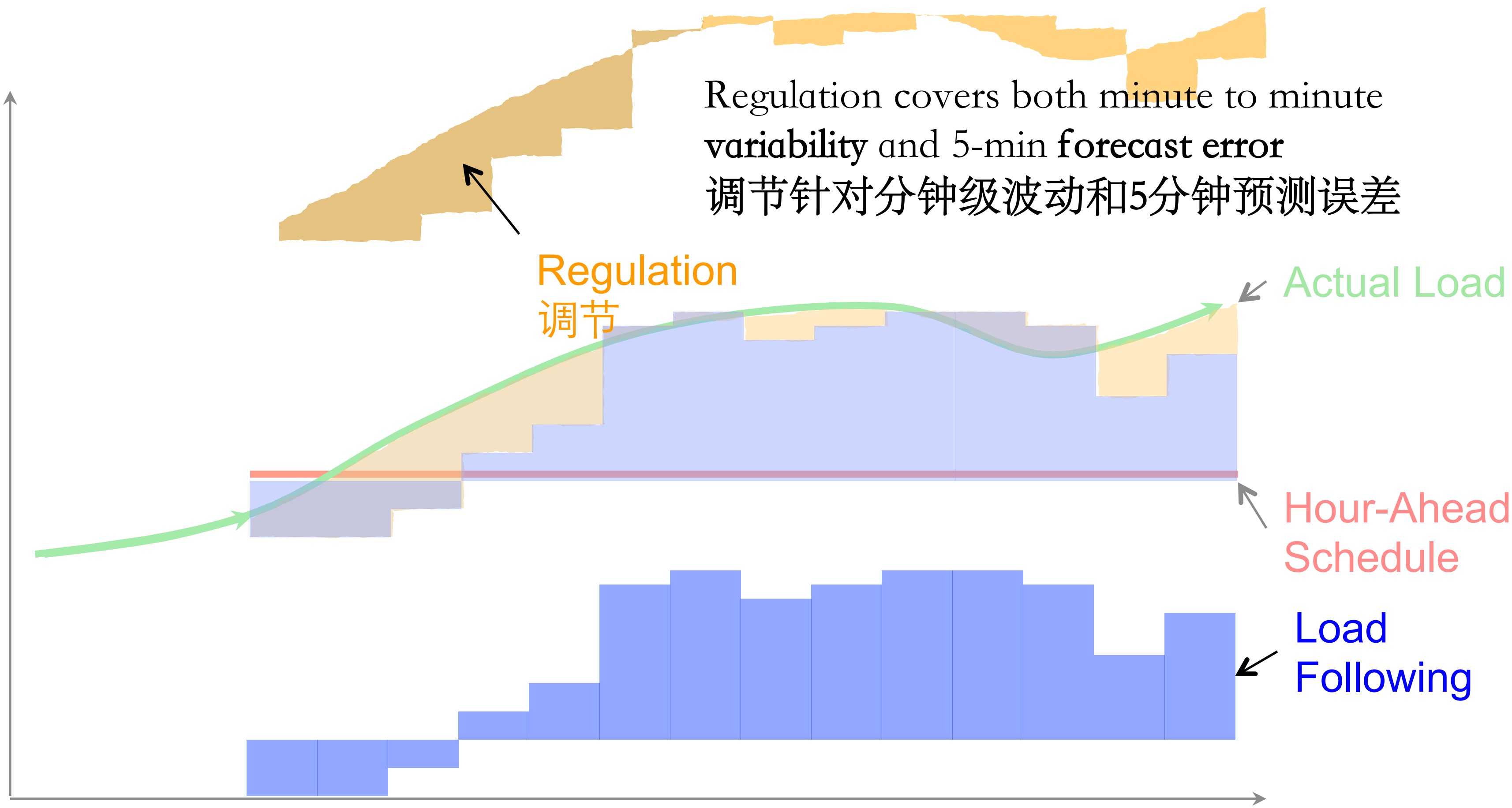
Source: Navigant 2011

- Flexible resources manage variability around schedules
  用灵活资源管理波动性
- Dispatch, Automatic Generation Control (AGC) and Contingency reserves must be able to keep system in balance
  调度、自动发电控制(AGC)和应急备用可以保持系统平衡

Example of Short-term System Balancing
短期系统平衡例子



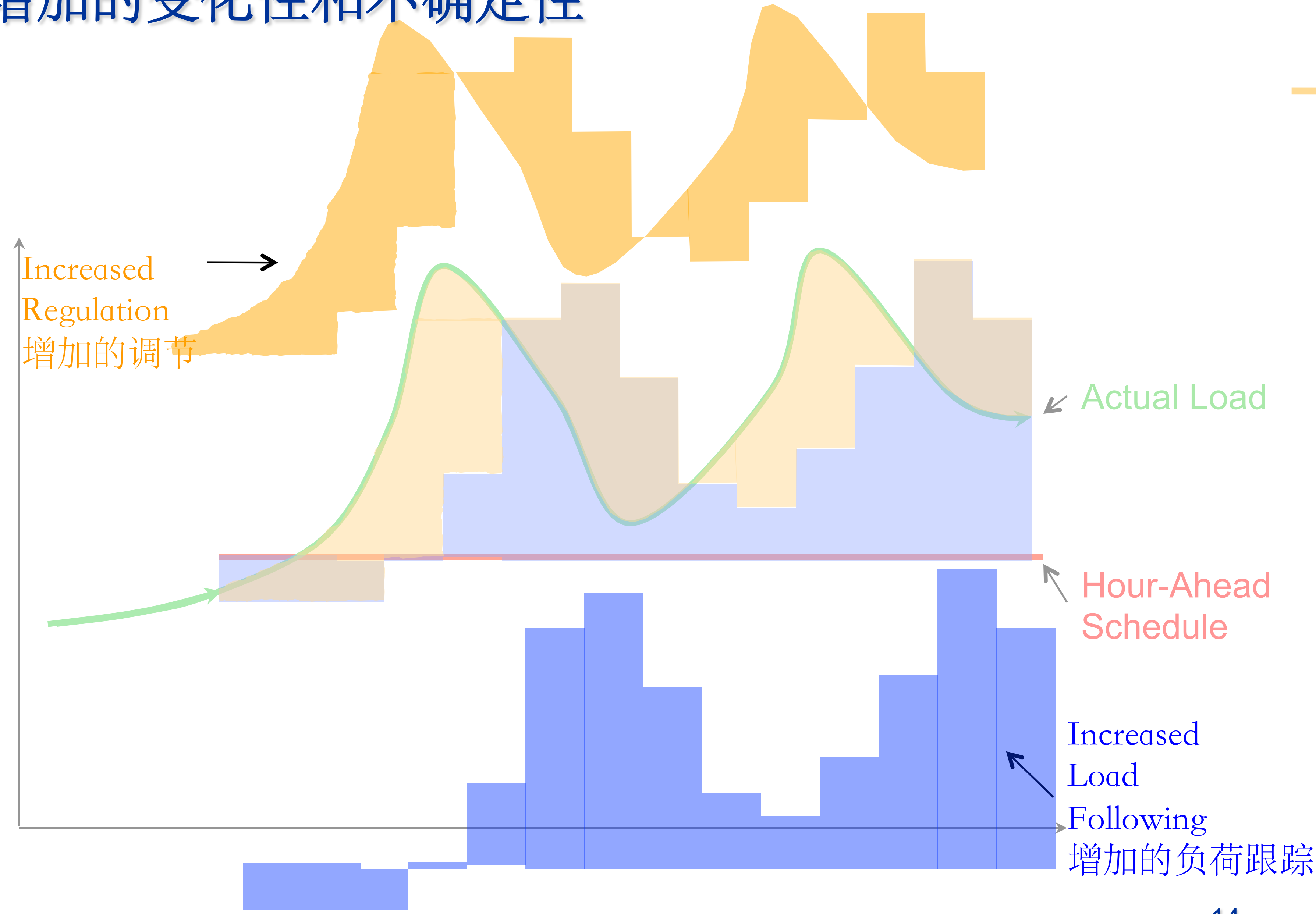
Example of Short-term System Balancing
短期系统平衡例子



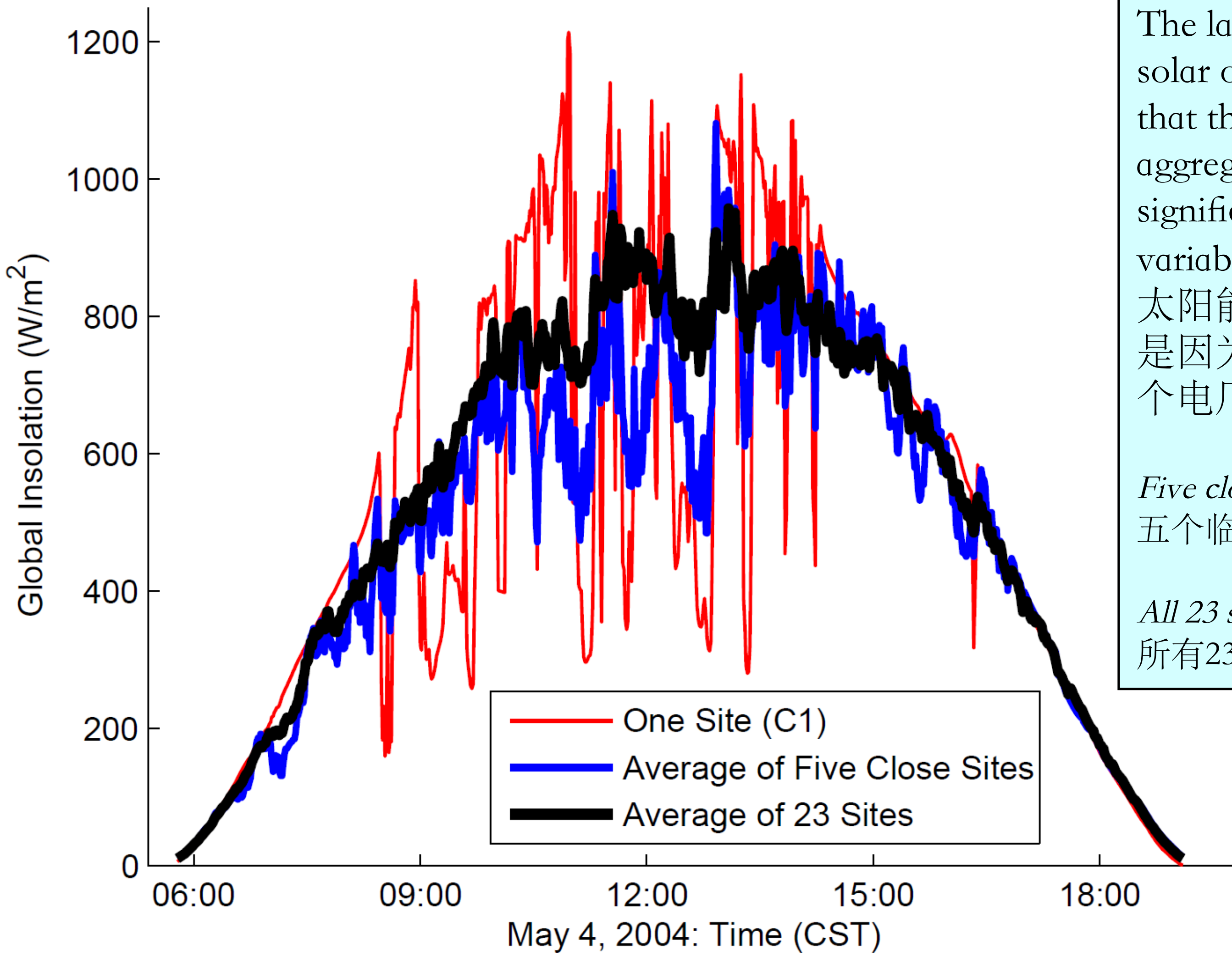
Regulation covers both minute to minute **variability** and 5-min **forecast error**
调节针对分钟级波动和5分钟预测误差

Load following covers both 5-min **variability** and hour-ahead **forecast error**
负荷跟踪针对五分钟内的波动和提前一小时的预测误差

Increased Variability and Uncertainty
增加的变化性和不确定性



Aggregate Variability of Multiple Sites Is Significantly Smoother than Individual Sites
多个电厂的总体变化比单个电厂变化平滑很多



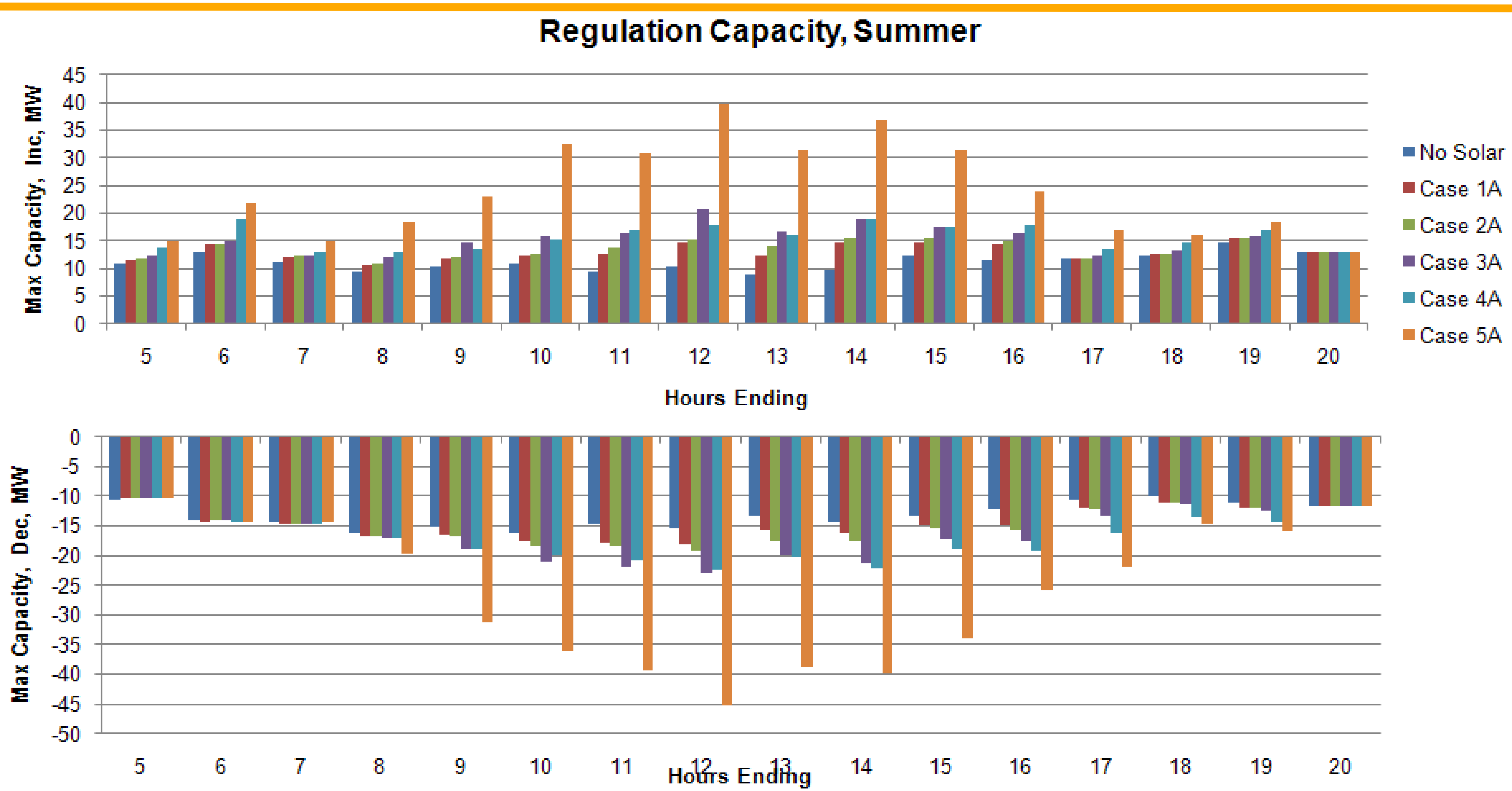
The lack of correlation in changes solar over short time scales means that the variability of the aggregated multiple sites is significantly smoother than the variability of an individual site.
太阳能变化在短期缺乏相关性是因为多个电厂总体变化比单个电厂变化要更平滑

Five closest sites: 50 – 170 km apart
五个临近的电厂：50-170 km距离

All 23 sites: 20 – 440 km apart
所有23 个电厂：20-440 km距离

Source: Mills and Wiser (2011)

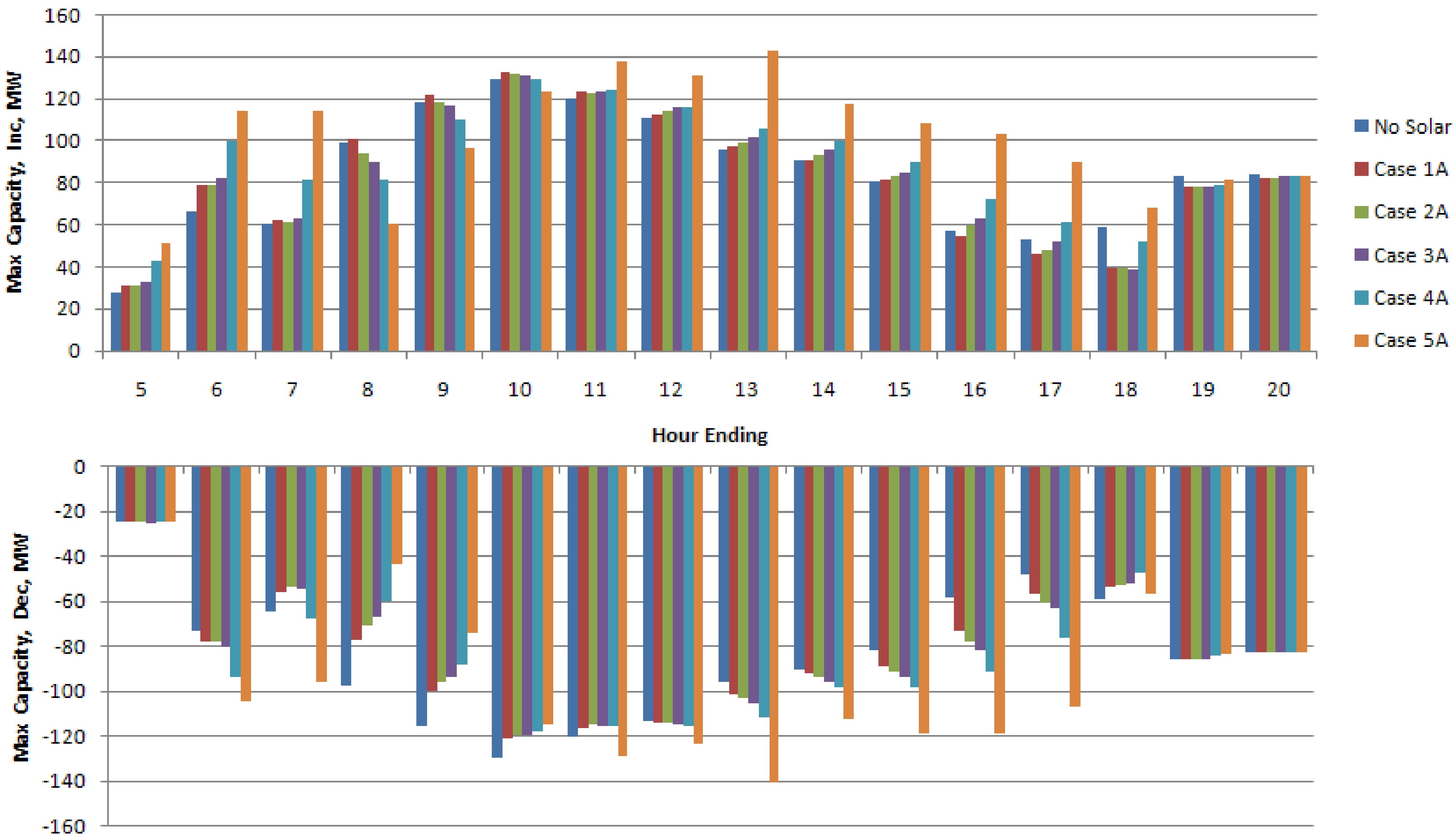
Regulation Requirements with Different Deployments and Penetration of PV
不同光伏应用及比例对调节的要求



Diverse deployment of PV => regulation increases at 3% of nameplate PV capacity 光伏多种应用=>调节需求增长了光伏铭牌容量的3%

Source: Navigant 2011

Load Following Requirements with Different Deployments and Penetration of PV
不同光伏应用和比例对负荷跟踪的要求



Source: Navigant 2011

Overview
概览

- Distribution System Impacts of distributed PV

  分布式太阳能光伏对配电系统的影响

- Bulk Power System Impacts 对大电力系统影响
  - System stability 系统稳定性
  - Contribution to resource adequacy 增加电源充裕度Scheduling PV generation and forecasting 光伏发电计划和功率预测
  - Managing short-term variability 短期波动性管理

- Estimates solar integration costs

  估算太阳能并网成本

Integration Costs Associated with Day Ahead Forecast Errors
日前预测误差导致的并网成本

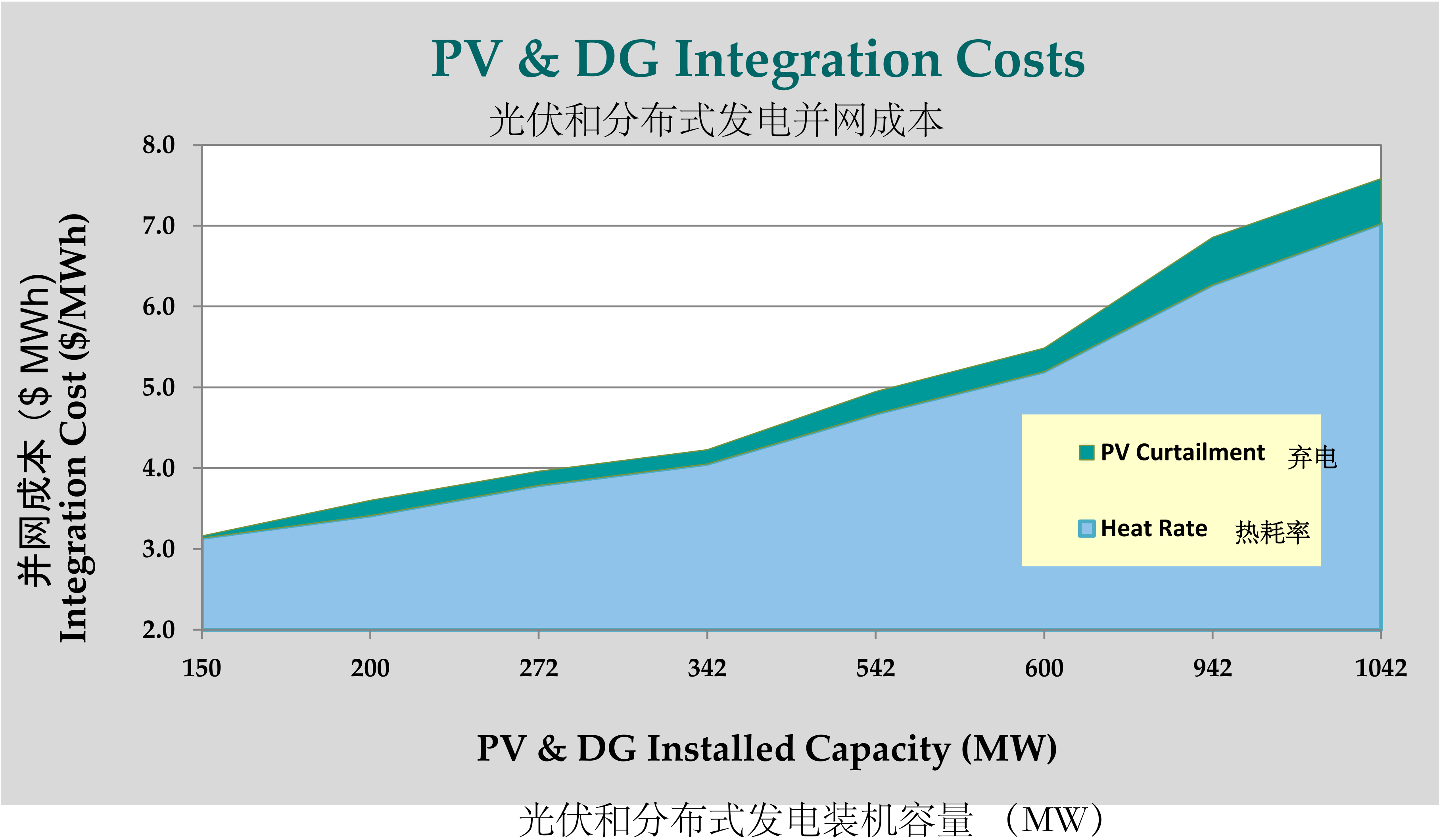
EnerNex Corporation. 2009. *Solar Integration Study for Public Service Company of Colorado*. Denver, CO: Xcel Energy, February

Table 3: Summary of Solar Integration Costs in $/MWh for Base Case Gas Assumption

Scenario	Solar Nameplate Capacity (MW)	Solar Energy (GWh)	Integration Cost ($/MWh of Solar Energy)
A	200	626	1.96
B	400	1044	1.49
E	400	948	1.25
C	600	1484	5.58
F	600	1531	6.06
D	800	1944	5.15

- Solar is a mix of PV and CSP depending on scenario
  各情景中太阳能技术（光伏和CSP）组合比例不同
- System has peak load of 7 GW, 3-12% penetration on capacity basis 系统峰荷7GW,太阳能装机容量占3-12%
- Integration cost is based on day-ahead forecast error
  并网成本计算基于日前预测误差

Integration costs based on increase balancing reserve requirements
平衡备用增加导致的并网成本



Source: Navigant 2011

Estimates of Short-term Balancing Costs are Impacted by Geographic Diversity 短期平衡成本预测受地理多样性的影响

Time Scale	Increased Balancing Reserve Costs ($/MWh)				
	Reserves Constant Throughout Year				Reserves Change with Position of Sun
	Solar			Wind	Solar
	1 Site	5 Sites	25 Site Grid		
1-min Deltas	$16.7	$4.8	$1.2	$0.9	$0.8
10-min Deltas	$17.3	$4.4	$1.0	$0.2	$0.7
60-min Deltas	$5.0	$1.6	$0.6	$0.5	$0.5
Total Cost	**$39.0**	**$10.8**	**$2.7**	**$1.6**	**$1.9**

These costs address only short-term variability and do not include many other costs and benefits associated with solar and wind 这些成本仅考虑短期波动性，不包括风能和太阳能的其他成本和收益

Cost estimates are developed using simple approximations and are only meant to illustrate relative changes in cost 成本估算应用简单的近似值，只反映成本的相对变化

Example costs based on 10% penetration of solar or wind on capacity basis 案例中的成本测算基于太阳能或风能占总装机容量10%的情况

Why are solar and wind costs comparable? 为什么风能和太阳能的成本是可比的?

Reserves can be held in proportion to clear-sky insolation for solar 太阳能所需备用可以按晴天太阳辐射水平安排

Reserves assumed to be held at same level all year for wind风能所需备用假设在全年保持同一水平

Source: Mills and Wiser (2011)

References
参考文献

Achilles, S., S. Schramm, and J. Bebic. 2008. Transmission System Performance Analysis for High-Penetration Photovolatics. February. http://www1.eere.energy.gov/solar/solar_america/pdfs/42300.pdf.

Brinkman, G., P. Denholm, E. Drury, R. Margolis, and M. Mowers. 2011. "Toward a Solar-Powered Grid." IEEE Power and Energy Magazine 9 (3) (June): 24-32. doi:10.1109/MPE.2011.940574.

California ISO (CAISO). 2010. Integration of Renewable Resources at 20% RPS. Folsom, CA: California Independent System Operator, August 31. http://www.caiso.com/2804/2804d036401f0.pdf.

California ISO(CAISO). Ongoing. Renewables Integration Studies and Reports. http://www.caiso.com/23bb/23bbc01d7bd0.html

EnerNex Corporation. 2009. Solar Integration Study for Public Service Company of Colorado. Denver, CO: Xcel Energy, February 9. http://www.xcelenergy.com/SiteCollectionDocuments/docs/PSCo_SolarIntegration_020909.pdf.

GE Energy. 2010. Western Wind and Solar Integration Study. Golden, CO: National Renewable Energy Laboratory, May. http://www.nrel.gov/wind/systemsintegration/wwsis.html.

Hamill, T. M., and T. Nehrkorn. 1993. A Short-Term Cloud Forecast Scheme Using Cross Correlations. *Weather and Forecasting* 8(4) : 401-411.

Hammer, A., D. Heinemann, E. Lorenz, and B. Lückehe. 1999. "Short-term forecasting of solar radiation: a statistical approach using satellite data." *Solar Energy* 67 (1-3) (July): 139-150. doi:10.1016/S0038-092X(00)00038-4.

Katiraei, K.F., and J.R. Aguero. 2011. "Solar PV Integration Challenges." IEEE Power and Energy Magazine 9 (3) (June): 62-71. doi:10.1109/MPE.2011.940579.

Lorenz, E., J. Hurka, D. Heinemann, and H.G. Beyer. 2009. "Irradiance Forecasting for the Power Prediction of Grid-Connected Photovoltaic Systems." IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 2 (1): 2-10.

Lorenz, E., A. Hammer, and D. Heinemann. 2004. Short term forecasting of solar radiation based on satellite data. In Eurosun Freiburg, Germany, June 20.

Madaeni, S. H, R. Sioshansi, and P. Denholm. 2011. "How Thermal Energy Storage Enhances the Economic Viability of Concentrating Solar Power." Proceedings of the IEEE PP (99): 1-13. doi:10.1109/JPROC.2011.2144950.

References (continued)
参考文献（续）

Mills, A. D, and R. H. Wiser. 2011. Implications of geographic diversity for short-term variability and predictability of solar power. In 2011 IEEE Power and Energy Society General Meeting, 1-9. IEEE, July 24. doi:10.1109/PES.2011.6039888.

Navigant, 2011. Large Scale PV Integration Study. Prepared for NVEnergy. http://www.navigant.com/insights/library/energy/large-scale_pv_integration_study/

Perez, R., K. Moore, S. Wilcox, D. Renne, and A. Zelenka. 2007. "Forecasting solar radiation - Preliminary evaluation of an approach based upon the national forecast database." *Solar Energy* 81 (6) (June): 809-812. doi:10.1016/j.solener.2006.09.009.

Piwko, R. J., X. Bai, K. Clark, G. A. Jordan, and N. W. Miller. 2007. *Intermittency Analysis Project: Appendix B: Impact of Intermittent Generation on Operation of California Power Grid*. California Energy Commission, PIER Research Development & Demonstration Program, July.