Electricity Grids with High Wind Penetrations
高比例风电的电网运营

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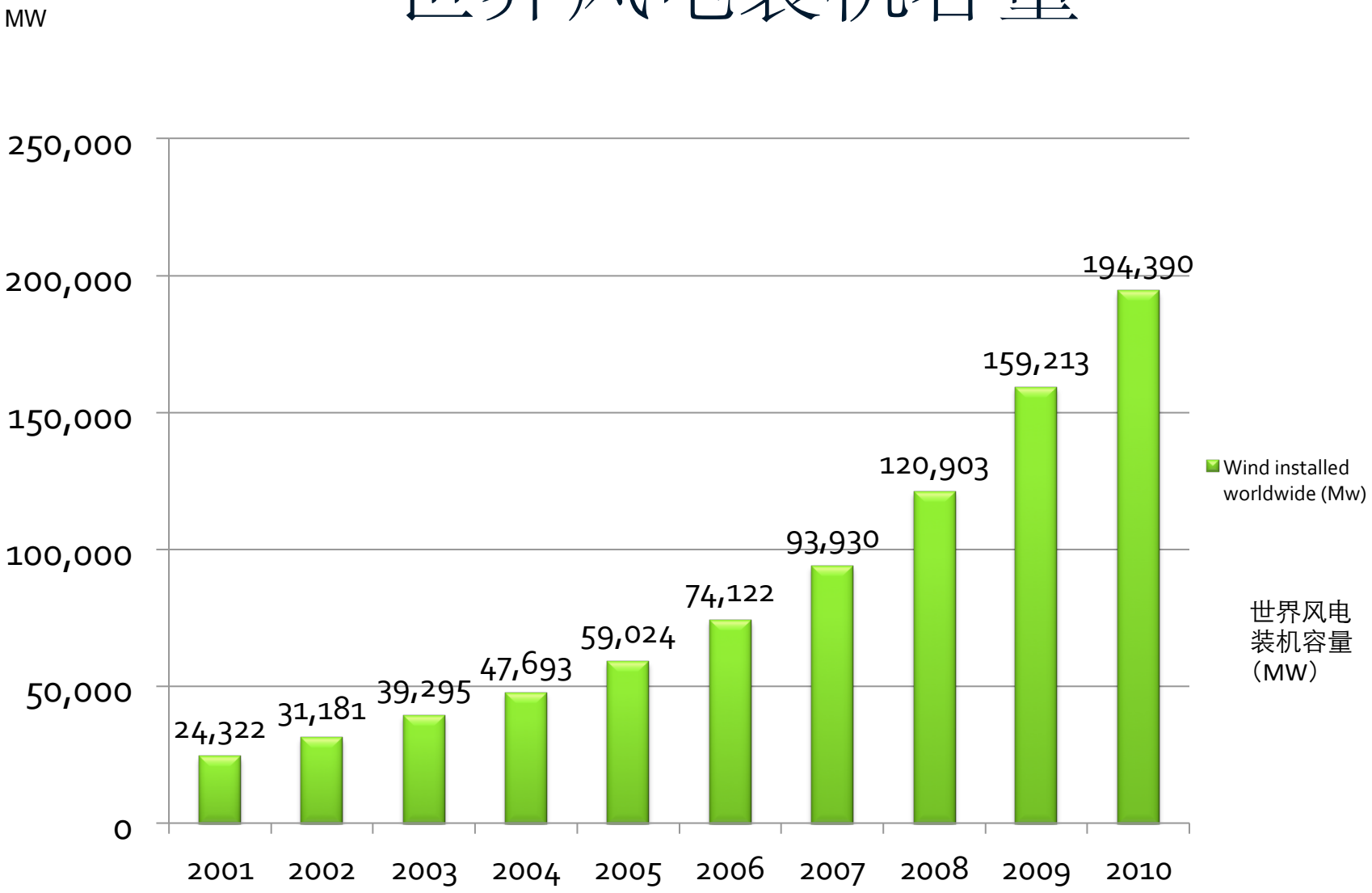
Beijing, Dec 7th 2011

electricity research centre

UCD DUBLIN

Wind installed worldwide
世界风电装机容量

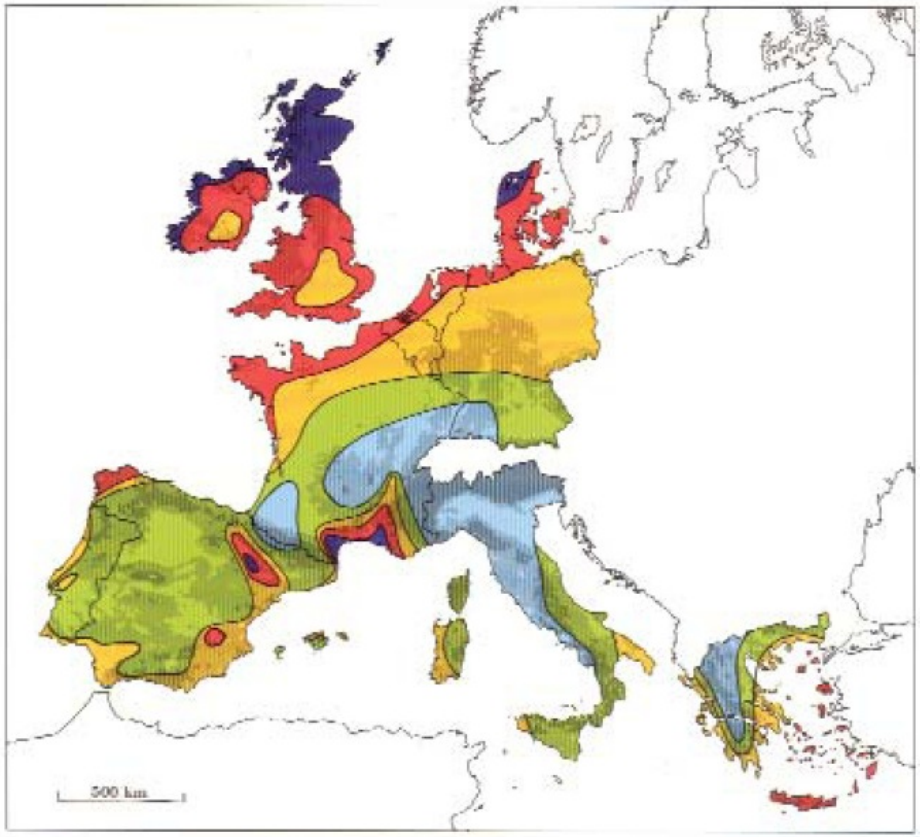


Source: GWEC, 2010

Wind (GWEC, 2010)
各国风电装机情况（世界风能协会，2010）

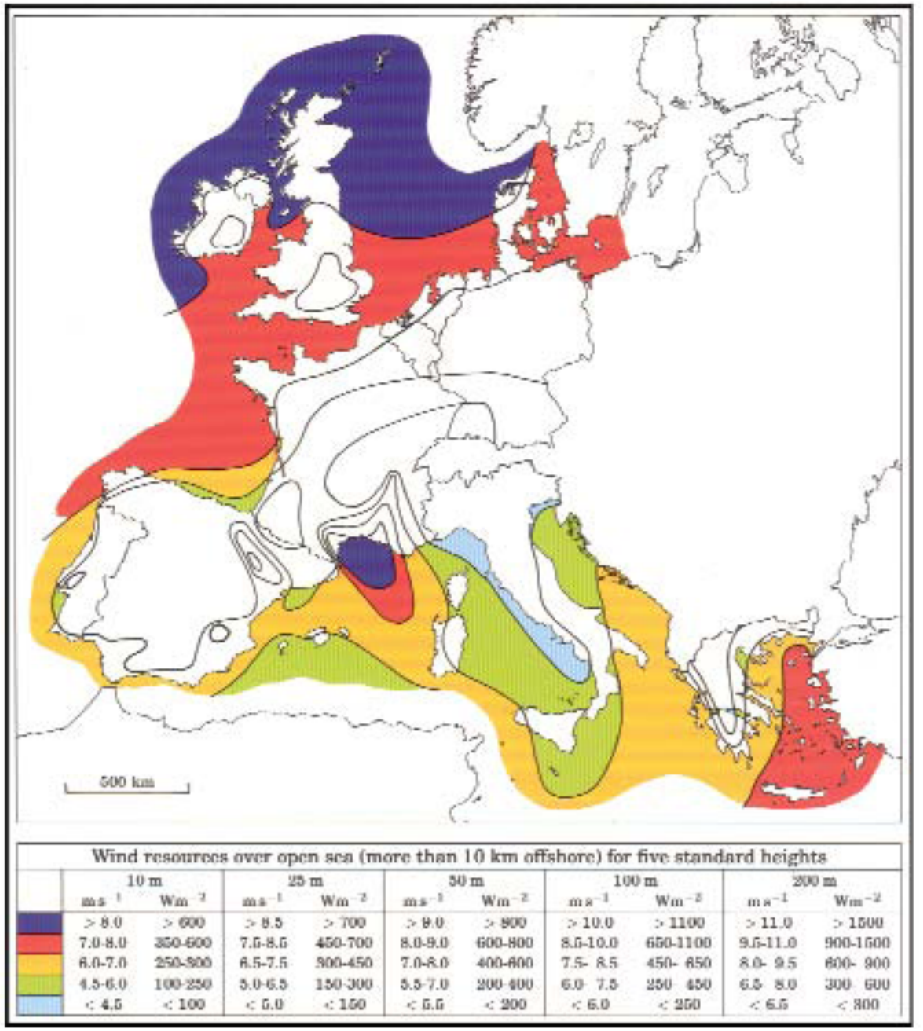
	Installed capacity in 2010 (MW) 2010新增装机（MW）	% of total world installed capacity 2010 占比(%)	Cumulative capacity end 201 0 (MW) 2010累计装机（MW）	% of cumulative capacity of world end 2010 占比(%)
China	16,500	46.1	42,287	21.8
USA	5,115	14.3	40,180	20.7
India	2,139	6.0	13,065	6.7
Spain	1,516	4.2	20,676	10.6
Germany	1,493	4.2	27,214	14.0
France	1,086	3.0	5,660	2.9
UK	963	2.7	5,204	2.7
Italy	948	2.6	5,797	3.0
Canada	690	1.9	4,009	2.1
Sweden	603	1.7		
Denmark			3,752	1.9
World	**35,802**	**100**	**194,390**	**100**

European Wind Resources
欧洲风能资源



Wind resources[1] at 50 metres above ground level for five different topographic conditions

	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	6.5-7.0	200-400	7.0- 8.5	400- 700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 6.5	< 200	< 7.0	< 400



Wind resources over open sea (more than 10 km offshore) for five standard heights

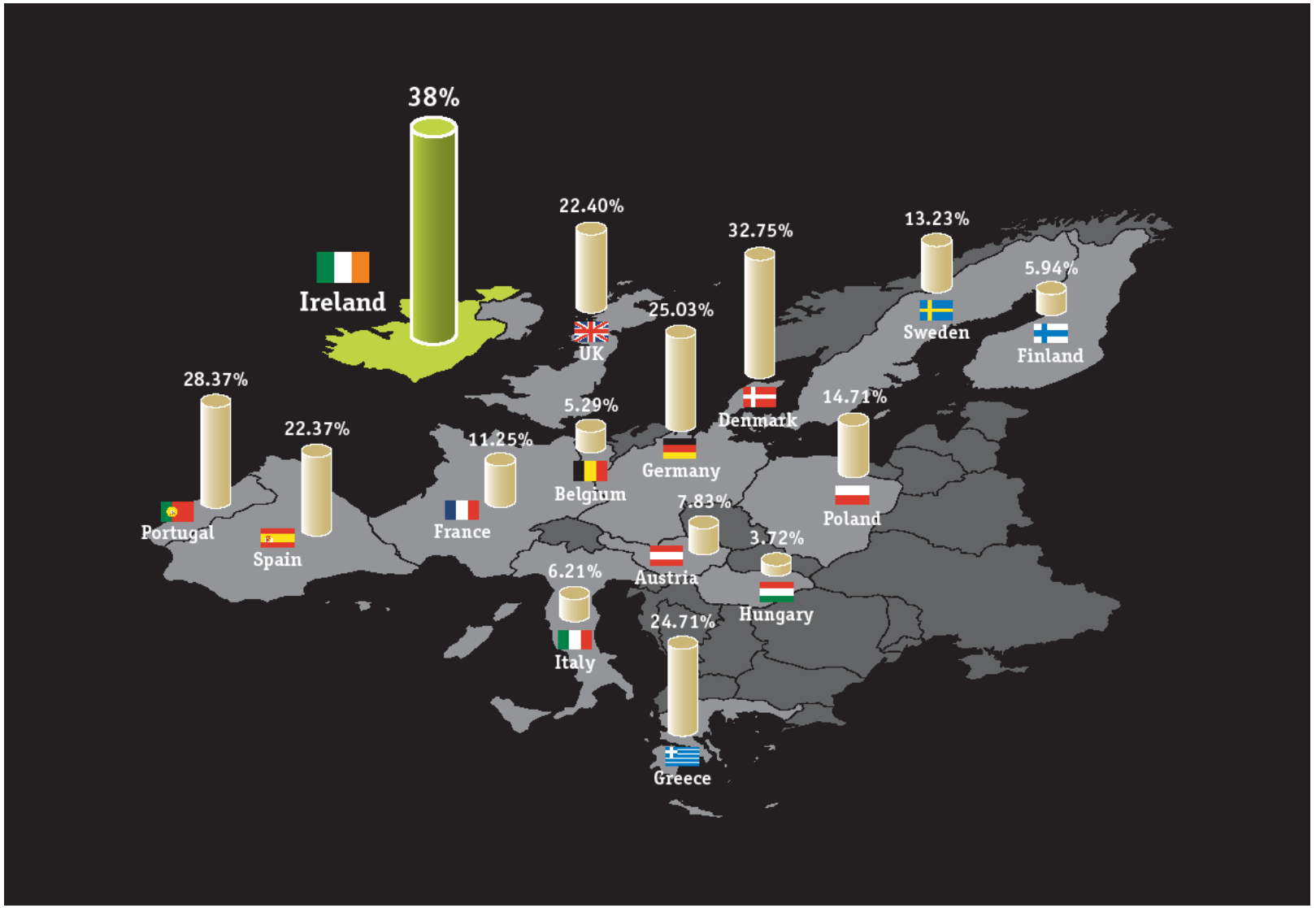
	10 m		25 m		50 m		100 m		200 m	
	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}
	> 8.0	> 600	> 8.5	> 700	> 9.0	> 800	> 10.0	> 1100	> 11.0	> 1500
	7.0-8.0	350-600	7.5-8.5	450-700	8.0-9.0	600-800	8.5-10.0	650-1100	9.5-11.0	900-1500
	6.0-7.0	250-500	6.5-7.5	300-450	7.0-8.0	400-600	7.5- 8.5	450- 650	8.0- 9.5	600- 900
	4.5-6.0	100-250	5.0-6.5	150-300	5.5-7.0	200-400	6.0- 7.5	250- 450	6.5- 8.0	300- 600
	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 6.0	< 250	< 6.5	< 300

Onshore 陆上

Offshore 海上

Sustainable development commission, Wind Power in the UK, 2005

EU Targets 20 20 20 - Wind energy as % of electricity
欧洲的“三个20%目标”-风电占总电量的比例



High Penetration
高比例

Wind Stats 2009
2009年风电统计

	Capacity 装机容量 (MW)#	Energy 发电量占比 (%)#	Wind capacity factor 容量系数 (%)*	System 电力系统
Denmark	3,480	19.3 %	22.8	Continental Europe & Nordel
Spain	19,149	14.4 %	24.8	Continental Europe
Portugal	3,616	15%	22.7	Continental Europe
Republic of Ireland	1,264	10.5 %	29.3	Island of Ireland
Germany	25,777	6.5 %	17.5	Continental Europe
United Kingdom	4,051	1.7%	26.1	England, Scotland, Wales & Island of Ireland
USA	35,086	1.9%	30 % (Wiser & Bollinger, 2010)	
China	26,010^	1%^^		

* Boccard, Nicolas,Capacity Factor of Wind Power: Realized Values vs. Estimates(October 25, 2008). Available at SSRN: http://ssrn.com/abstract=1285435

^ World Wind Energy Report 2009, WWEA

^^ http://energy-statistics.blogspot.com/2010/10/china-wind-energy-statistics.html

IEA, Wind Energy, Annual Report, 2009

Penetration metrics
比例指标

- **Capacity penetration (%)** - is the installed capacity of wind as a percentage of total installed generation. This measure gives a relative measure of the wind to the rest of the system but fail to capture the capacity factor or operational penetration levels. 容量比例（%）-是风电装机容量占总的装机容量的比率。这个指标可以测算风电容量在系统中的百分比，但不能反映容量系数，也不能得知实际发电的比例。
- **Energy penetration (%)** - is taken as the ratio of annual wind energy to annual total energy demand on the grid (excludes any net exports). This metric captures the capacity factor and operating penetration levels but as an average measure fails to account for the extremes. 能量比例（%）-是年度风力发电量占电网总能源需求的比率 （不包括净出口电量）。这个指标可以体现容量系数和实际发电情况，但作为一种平均测量不能反映极端情况。
- **Maximum instantaneous penetration (%)** - is the maximum observed ratio of wind energy to demand (including exports) over a defined period (typically one year) at any instant in time (typically on an hour/ half hourly intervals). This metric captures the extreme of wind generation relative to other generation as exports are included. This metric can be reported excluding exports but can be misleading and is defined here as **Maximum instantaneous penetration (excluding exports) (%)**. Both these metrics differ from the others as they are observed values which makes them somewhat more meaningful. 最大瞬间比例（%）-是特定一段时期内（通常为一年）任意一个瞬间 （通常是1小时/半小时 间隔）观测到最大的风力发电量与总电量需求的比值 (包括出口电量）。这种指标可以体现风力发电相对其他能源发电（包括出口电量）的极端情况。这个指标也可以对不含出口电量的结果汇报，为避免产生歧义，这种情况称为“最大瞬间穿透率（不包括出口电量)”。这两个指标是观测数值，这点与其他指标不同，在某种程度上更有参考意义。

Penetration metrics （cont.）
比例指标（续）

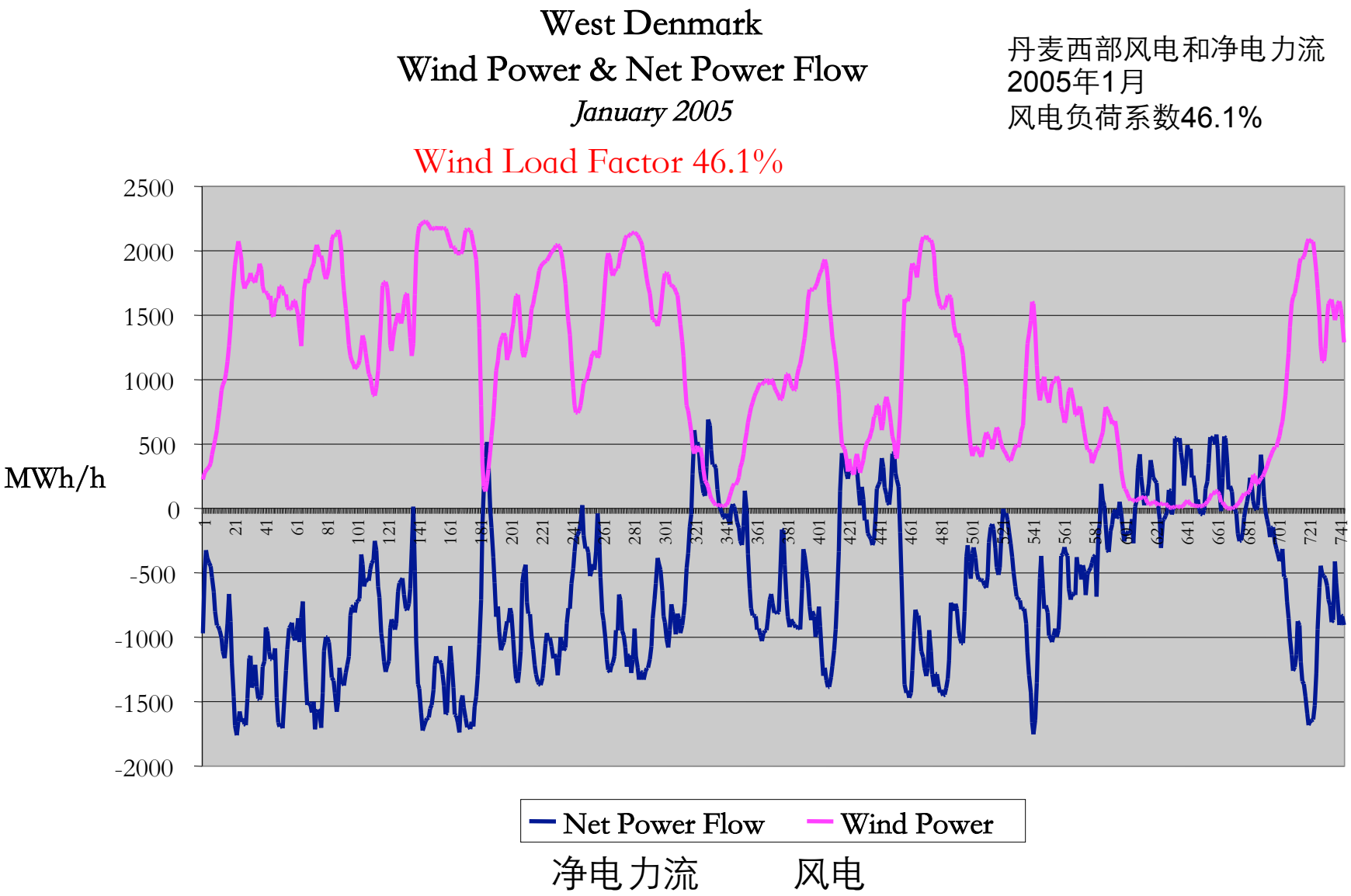
- **Maximum possible instantaneous penetration (%)** - is the ratio of maximum wind (i.e. installed capacity) to minimum demand, assuming zero exports. Maximum wind, minimum demand and zero exports is highly unlikely and this is truly an extreme value. Therefore Söder *et al.*, (2007) modified this metric to include maximum export defined here as the **Söder Metric** - the ratio of maximum wind (i.e. installed capacity) to minimum demand plus maximum export. 最大可能瞬间比例（%）-是假定出口电量为0的情况下，最大风电（装机容量）与最小电力需求的比值。最大风电、最小需求和0出口电量在很大程度上是不可能发生的，所以这是一个真正的极端值。因此Söder （2007）论文中修改了这个指标来包括最大出口电量，这里定义为**Söder指标**-即最大风电（装机容量）同最小电力需求与最大出口电量之和的比值。

Score card
分值表

	Capacity pen. (%)	Energy pen. (%)	Max. inst. pen. (no exports) (%)	Max. possible inst. pen. (%)	*Söder Metric* (%)
Ireland	16.36	10.00	> 50	81.82	67.92
Iberian Peninsula	20.88	15.00	> 55	99.30	93.76
West Denmark	34.95	30.00	>100	195.71	59.05
ERCOT	11.40	8.00	> 25	27.43	26.61
South Australia	22.06	20.00	86	118.63	67.08
Tasmania	5.06	5.00	17 %	18.04	9.96
			> 40	57.14	
Crete	16	15.1			57.14

Penetration Metrics for Ireland, Iberian Peninsula, West Denmark,
Electric Reliability Council of Texas (ERCOT), South Australia and Tasmania and Crete.
http://www.eirgrid.com, http://www.ren.pt, http://www.ree.es, http://www.energinet.dk, http://www.ercot.com, http://www.aemo.com.au, http://www.dei.com.gr

Rest of Europe integrates West Danish Wind
丹麦西部风电并入欧洲其他地区电网



Wind Installed in Republic of Ireland
爱尔兰的风电装机

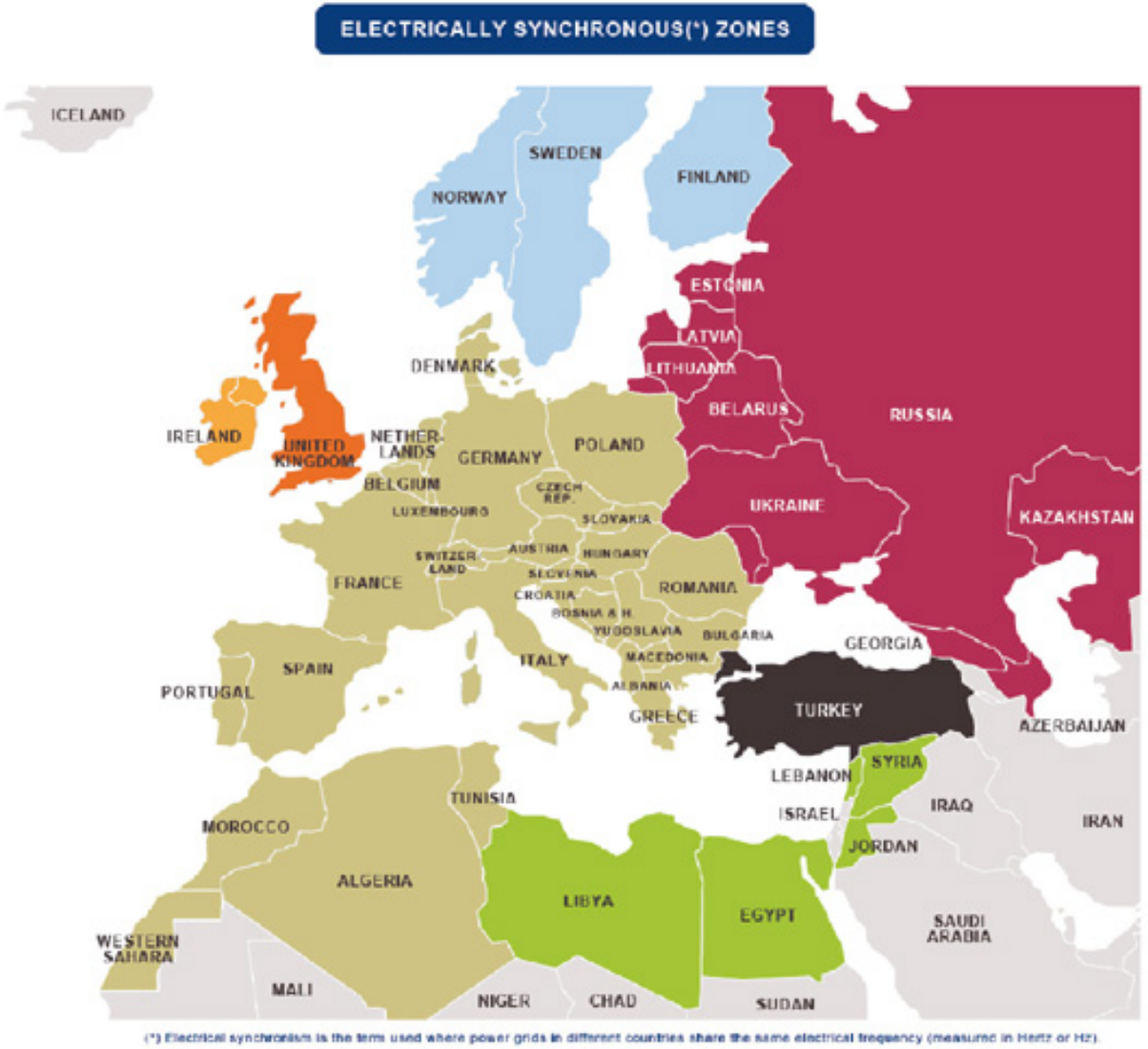
MW

1600
1400
1200
1000
800
600
400
200
0

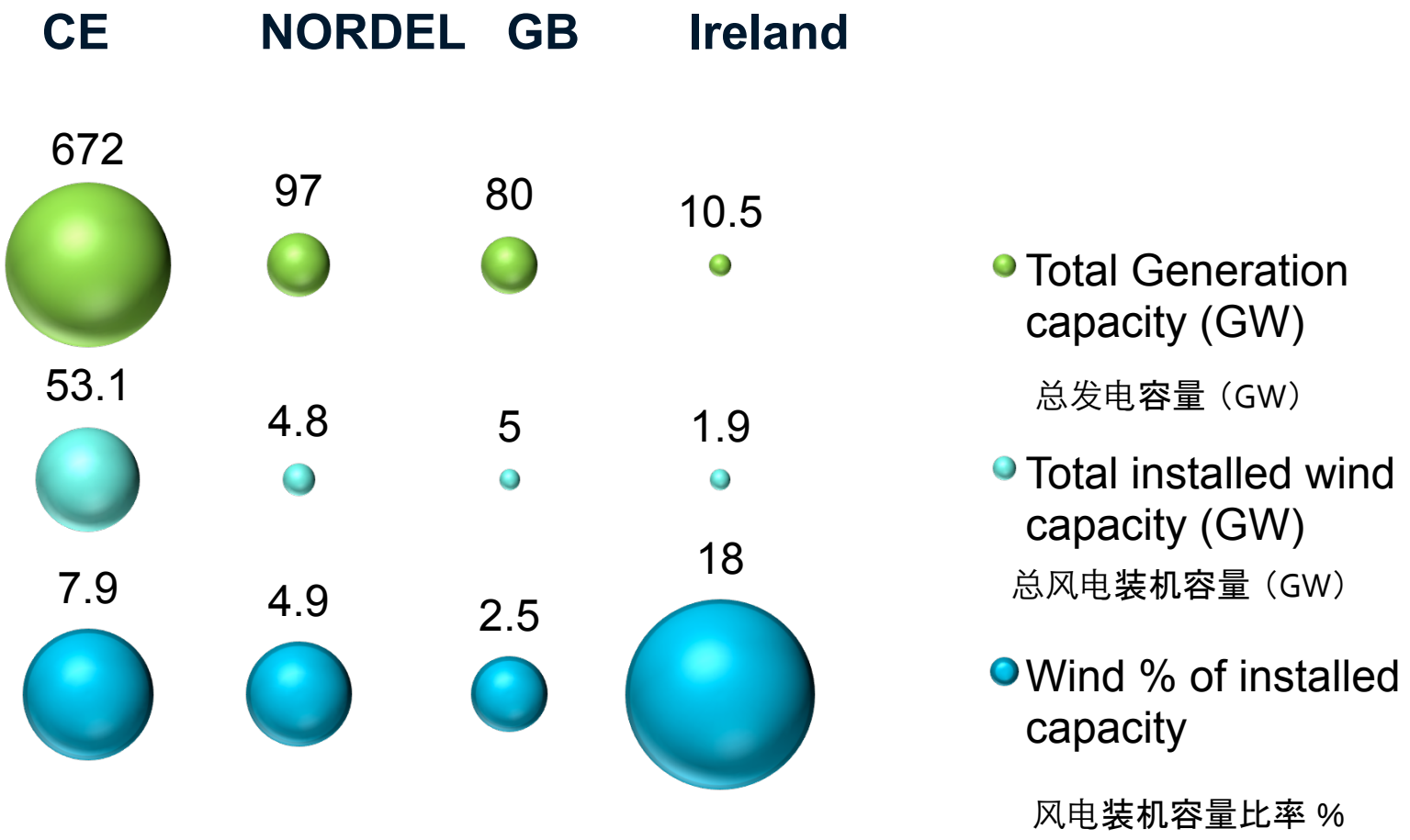
1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010

Source: EirGrid

Synchronous grids in Europe
欧洲同步电网



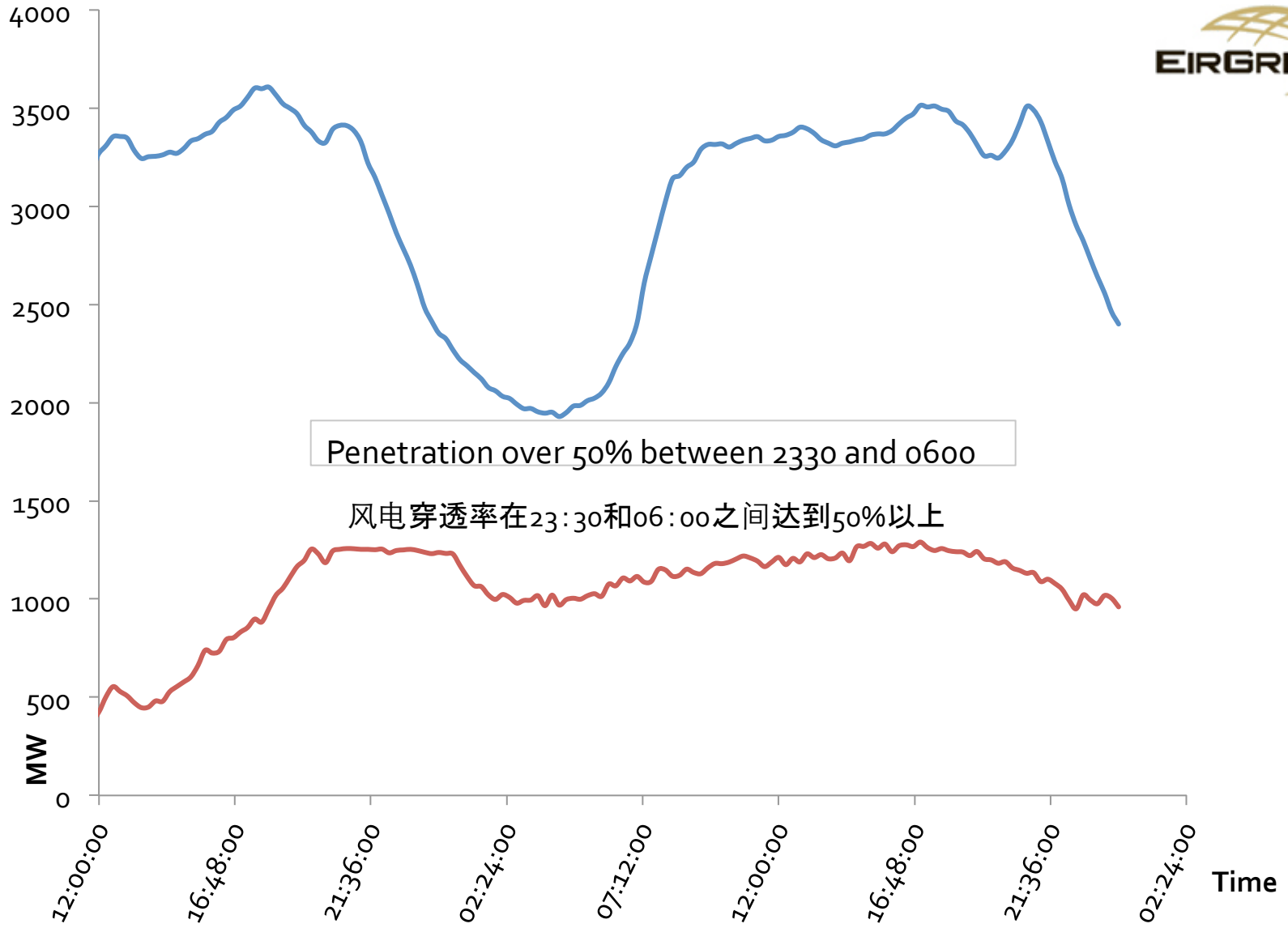
Ireland: Very High Wind Penetration
爱尔兰：特高风电比例



Figures for end 2008

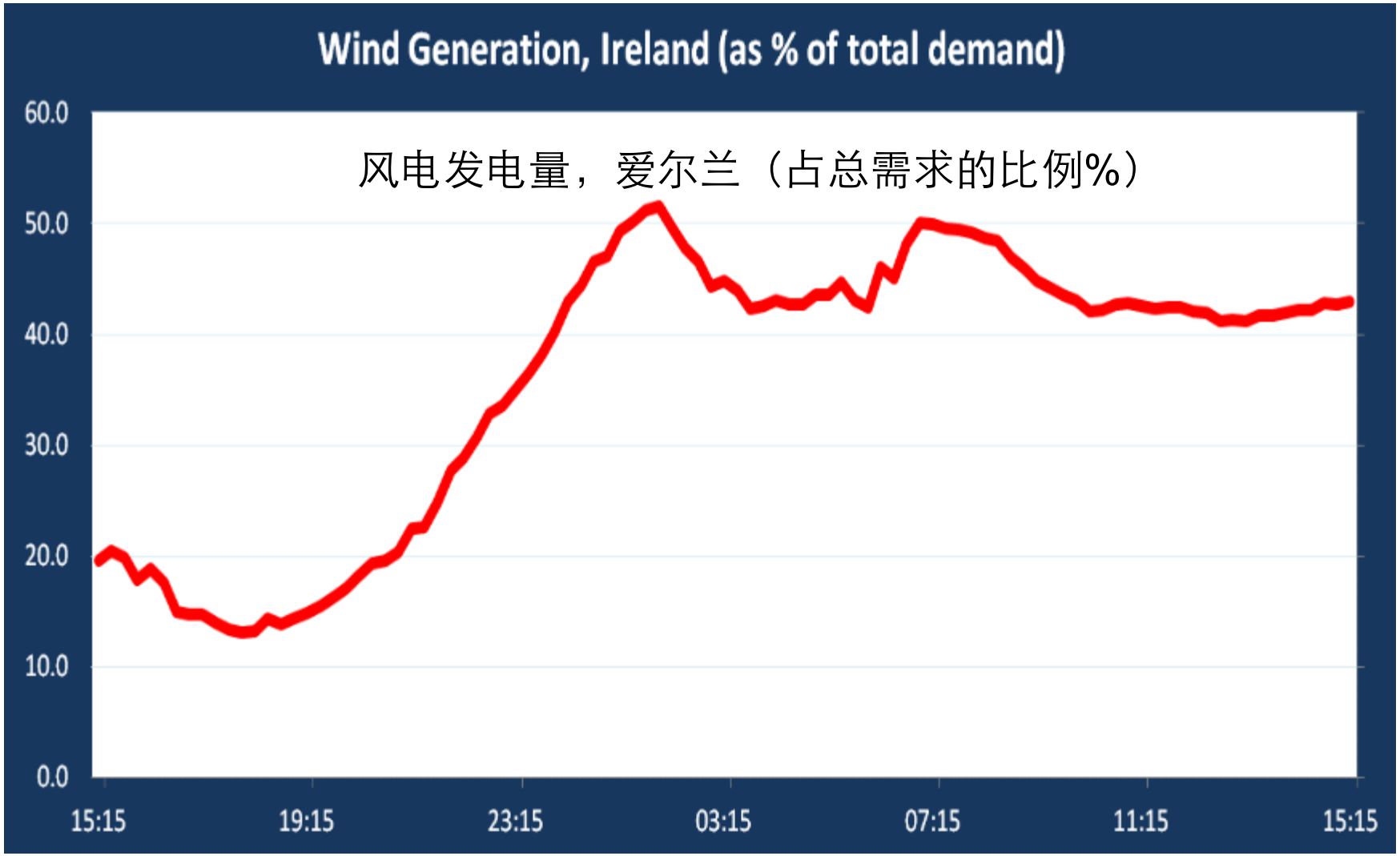
Source: Global wind energy outlook 2008, EirGrid, UK National Grid, NORDEL, Eurelectric

World Record Wind Penetration in Ireland
爱尔兰风电比例创世界记录

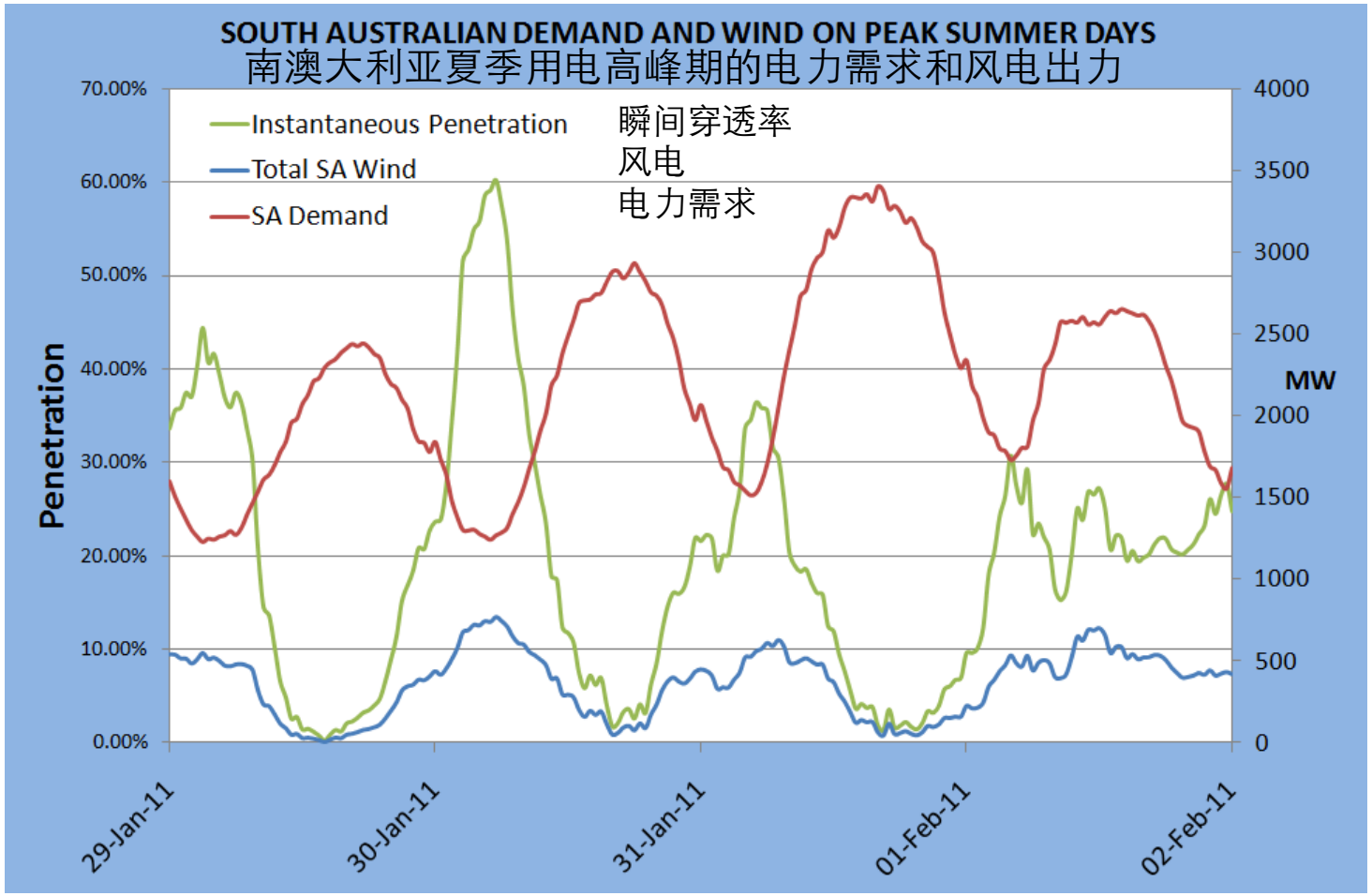


Sept 6 & 7th 2011

http://erc.ucd.ie/RealTimeData/chartsirish.html Nov 25/26, 2011



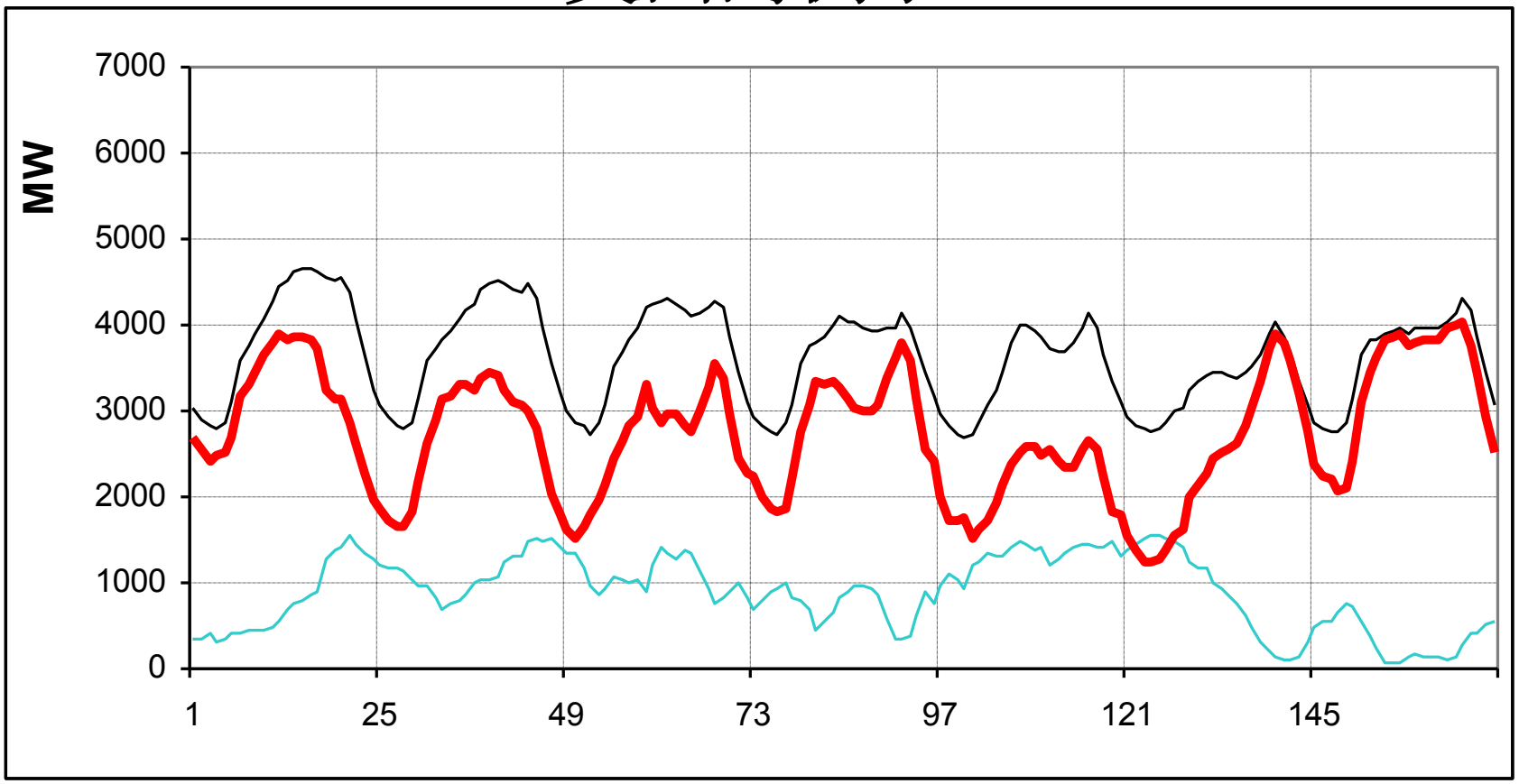
A good example in Australia
澳大利亚成功案例



南澳大利亚连续四天的风电、电力需求和瞬间穿透率（%，不计出口电量）

Four days of wind and demand South Australia. Instantaneous penetration (excluding exports) (%) also shown (http://aemo.com.au).

Another example from USA
美国的例子



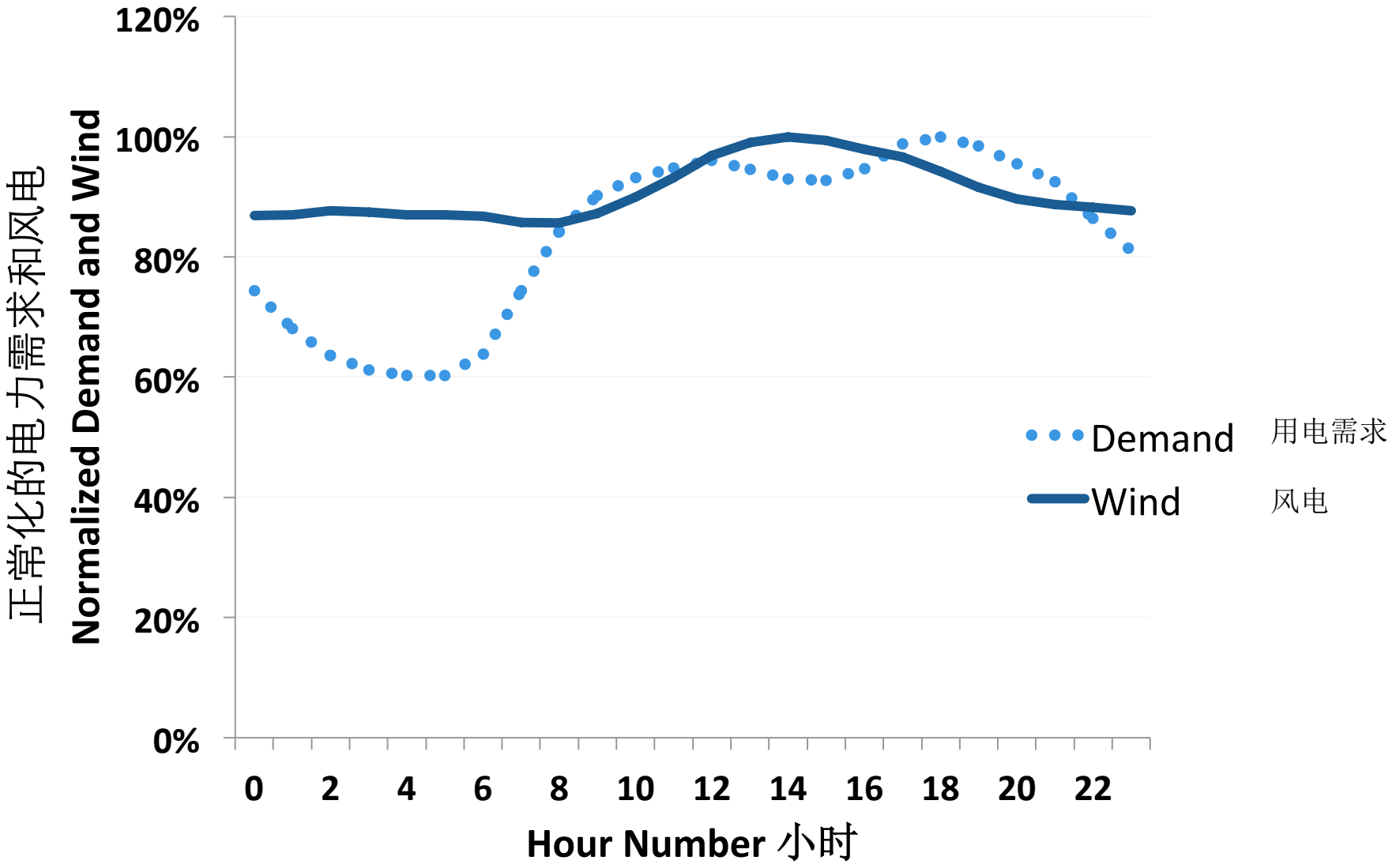
Hourly Record: 55.6% October 9, 2011; Daily Record: 37.0% October 8, 2011

小时记录:55.6% 2011/10/9
日记录:37% 2011/10/8

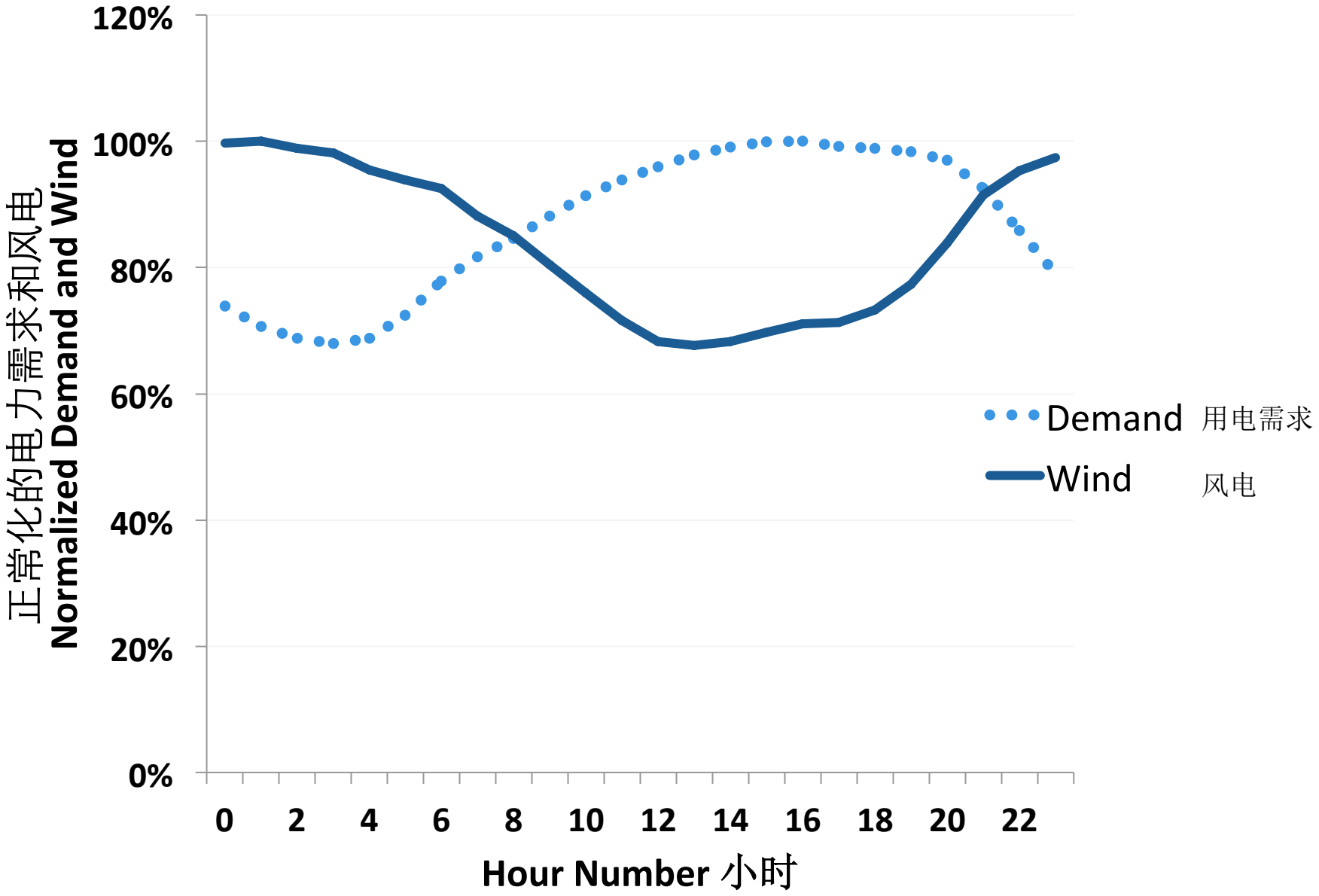
Public Service of Colorado - October 4-10, 2011

Dance partners
舞蹈伙伴

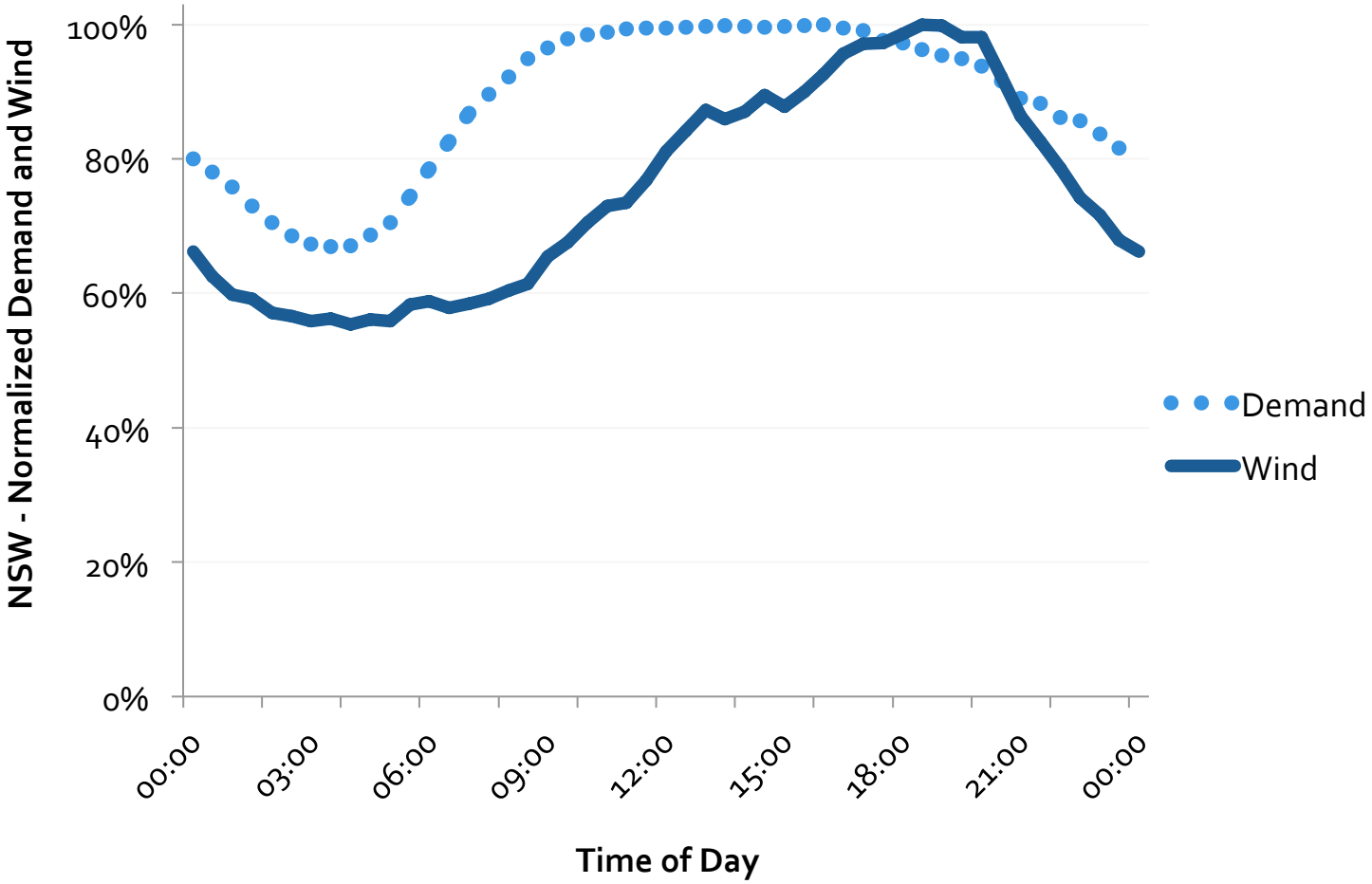
Daily wind and demand profile Ireland
爱尔兰日风电和负荷曲线



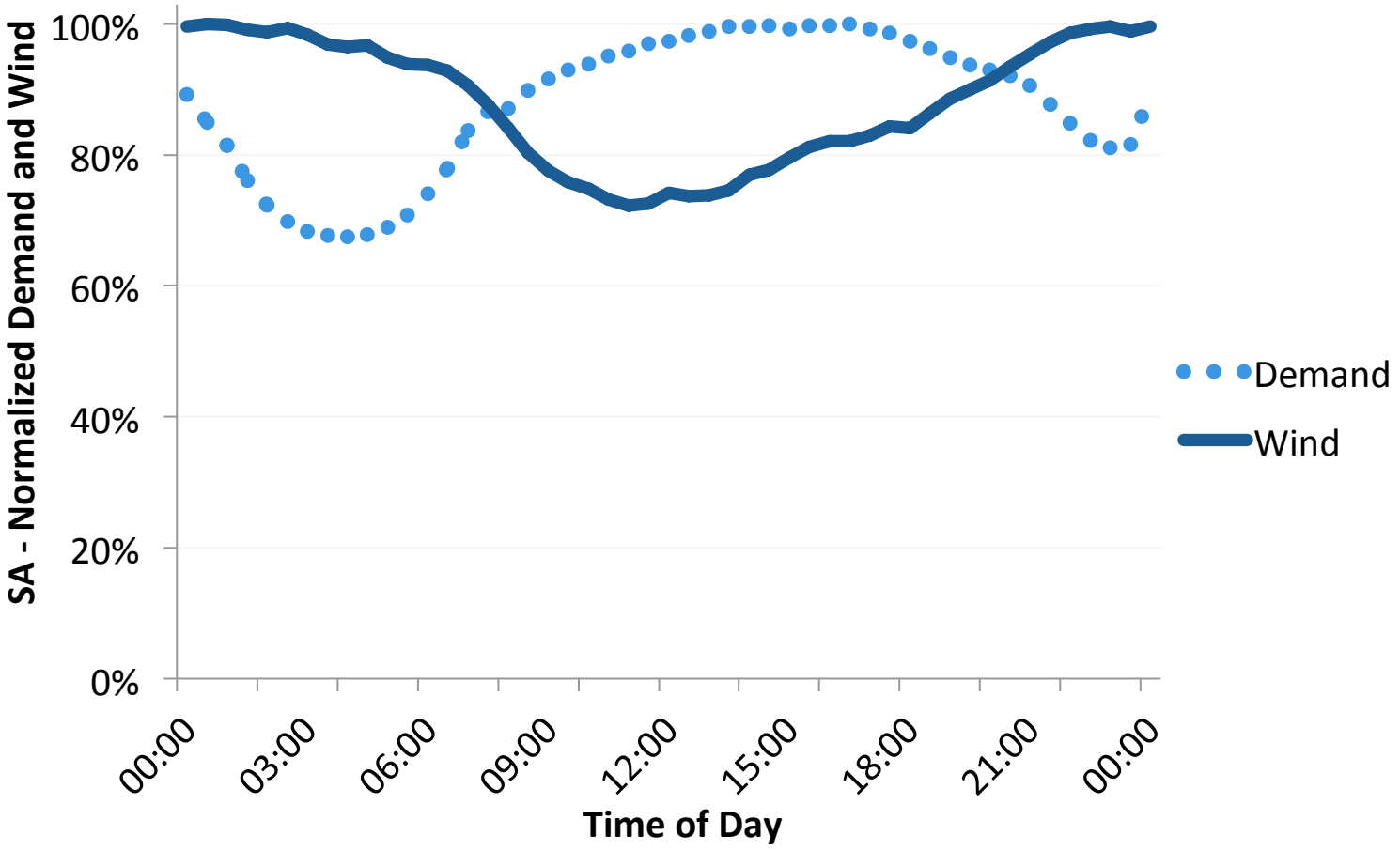
Daily wind and demand profile Texas (ERCOT)
得克萨斯州日风电和负荷曲线（ERCOT）



Daily wind and load profile NSW (Australia)
澳大利亚新南威尔士风电和负荷曲线

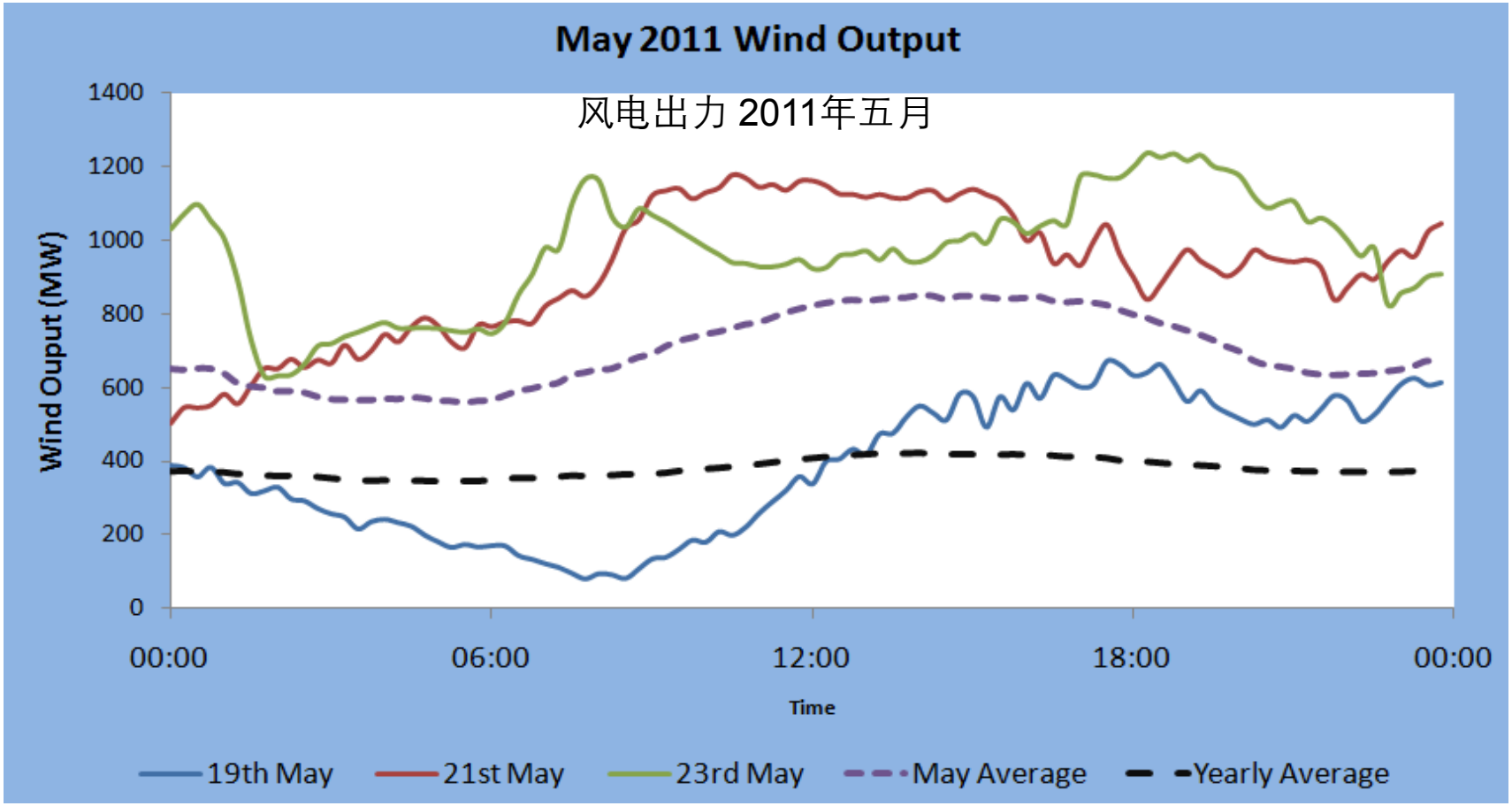


Daily wind and load profile Tasmania (Australia)
塔斯马尼亚（澳大利亚）日风电和负荷曲线



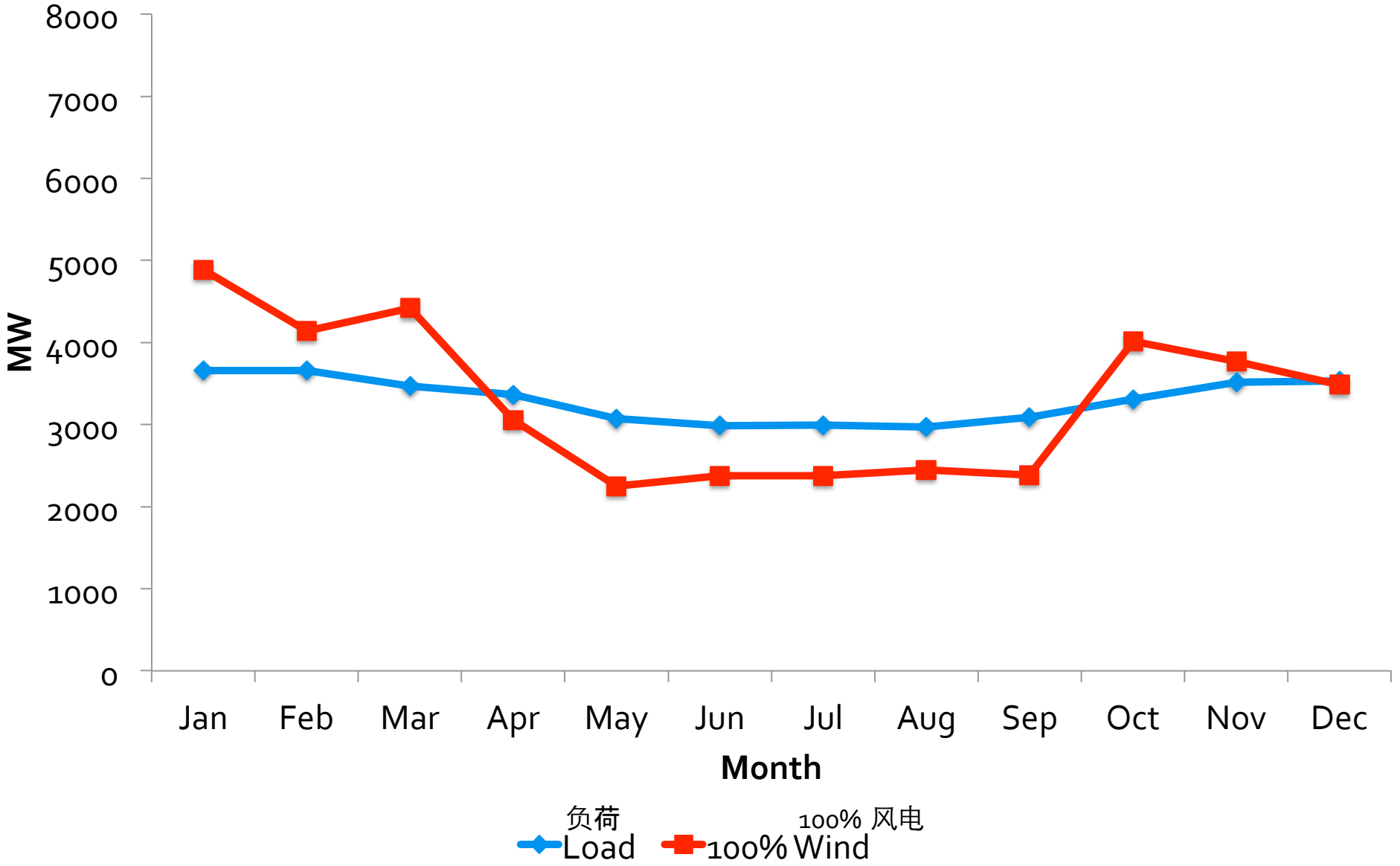
Variability
变化性

Variability 变化性

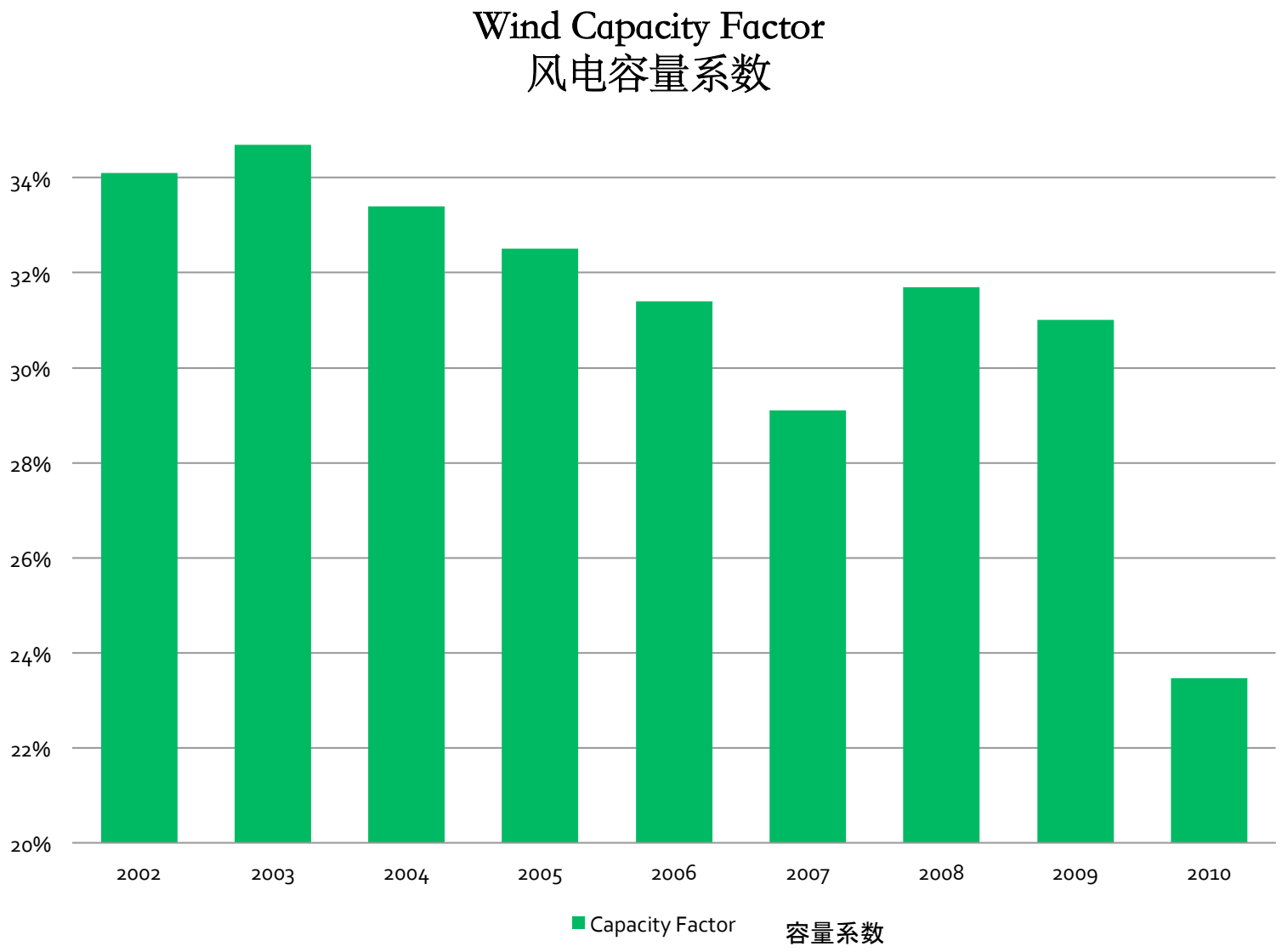


Wind power output for Ireland, three days in May 2011,
May average and typical yearly average (http://www.eirgrid.com)
爱尔兰风电出力，2011年五月三天（19，21，23），五月平均和典型年平均

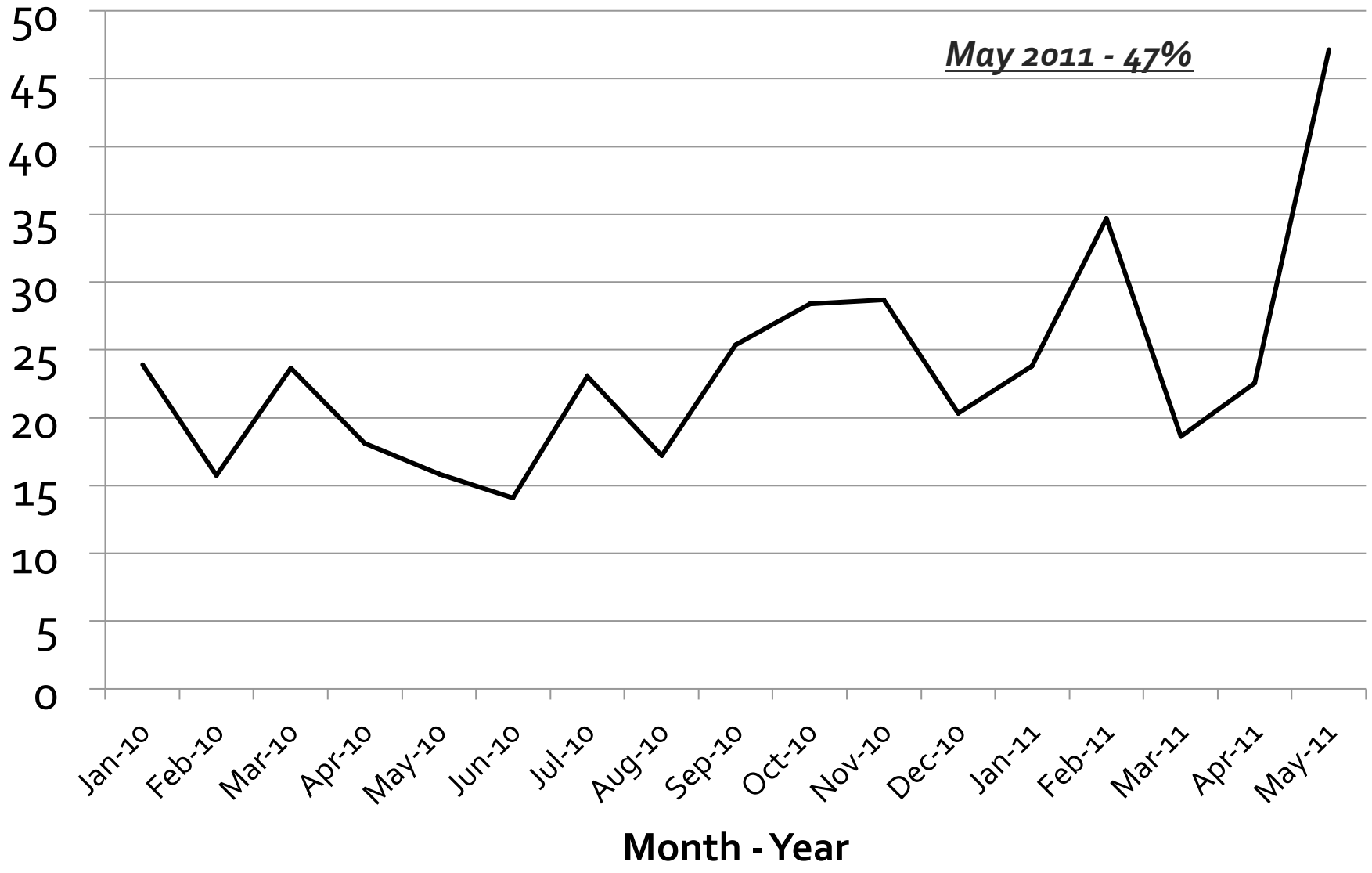
Seasonally 季节性变化



Yearly 年变化


Wind Capacity Factor
风电容量系数
34%
32%
30%
28%
26%
24%
22%
20%
2002
2003
2004
2005
2006
2007
2008
2009
2010
Capacity Factor
容量系数

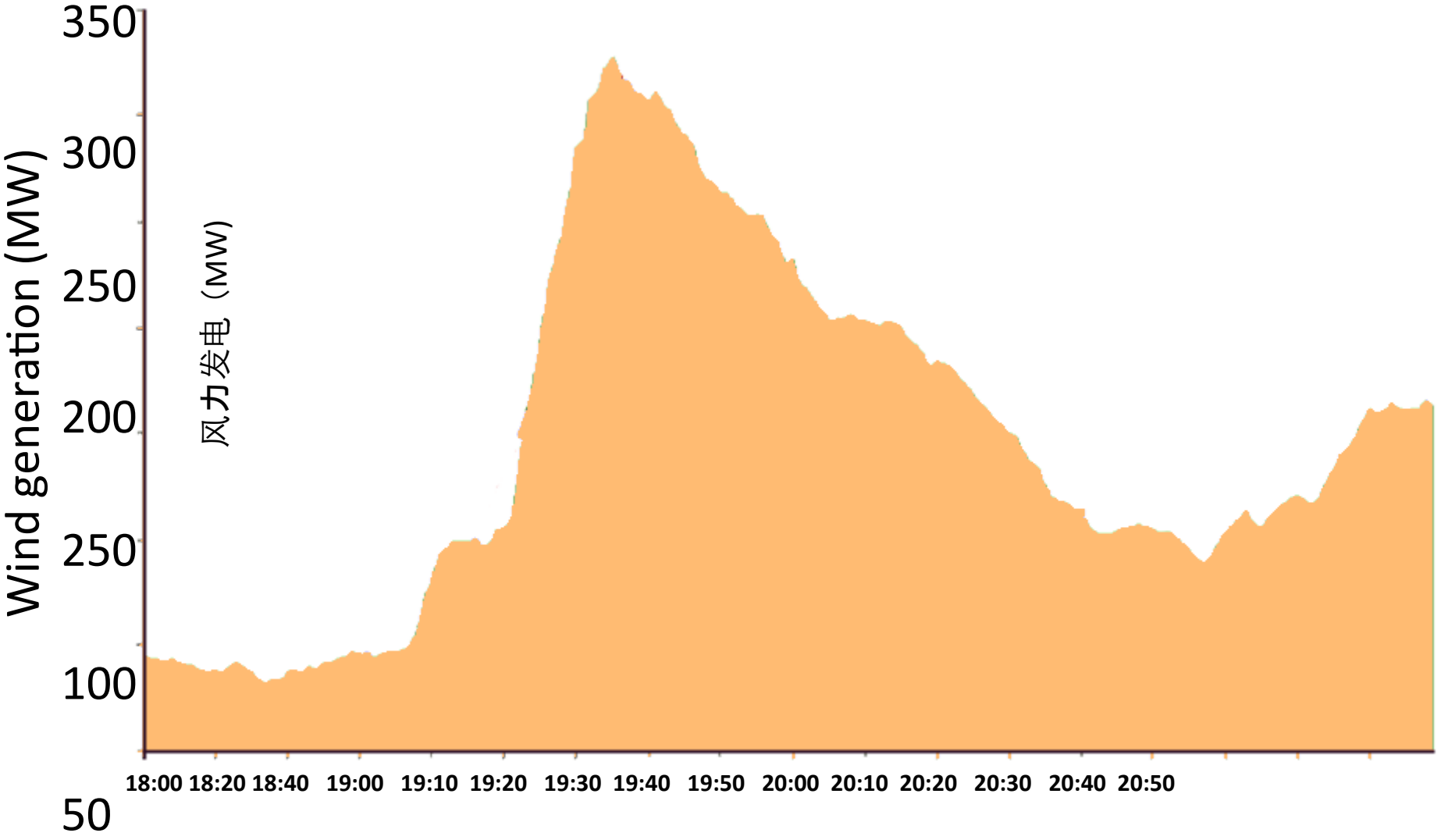
Monthly　月变化


May 2011 - 47%
50
45
40
35
30
25
20
15
10
5
0
Jan-10
Feb-10
Mar-10
Apr-10
May-10
Jun-10
Jul-10
Aug-10
Sep-10
Oct-10
Nov-10
Dec-10
Jan-11
Feb-11
Mar-11
Apr-11
May-11
Month - Year

Flexibility
灵活性

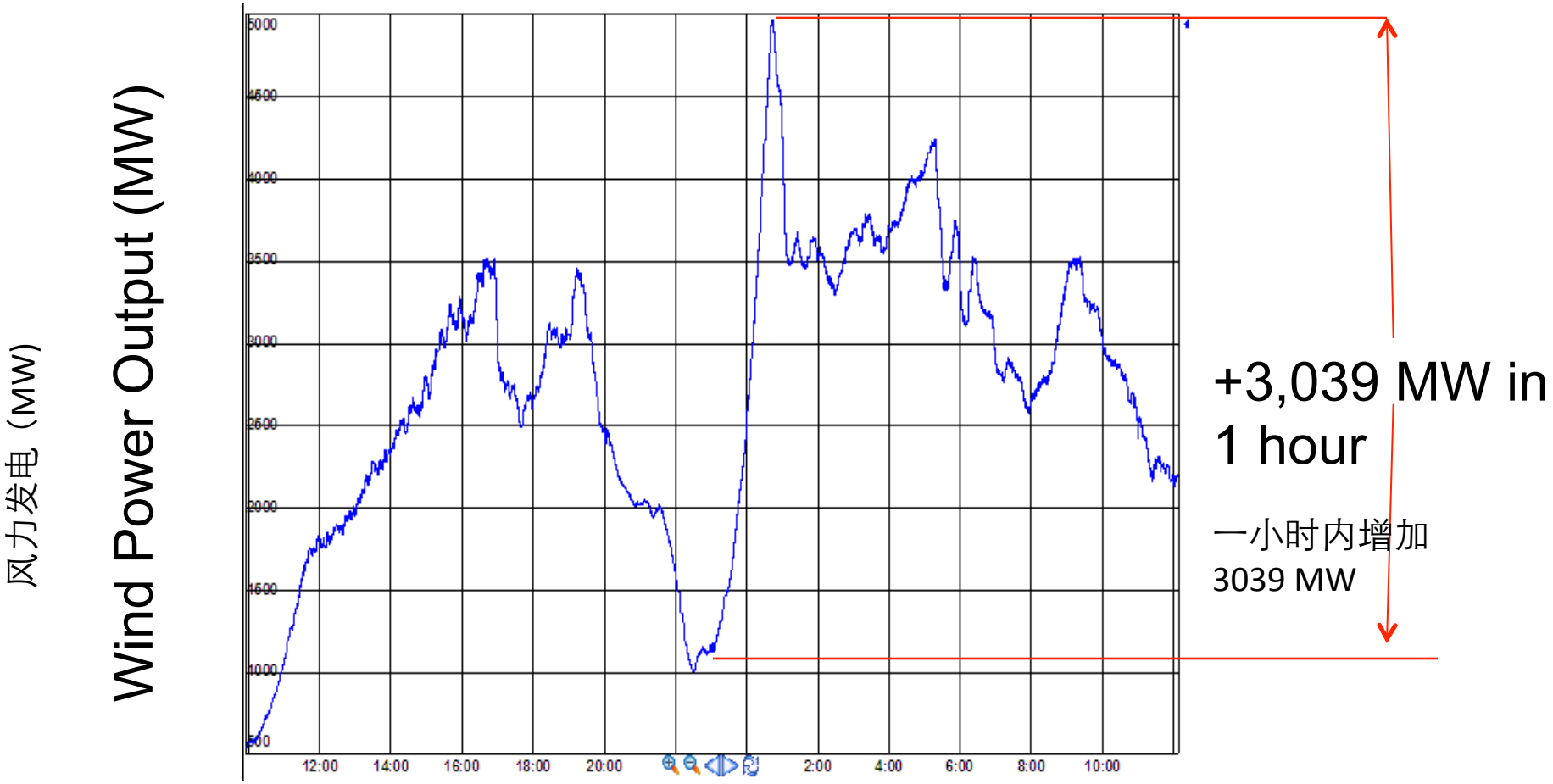
Ramp AESO - 30th July 2009

爬坡：阿尔伯塔省电力运行机构 (*AESO*) -2009/7/30

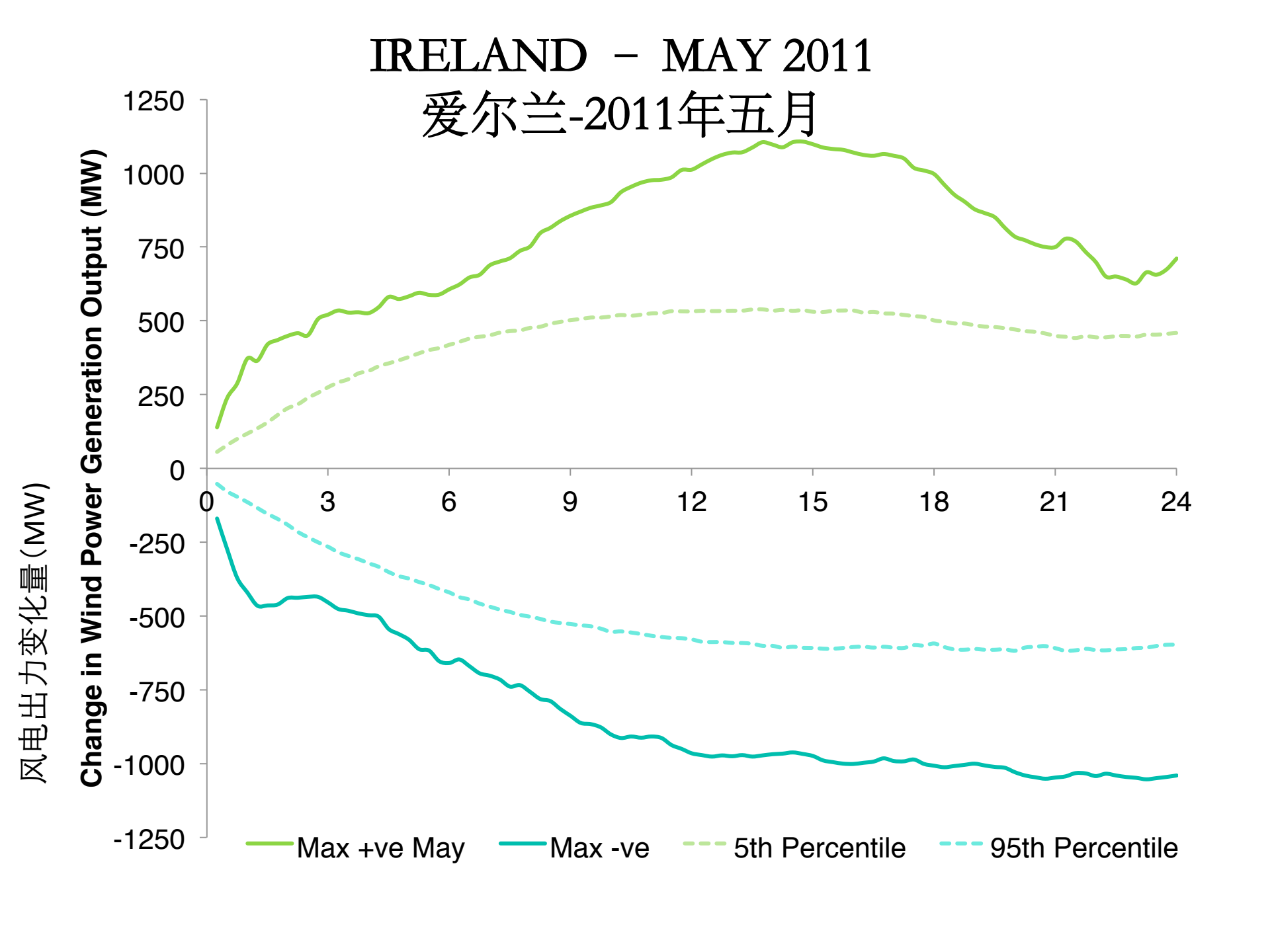


Source: http://www.nerc.com/docs/pc/ivgtf/IVGTF_Task_1_4_Final.pdf

Ramp ERCOT - 18/19th April 2009
爬坡：得克萨斯电力可靠性委员会-2009/4/18-19

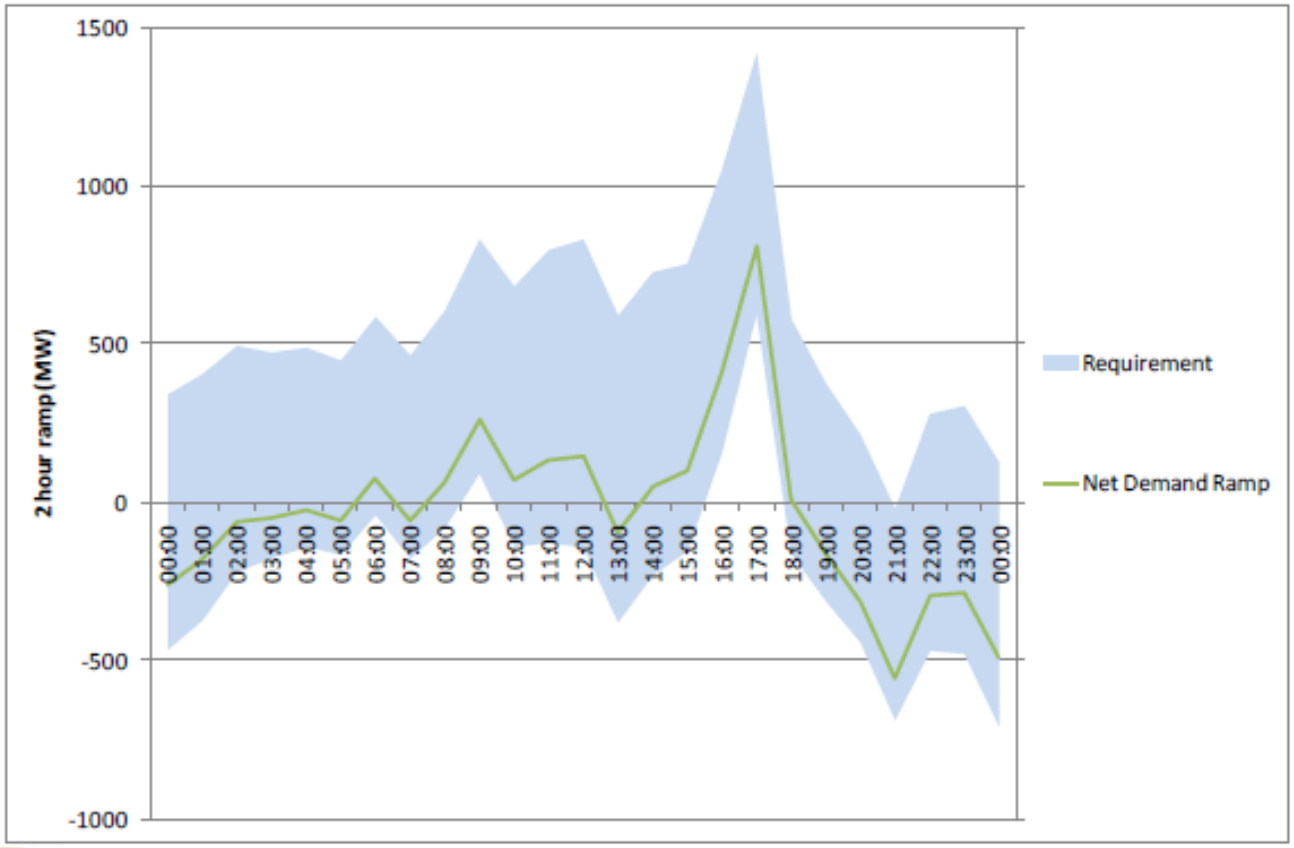


Source: http://www.nerc.com/docs/pc/ivgtf/IVGTF_Task_1_4_Final.pdf


IRELAND – MAY 2011
爱尔兰-2011年五月
Change in Wind Power Generation Output (MW)
风电出力变化量(MW)
1250
1000
750
500
250
0
-250
-500
-750
-1000
-1250
0
3
6
9
12
15
18
21
24
Max +ve May
Max -ve
5th Percentile
95th Percentile

Ramping Online Assessment 爬坡在线评估

两小时爬坡(MW)



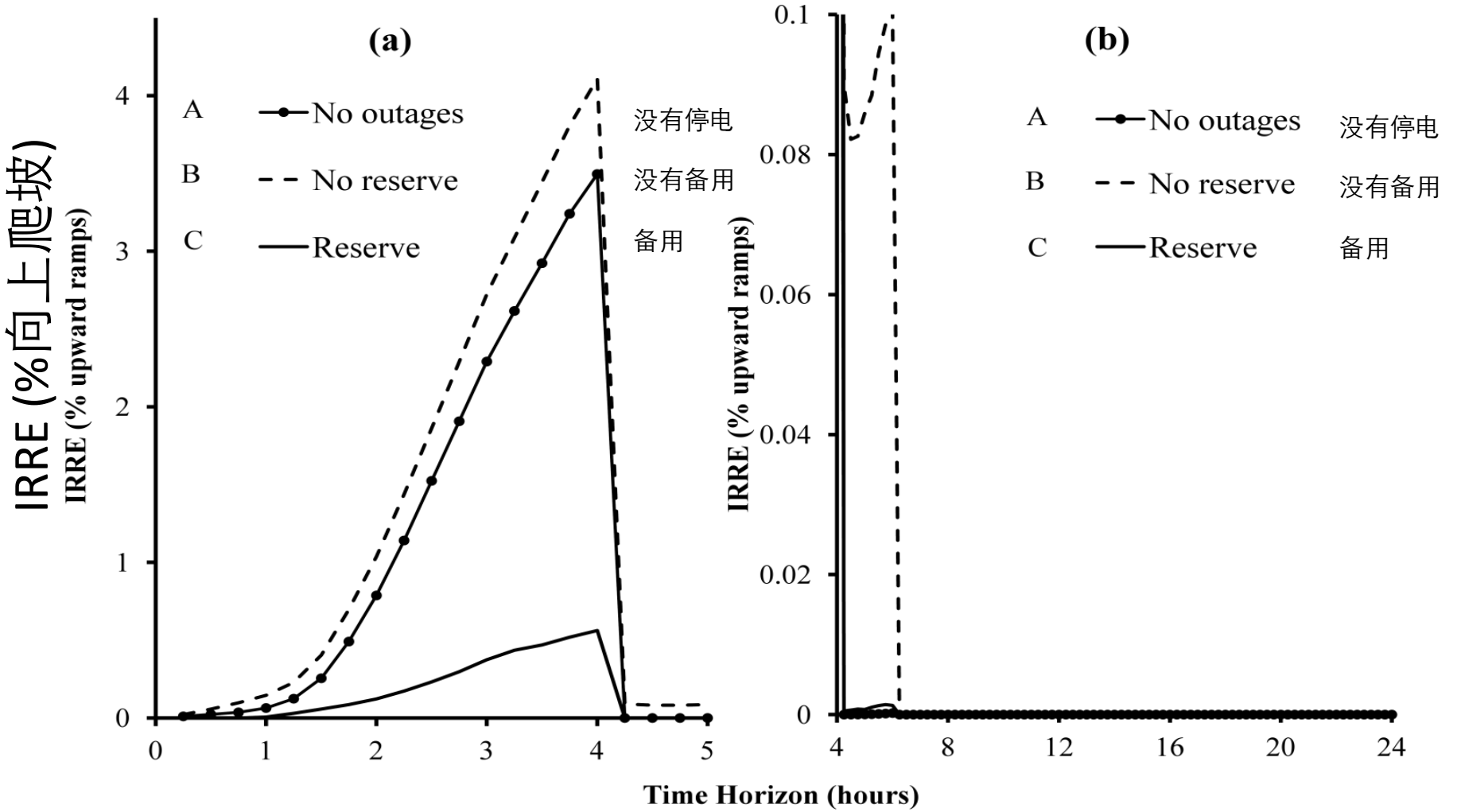
需求

净负荷爬坡

EIRGRID

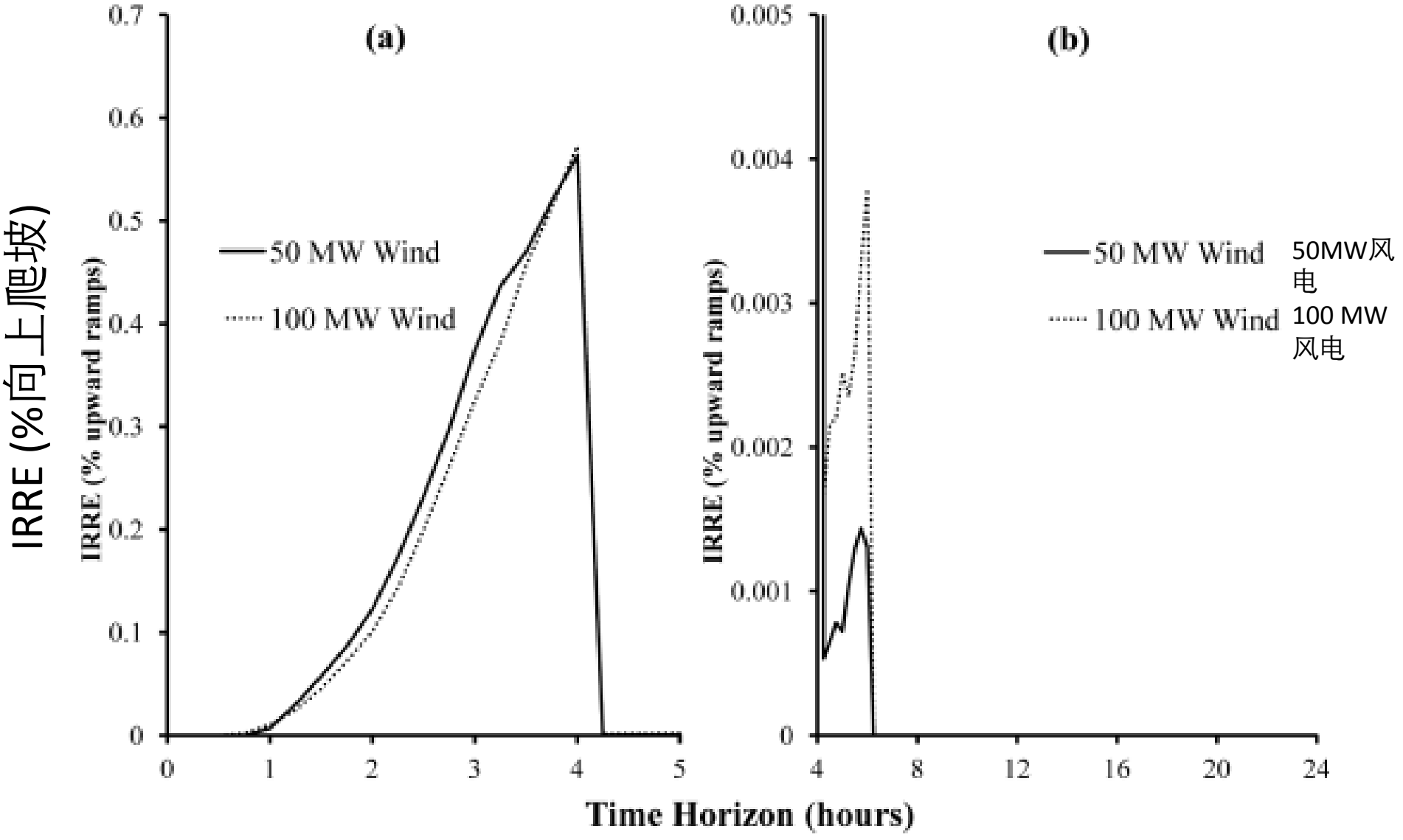
SONI
System Operator for Northern Ireland

Flexibility metrics 灵活性指标

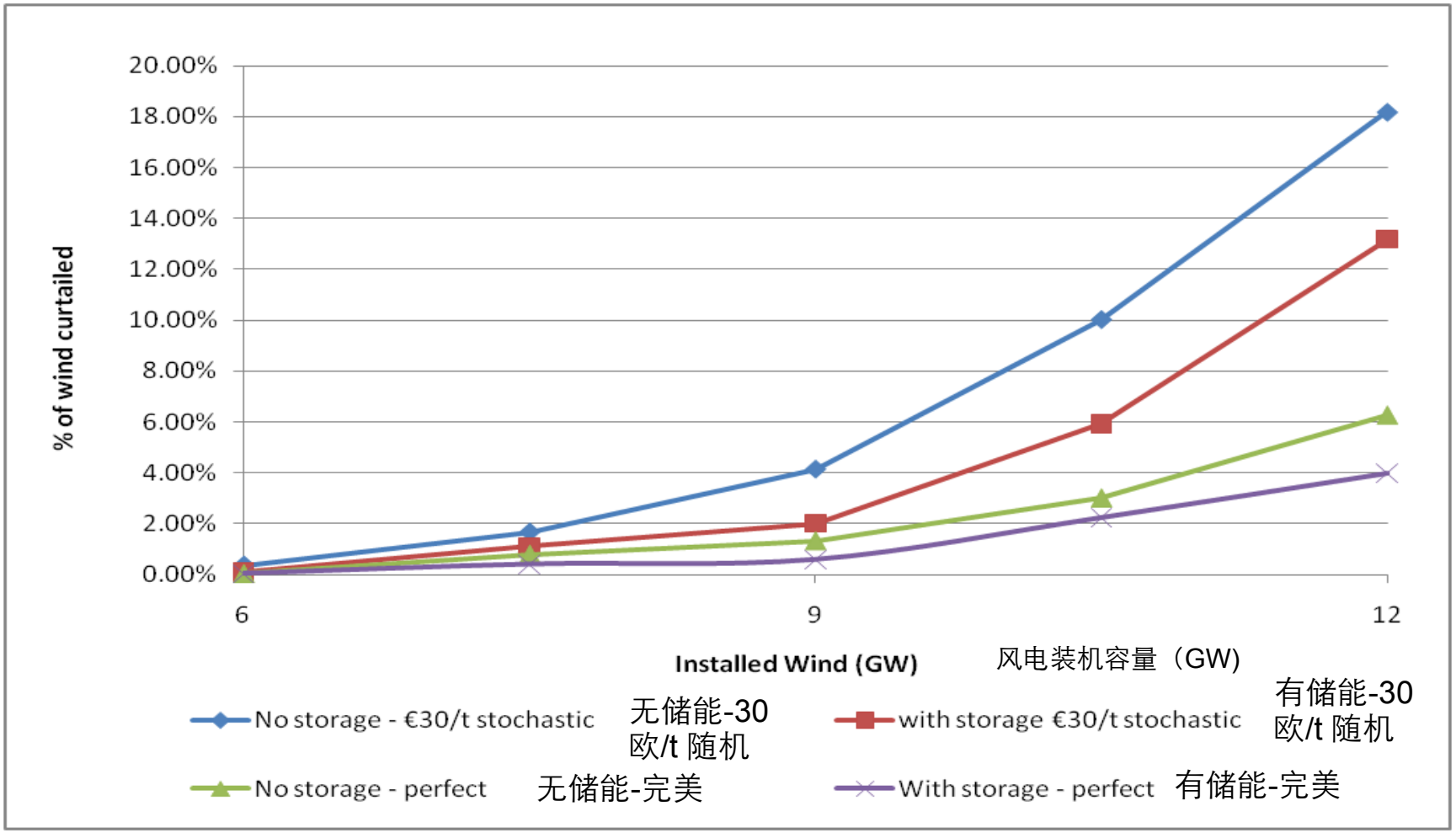


Lannoye, Flynn & O'Malley, *Evaluating Power System Flexibility*, IEEE Trans. Power Systems, in press, 2011

Metrics: Increased wind generation 指标：增加的风电

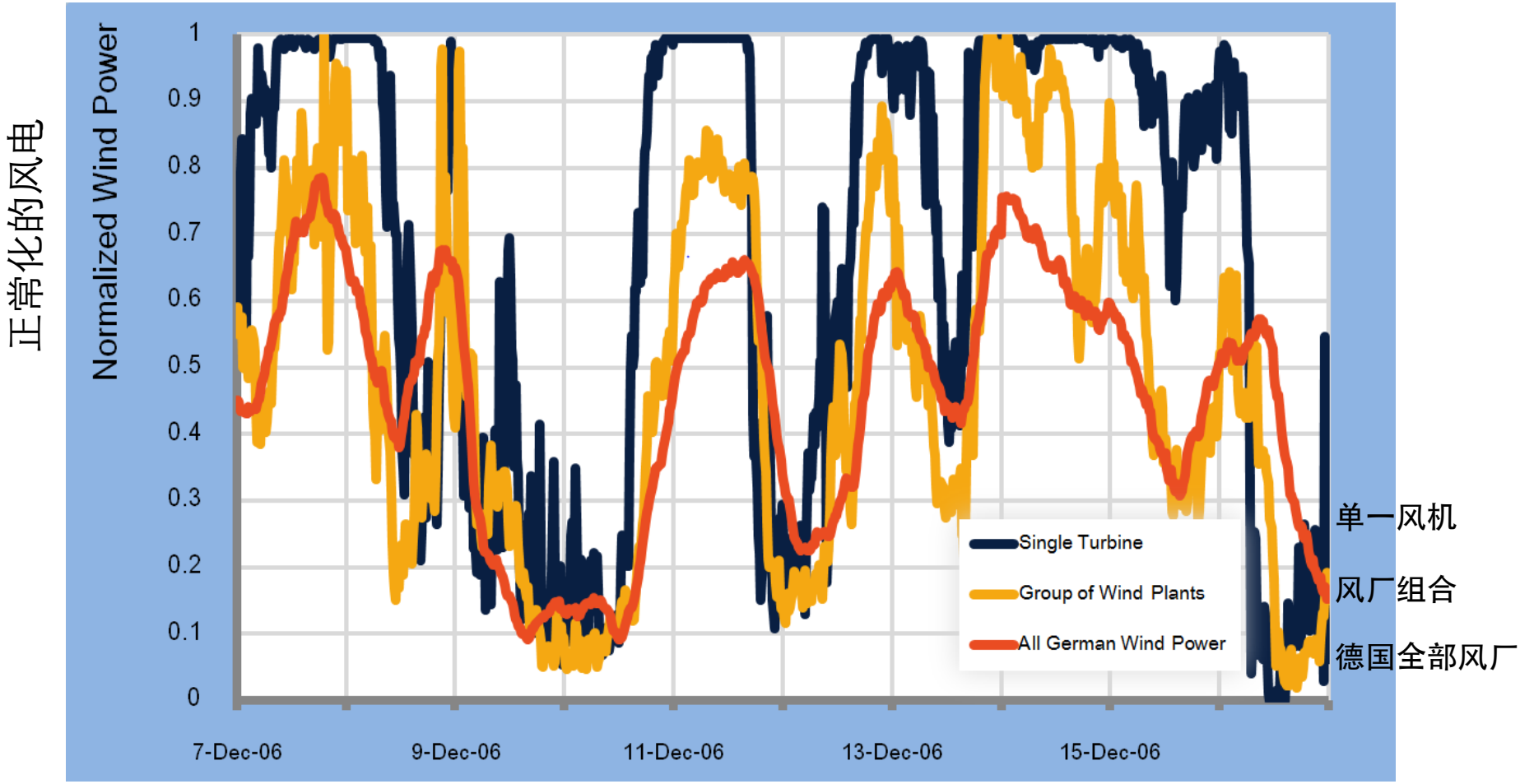


Storage, curtailment and forecasting
储能、弃风、预测



Tuohy, A. and O'Malley, M.J., "Pumped Storage in Systems with Very High Wind Penetration", *Energy Policy*, Vol. 39, pp. 1965-1974, 2011. "高风电穿透率系统中的抽水蓄能"

Aggregation 加合效应



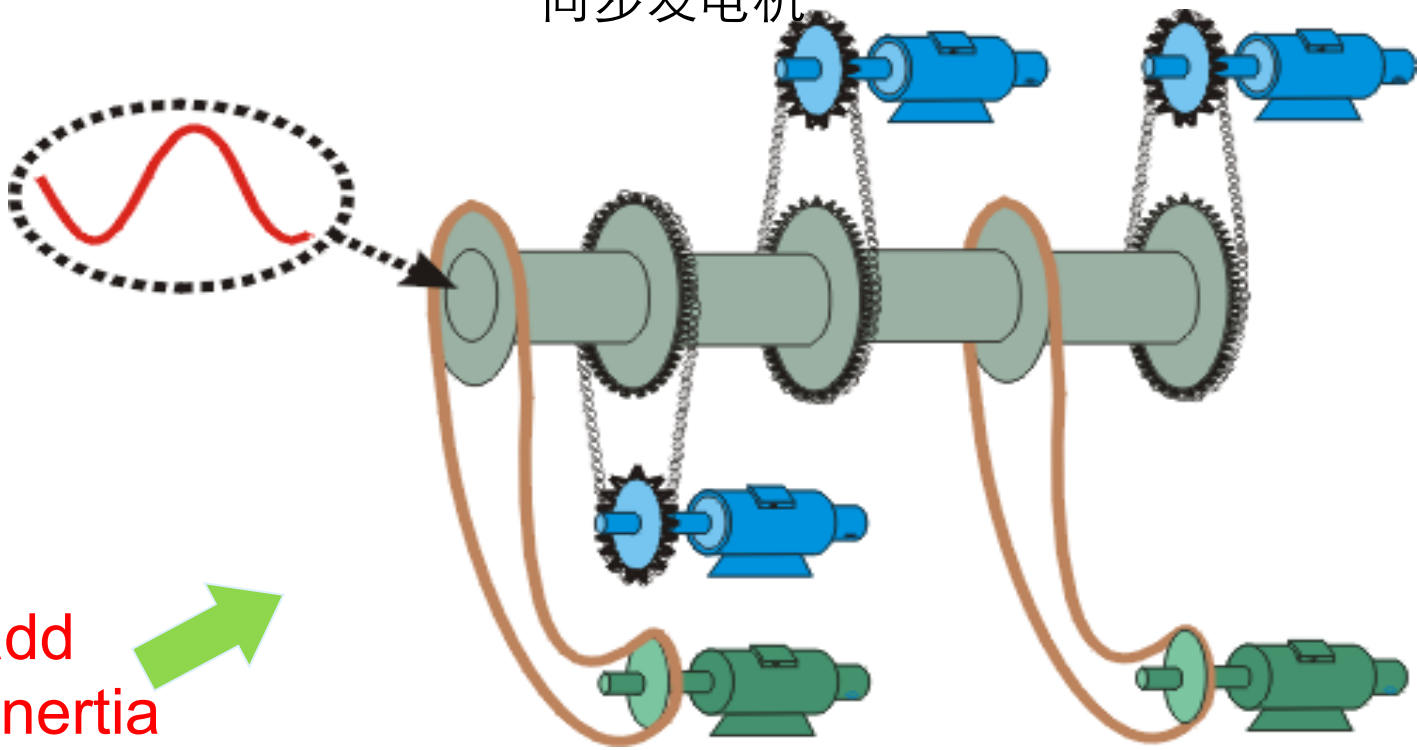
Impact of aggregation on wind variability. Time series of wind power output normalised for a single wind turbine, a group of wind power plants, and all wind power plants in Germany over a 10 day period in 2006(Wiser et al., 2011). 加合对风电变化性的影响。单个风机、风厂组合和德国全部风厂在2006年连续10天中风电出力的时间序列分析。

Asynchronous generation technologies are changing the grid fundamentally
异步发电技术正在使电网发生根本性改变

Simple Electricity Grid Model
简单电网模型

Synchronous generator
同步发电机

50/60 Hz

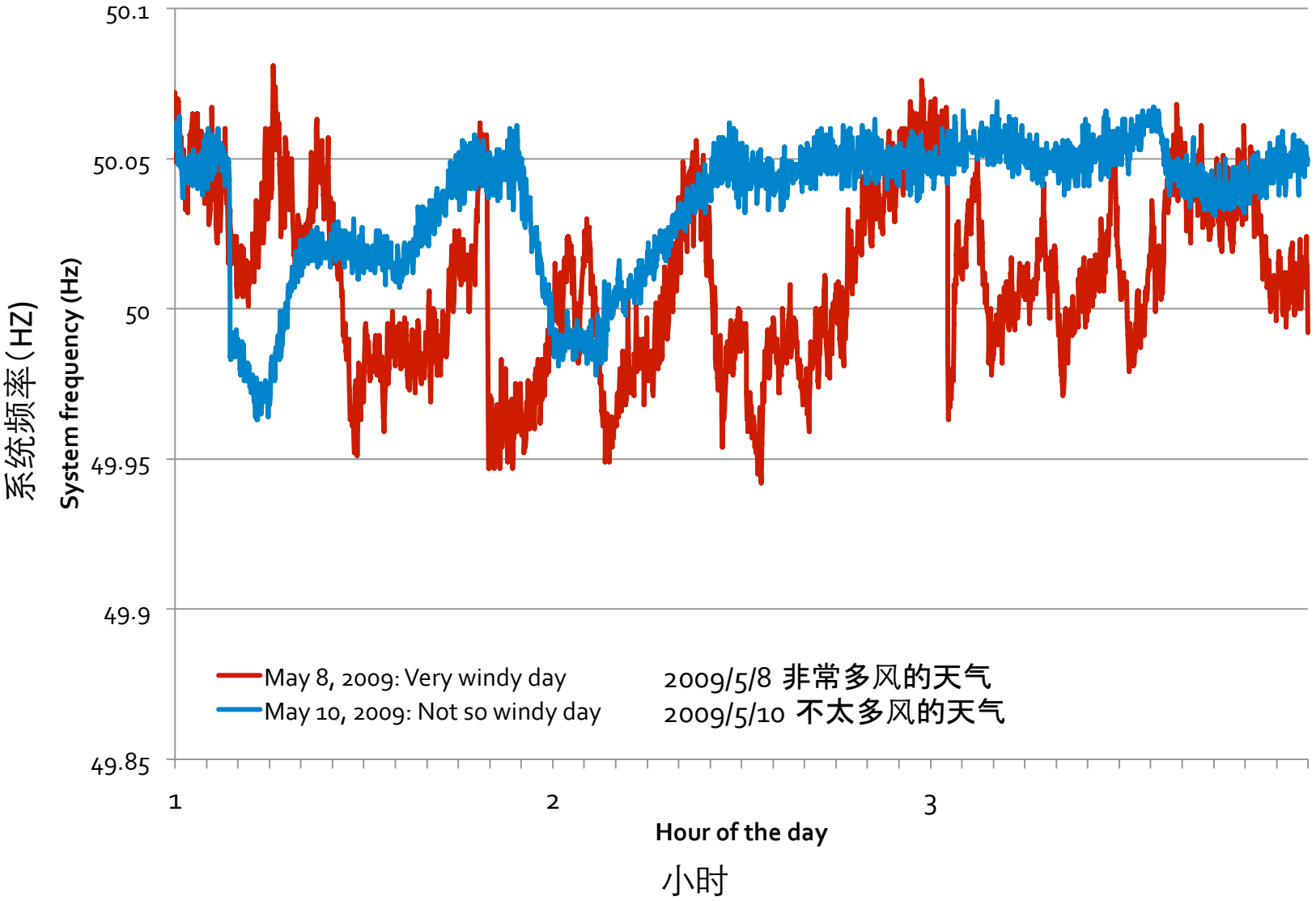


Does not add
to system inertia
不增加系统惯性

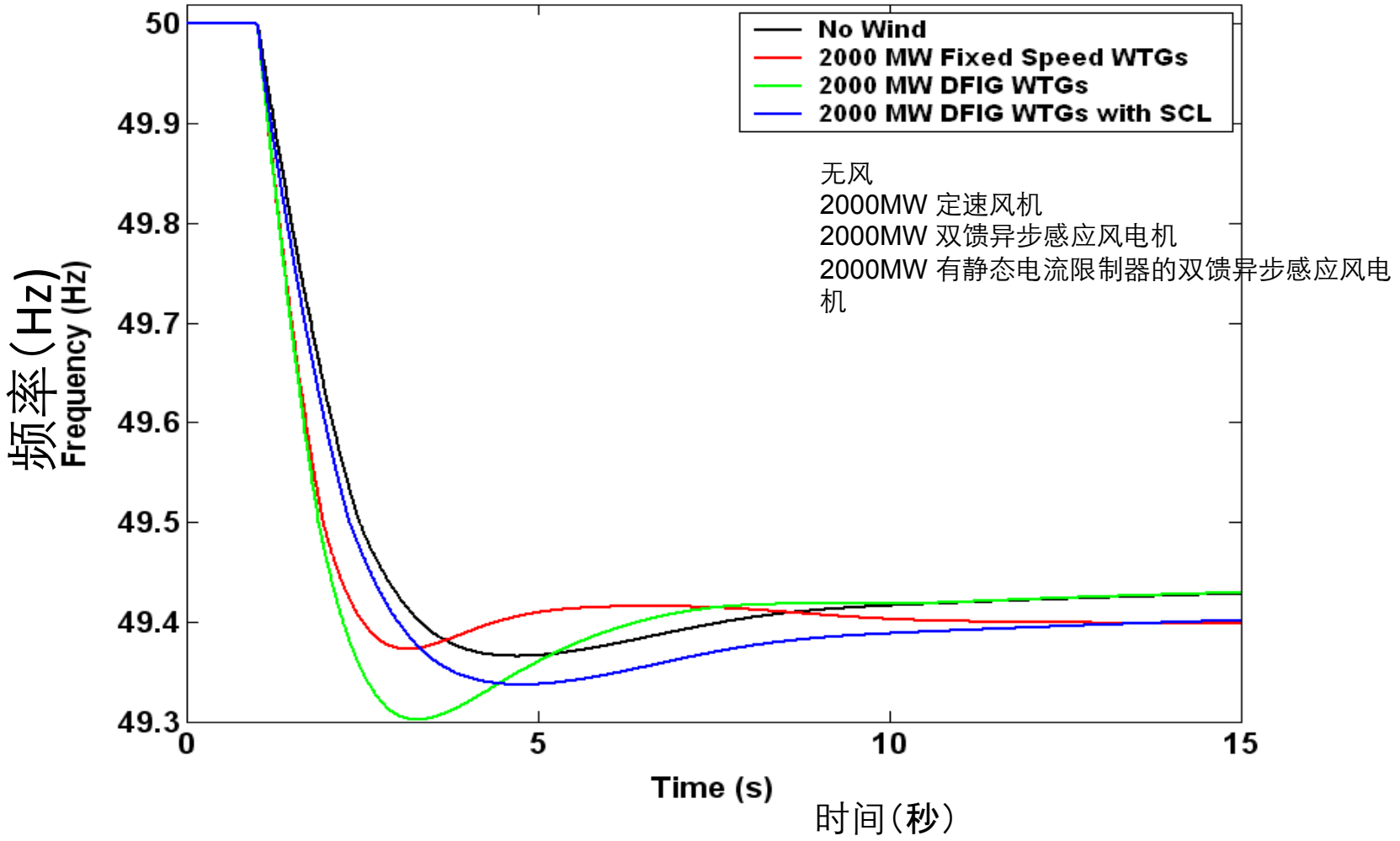
Doubly fed induction
generator wind turbine
双馈异步感应风电机

Fixed speed wind
turbine generator
定速风机

Steady state frequency in Ireland
爱尔兰均衡状态的频率

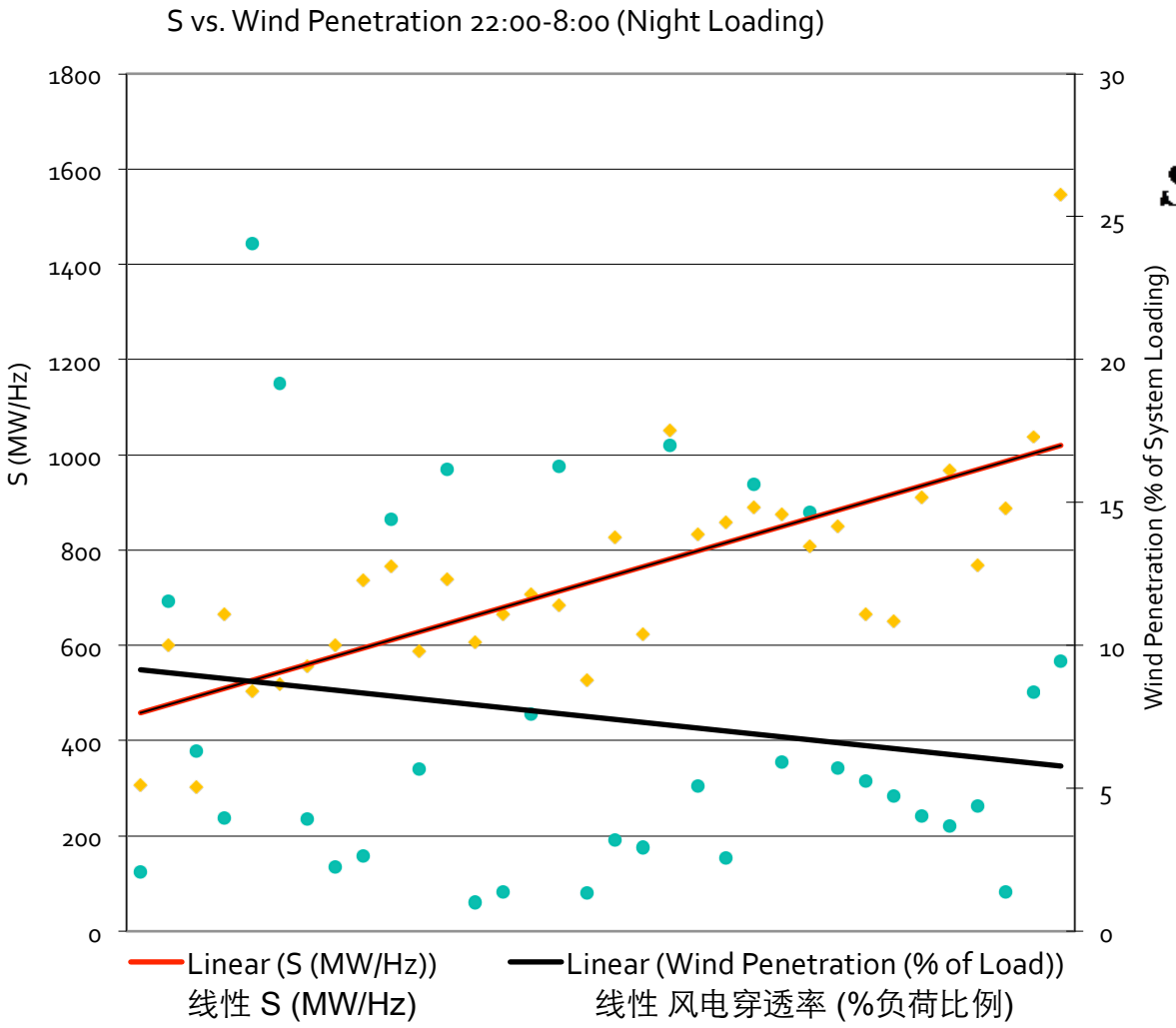


Frequency Response 频率响应



Lalor, G., Mullane, A., and O'Malley, M.J., "Frequency Control and Wind Turbine Technologies", *IEEE Transactions on Power Systems*", Vol. 20, pp. 1903 – 1913, 2005.

Historical data Ireland 爱尔兰历史数据



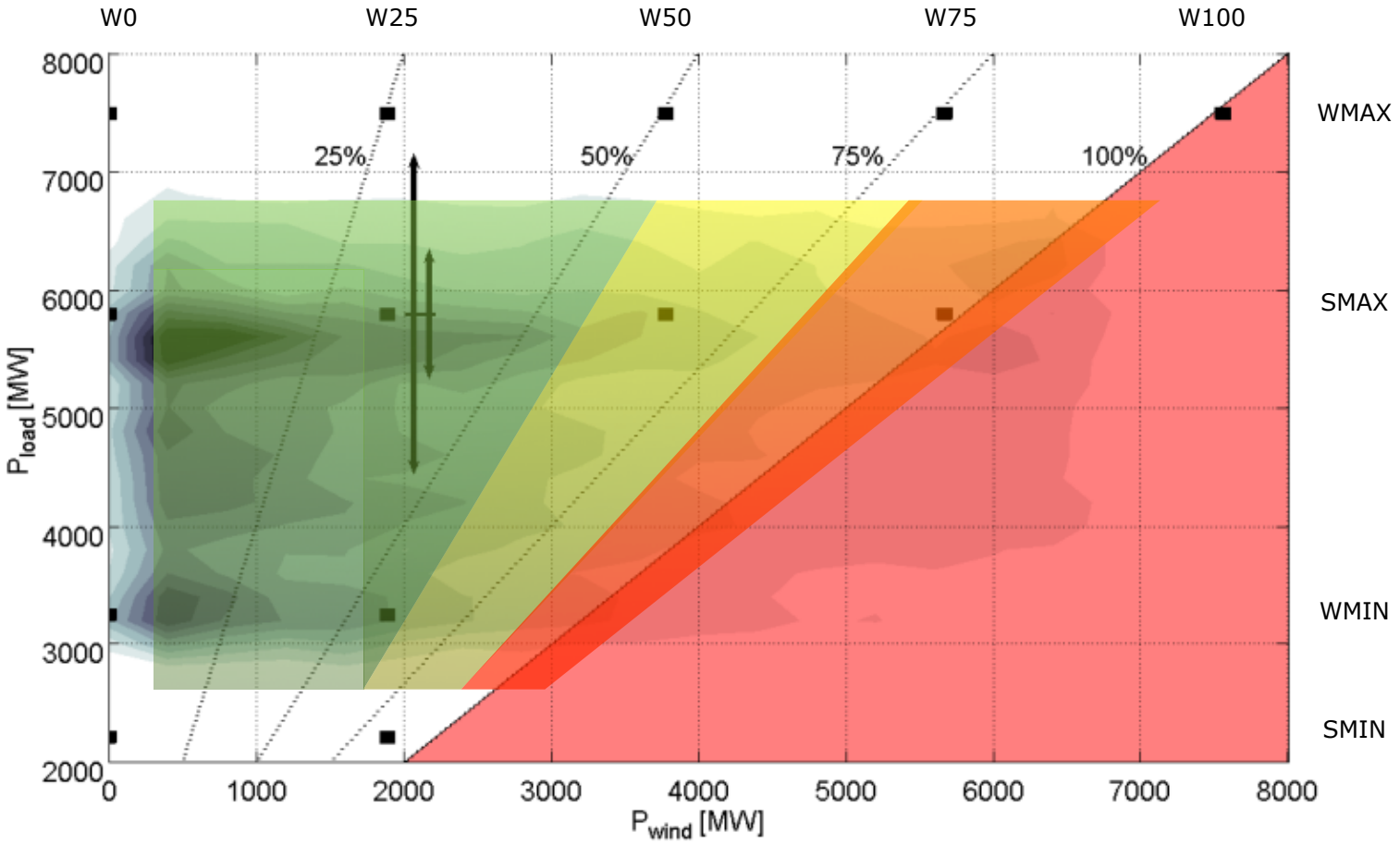
Dudurych, I.M.; , "Statistical analysis of frequency response of island power system under increasing wind penetration," *Power and Energy Society General Meeting, 2010 IEEE* , vol., no., pp.1-6, 25-29 July 2010

- Frequency response
  频率响应

$$S = \left(\frac{MW_{Lost}}{f_{pre\text{-}event} - f_{nadir\,post\text{-}event}} \right)$$

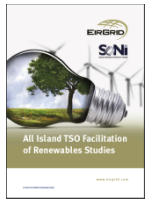
  - Wind penetration increases 风电穿透率提高
  - Stiffness decreases刚性减少
    - Indicates increased vulnerability to a loss of generation event 说明对于发电机组跌落事件的脆弱程度增大
- **Should there be a market in frequency response ?**
  是否应该有一个频率响应的市场

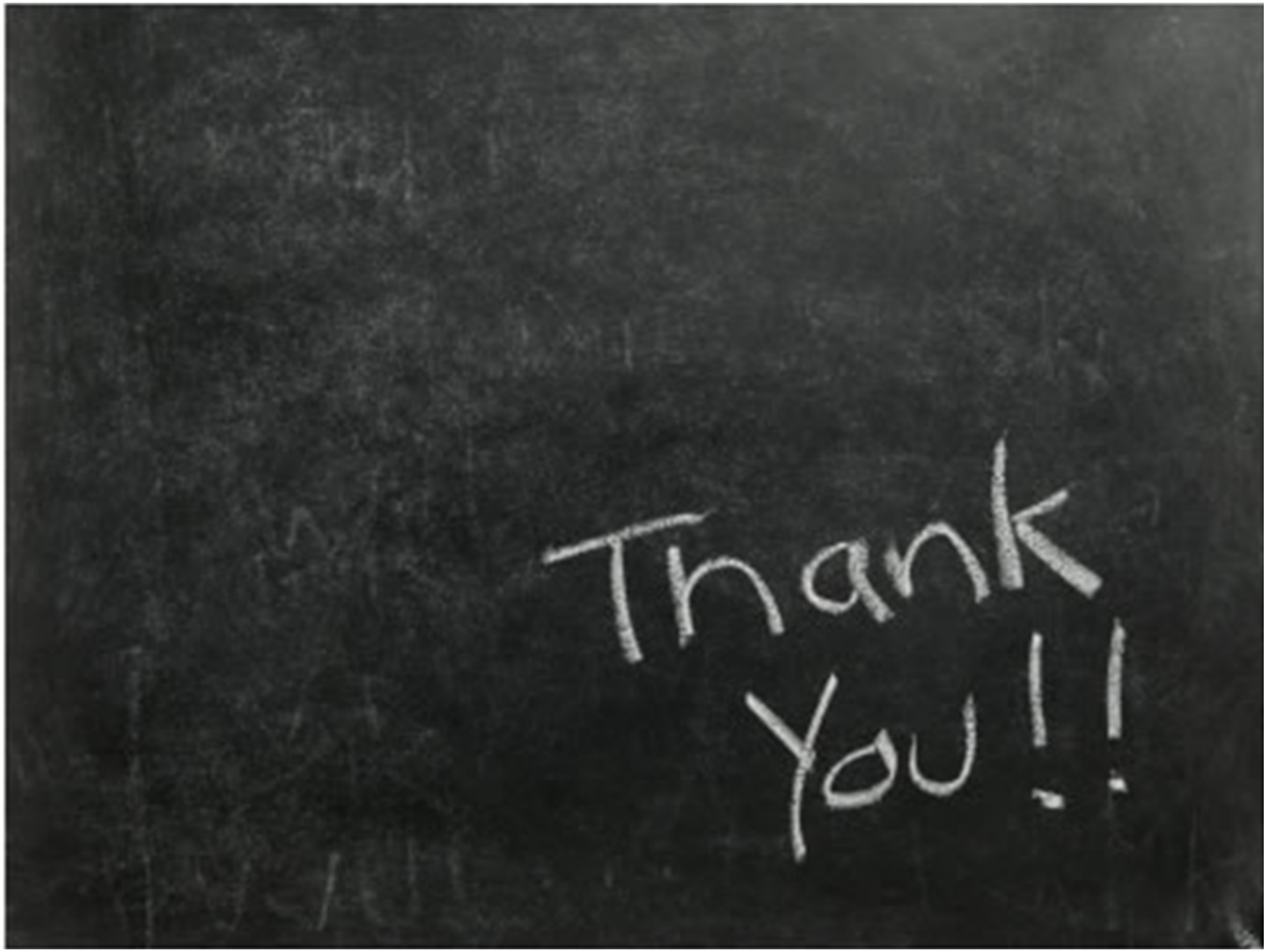
Operational Boundaries
运行边界



EirGrid, "All Island TSO Facilitation of Renewable Studies", Final Report, 2010 .

http://www.eirgrid.com/media/Renewable%20Studies%20V3.pdf




Thank
You!!

Electricity Grids with High Wind Penetrations
高比例风电的电网运营

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