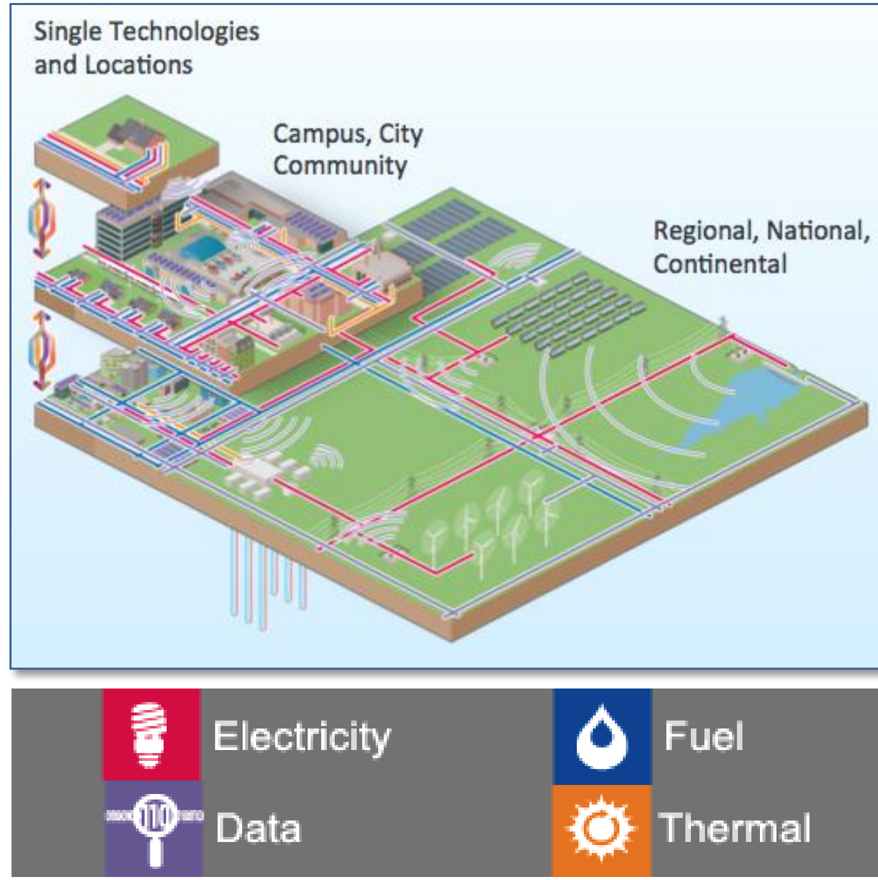
Integration of variable renewables into electricity grids

Mark O'Malley

mark.omalley@ucd.ie

ESI 101, 24th July 2014
NREL, CO, USA



iiESI International Institute™ for Energy Systems Integration

Schedule

Mon 21/07/2014		
09:00 - 10:00	Introduction to ESI and Overview of ESI 101	Mark O'Malley
10:00 –11:00	Benefits of ESI	Ben Kroposki
11:00 - 11:30	Coffee	
11:30 - 12:30	Forecasting of Load, Heat, Wind and Solar	Henrik Madsen
12:30-1:30	Lunch	
1:30-5:00	Project Work	

Tues 22/07/2014		
09:00 - 10:00	Energy Infrastructure Expansion Planning	Jim McCalley
10:00 –11:00	Energy-Water Nexus	Pete Thomson
11:00 - 11:30	Coffee	
11:30 - 12:30	Gas – Electricity Nexus	Jim McCalley
12:30-1:30	Lunch	
1:30-2:30	Tour of ESIF	Ben Kroposki
2:30-5:00	Project Work	

Wed 23/07/2014		
09:00 - 11:00	Distributed Energy Systems, DER, CHP and Microgrids	Bob Lasseter
11:00 - 11:30	Coffee	
11:30 - 12:30	Energy – Transport Nexus	Jim McCalley
12:30-1:30	Lunch	
1:30 - 2:30	Regulatory Issues and Business Models In ESI	Jaqueline Cochran
2:30-5:00	Project Work	
5:00-10:00	Social Trip to Mount Evans	

Thurs 24/07/2014		
09:00 – 10:30	Greybox Modeling	Henrik Madsen
10:30 - 11:00	Introduction to Greybox Modeling Exercise	Niamh O'Connell
11:00 - 11:30	Coffee	
11:30 - 12:30	Introduction to Variable Renewables into Electricity Grids	Mark O'Malley
12:30-1:30	Lunch	
1:30-5:00	Grey Box Modeling Exercise	

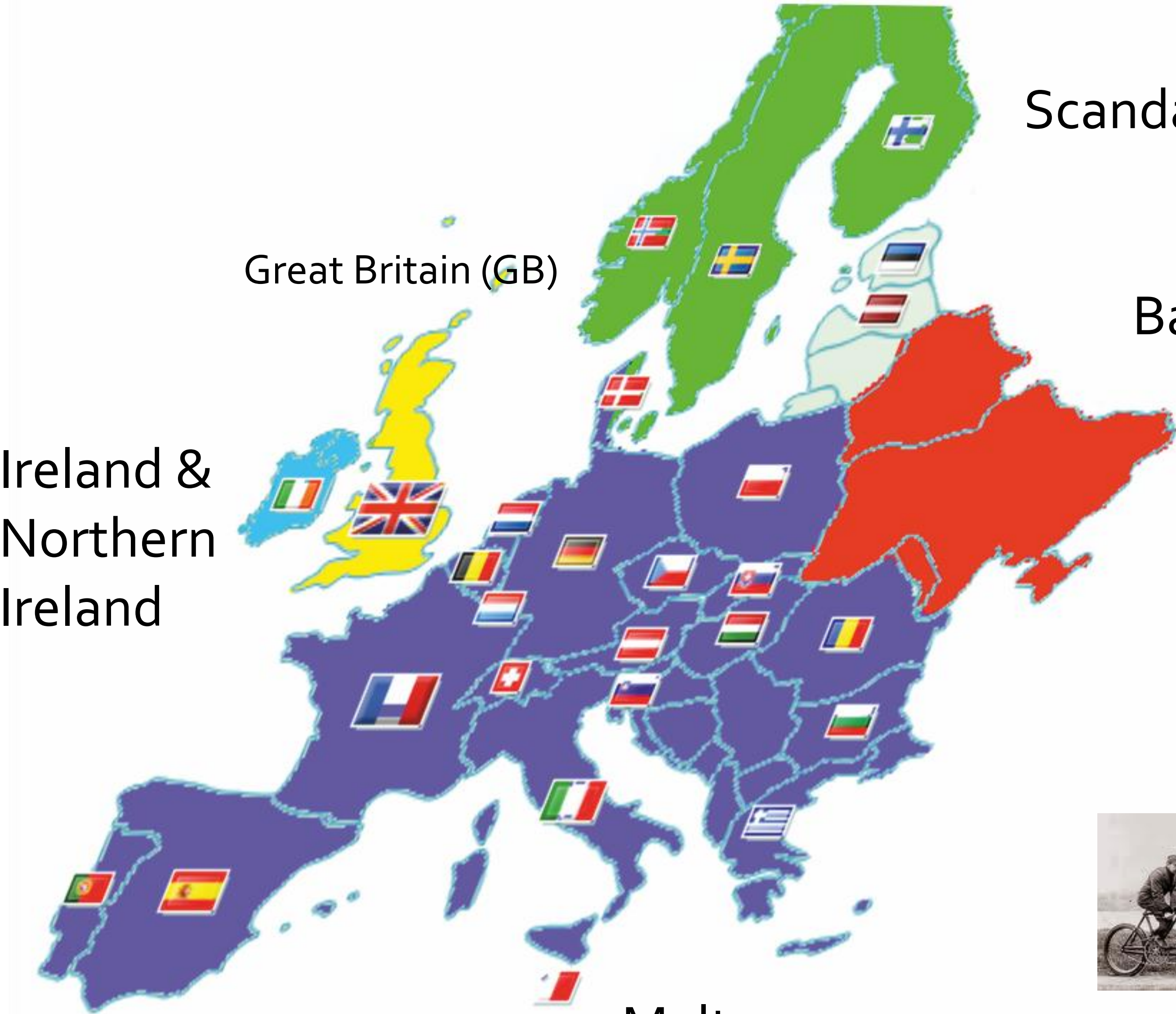
Fri 25/07/2014		
09:00 – 10:00	Statistical Modeling for ESI	Chris Dent
10:00 - 11:00	Project Report Out	
11:00 - 11:30	Coffee	
10:00 - 11:00	Project Report Out	
12:30-1:30	Lunch	
1:30 - 2:30	Project Report Out	
2:30 – 2:45	Wrap Up	Mark O'Malley

Agenda

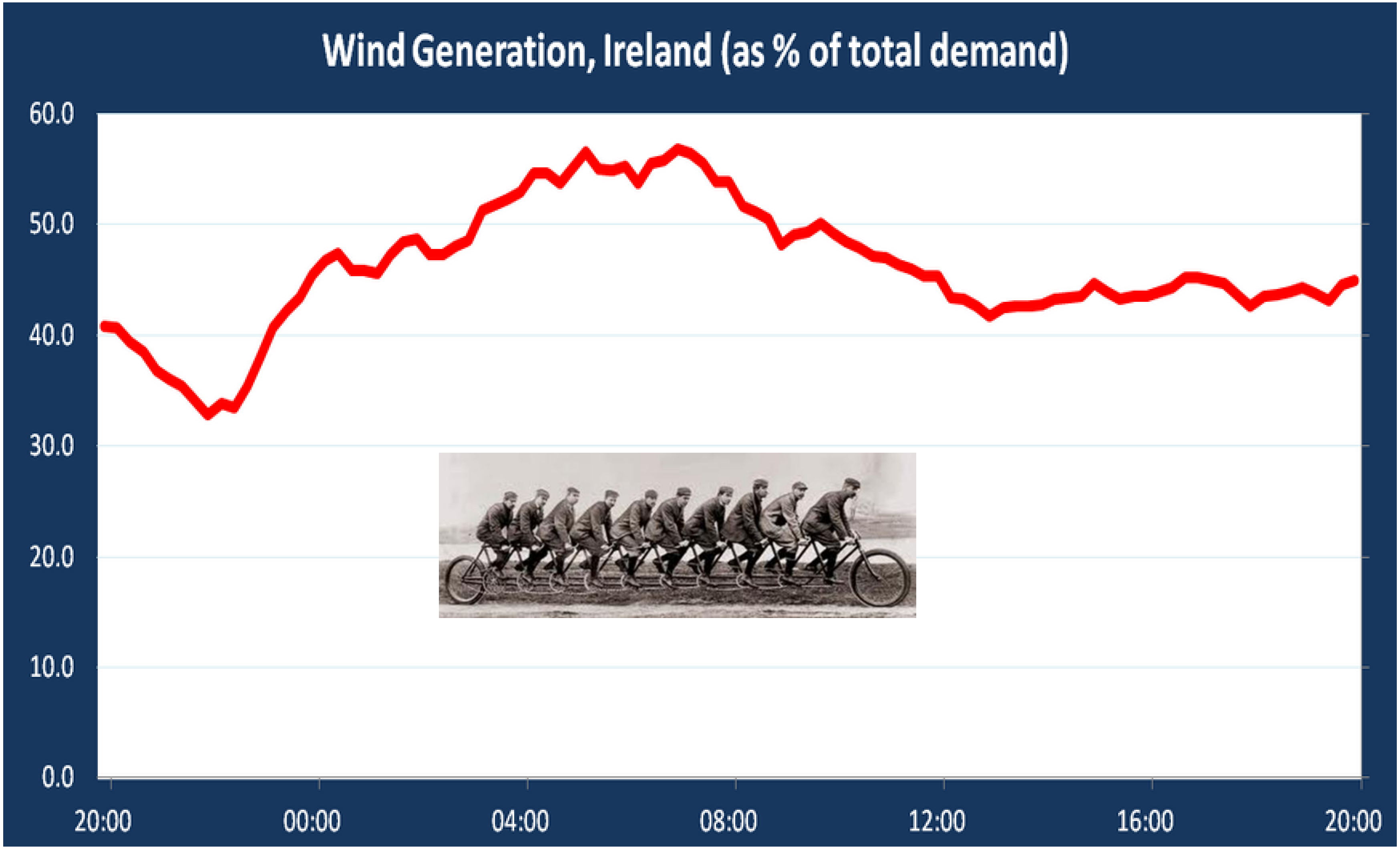
- Ireland
- Supply demand balance & flexibility
- Variable renewable resource characteristics
- Transmission
- Thermal plant flexibility
- Renewable energy generators & stability
- Storage
- Demand response
- New technologies

Ireland

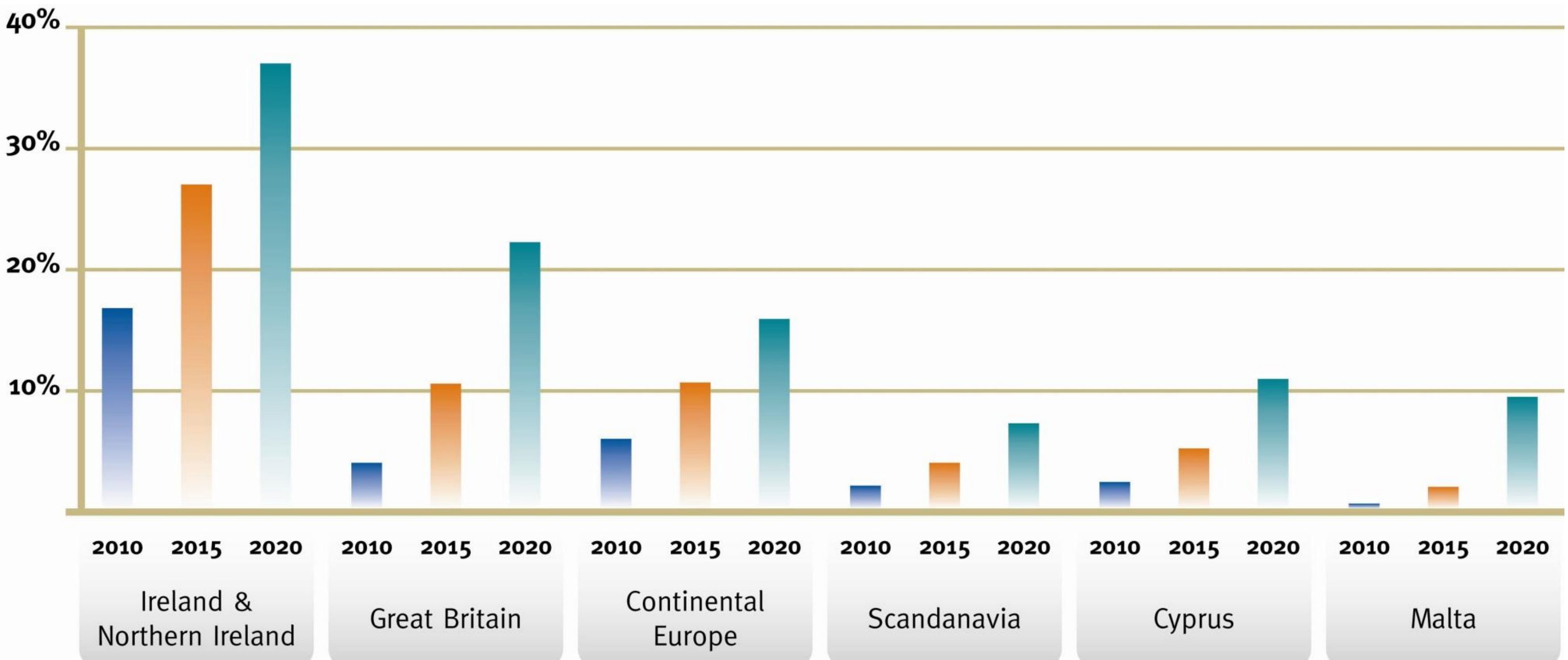
Les réseaux synchrones en Europe



13/14 Avril 2013 – Record du monde pour un réseau électrique synchrone?



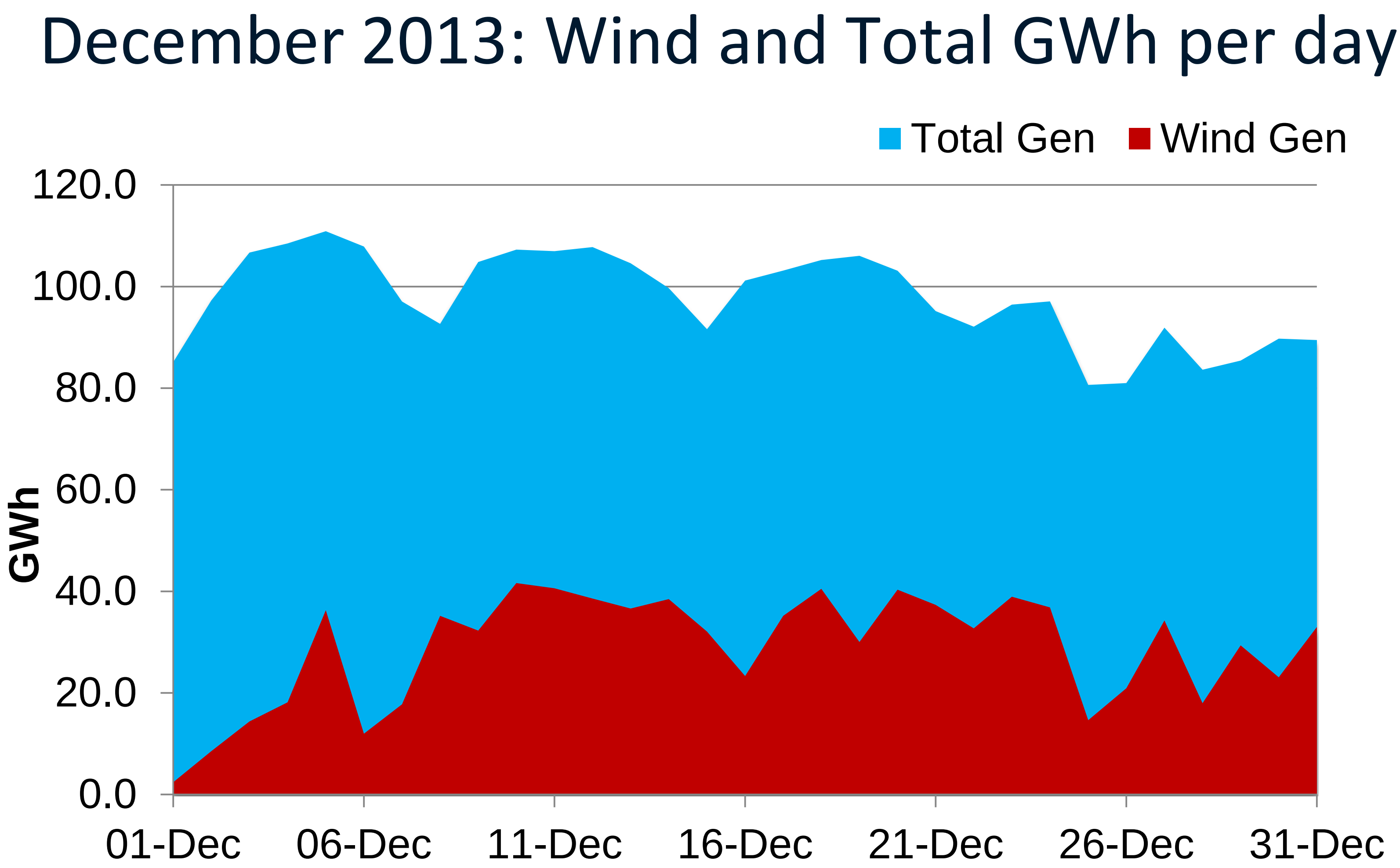
Targets for non-synchronous sources in European Systems



http://www.eirgrid.com/operations/ds3/

* Based on analysis of National Renewable Action Plans (NREAPs) as submitted by Member States

What is possible

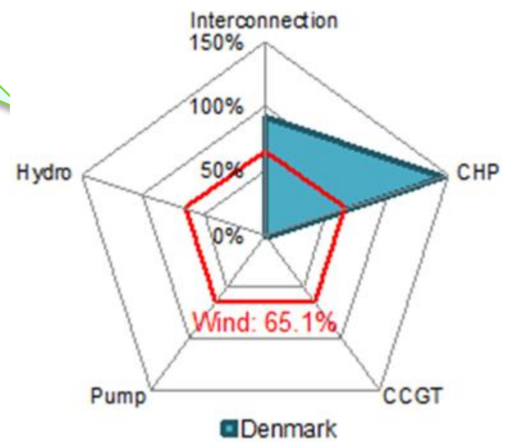


Top wind integration performance (2011)

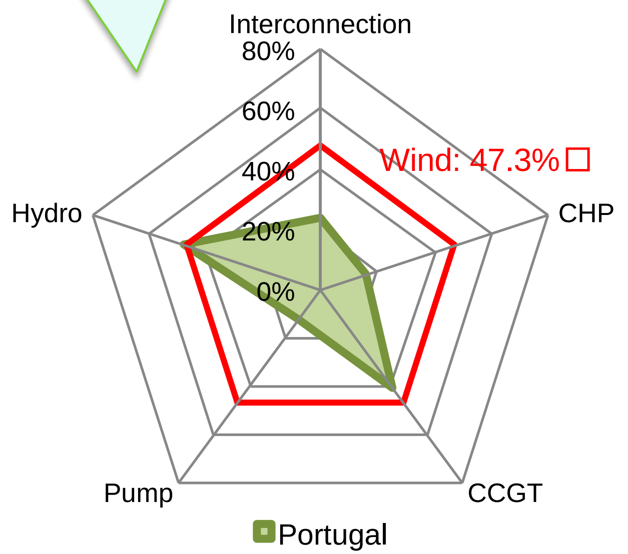
	% Electricity from wind (IEA, 2011)	% Wind Energy Curtailed	Balancing	Notes
Denmark	*28.0*	*< 1 %*	*Interconnection, flexible generation (including CHP) & good markets*	*Renewable target (mainly wind) is 50 % by 2020 and 100% by 2050*
Portugal	*18.0*	*Low*	*Interconnection to Spain, gas, hydro & good market*	*Iberian peninsula: Spain & Portugal all well connected to one another but operate a single market MIEBEL*
Spain	*16.4*	*< 1 % (but increasing due to excess hydro and low demand)*	*Gas, hydro & good market*	
Ireland	*15.6*	*2.3 % in 2011* *EirGrid and SONI, 2012; "2011 Curtailment Report"*	*Gas 50 % , good markets, etc.*	*Curtailment reduced in 2012 to 2.1 % and 2.0 % in 2013*

Flexibility chart

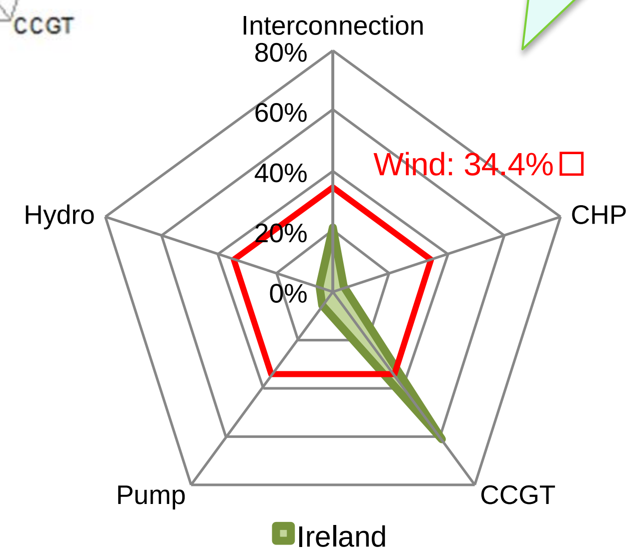
Denmark(Interconnection-oriented)



Portugal (Hydro-oriented)



Ireland (CCGT-oriented)



Y. Y asuda et al.: “Flexibility Chart – Evaluation on Diversity of Flexibility in Various Areas”, 13th Wind Integration Workshop, WIW13-1029, (2013, 10, London).

Examples of changing regulatory expectations: Integrating Variable Renewable Energy

- **Power system operation must carefully consider two sources of flexibility:**
  - Physical power system: generators, transmission, storage, interconnection…
  - Institutional system: including dispatch decisions closer to real time, better use of forecasting, better collaboration with neighbors
- ***Smart grids require smart frameworks and markets***

The ingredients of success – today 20 % wind

	INSTITUTIONAL
POLICY ENVIRONMENT	Supportive
MARKETS AND SCHEDULING	Supportive
FORECASTING	Supportive
ANCILLARY SERVICES	Some
REGULATION, GRID CODES	Supportive but challenging
PLANNING	Supportive but challenging
VARIABLE RENEWABLE CURTAILMENT	Negligible

	PHYSICAL
TRANSMISSION & INTERCONNECTION	Supportive
THERMAL PLANT FLEXIBILITY	Supportive but challenging
RESOURCE CHARACTERISTICS	Supportive
RENEWABLE ENERGY GENERATOR CAPABILITIES	Supportive but challenging
STORAGE	Some
DEMAND SIDE	Negligible
NEW TECHNOLOGIES: FACTS, ETC	Negligible

- Supportive
- Supportive but challenging
- Some
- Negligible

Work remaining for 40 %

	INSTITUTIONAL
POLICY ENVIRONMENT	Supportive
MARKETS AND SCHEDULING	Supportive
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DEMAND SIDE	Negligible
NEW TECHNOLOGIES: FACTS, ETC	Negligible

Key Take Away

- High penetrations of variable renewables is happening now in many regions/countries

- They have got many of the key ingredients right
  - Strong coordinated institutional support
  - Good basic engineering on physical side

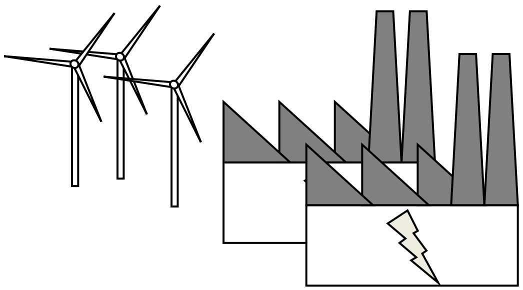
- Much of this can translate but every system has unique physical characteristics.

Supply demand balance & flexibility

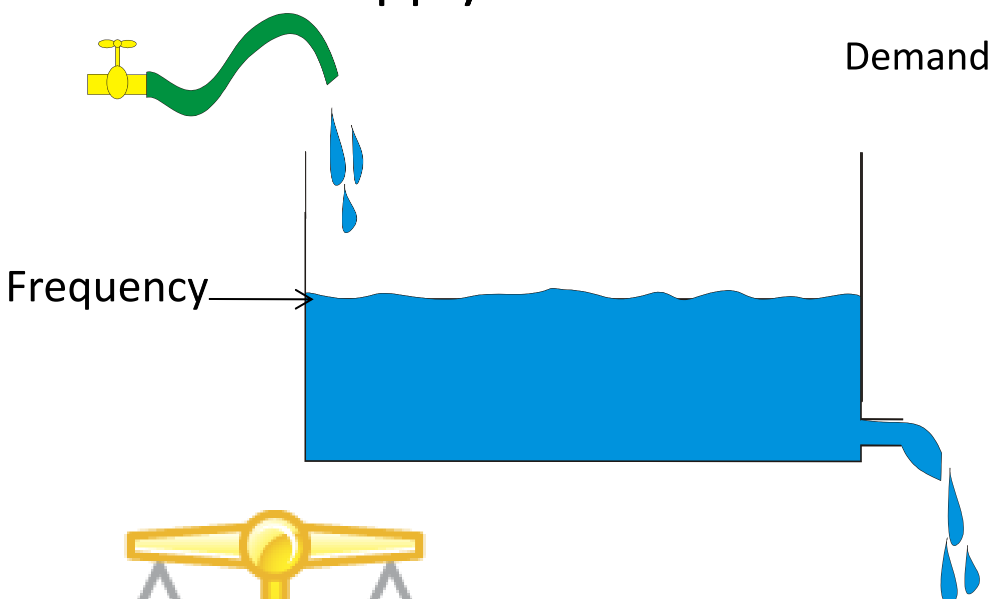
Supply demand balance & frequency control

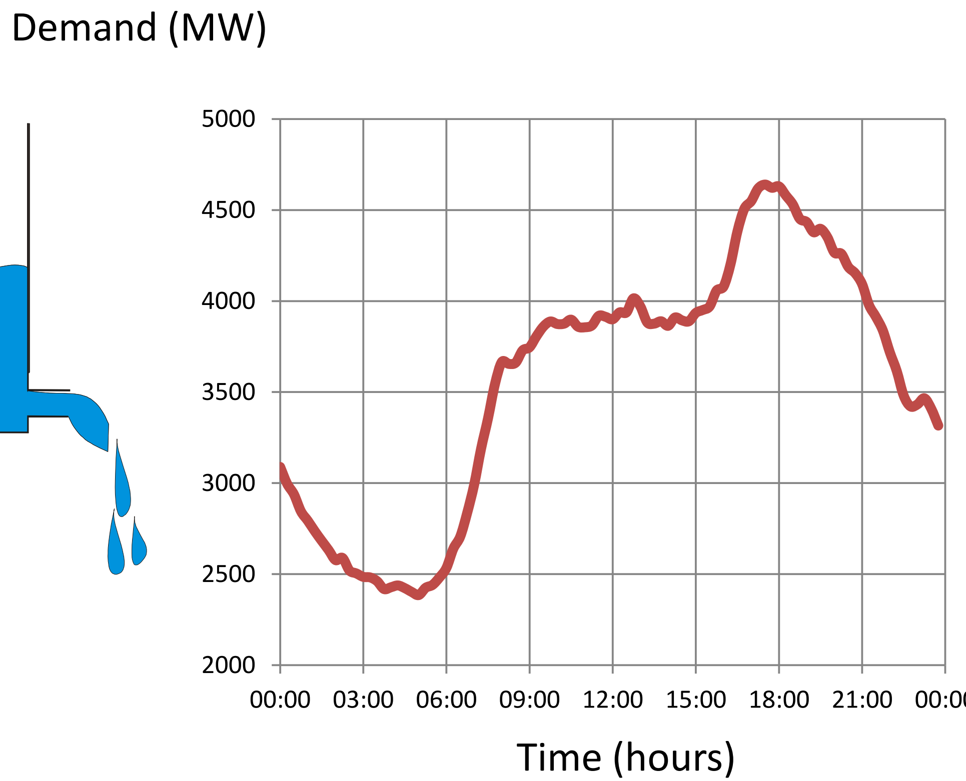
If generation and demand are matched water level (system frequency) will remain constant

Mismatches will result in a change in water level (system frequency)

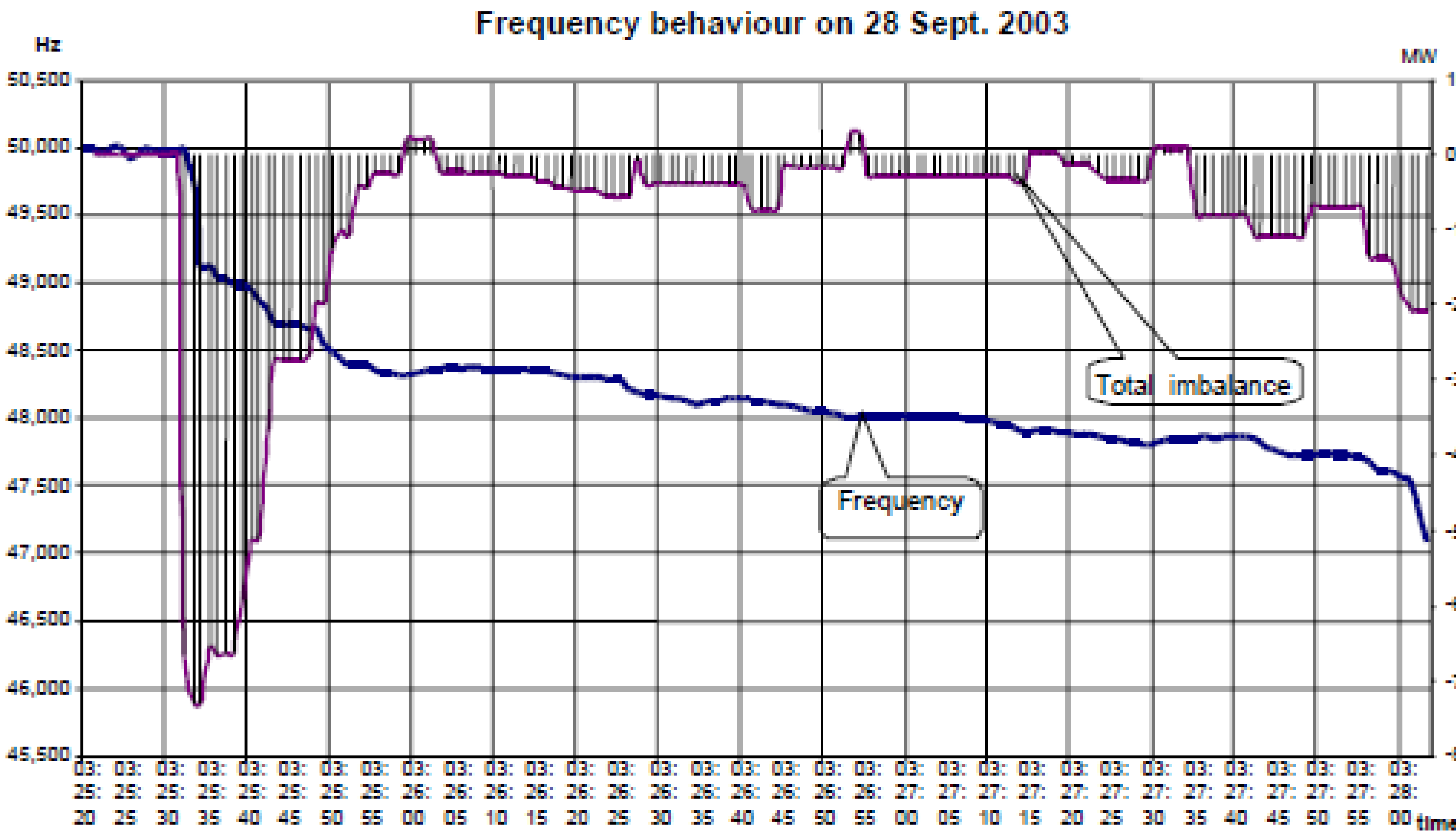


Supply





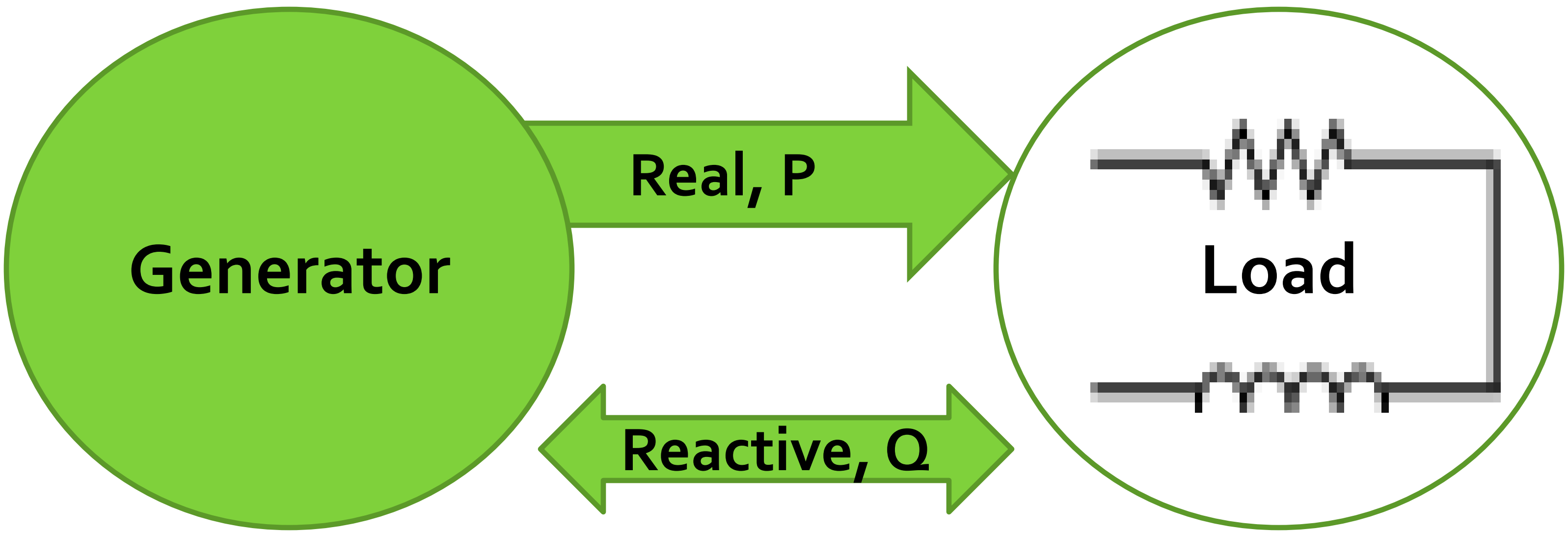
Italian blackout Sept 28th 2003

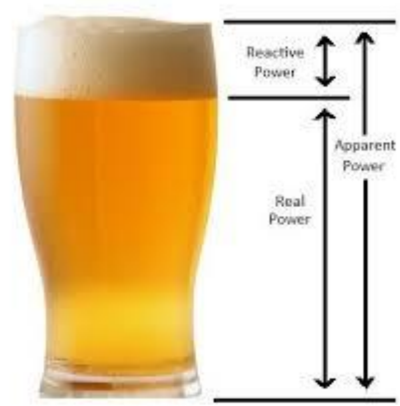


UCTE, Final Report of the Investigation Committee on the 28th September 2003 Blackout in Italy, 2004.

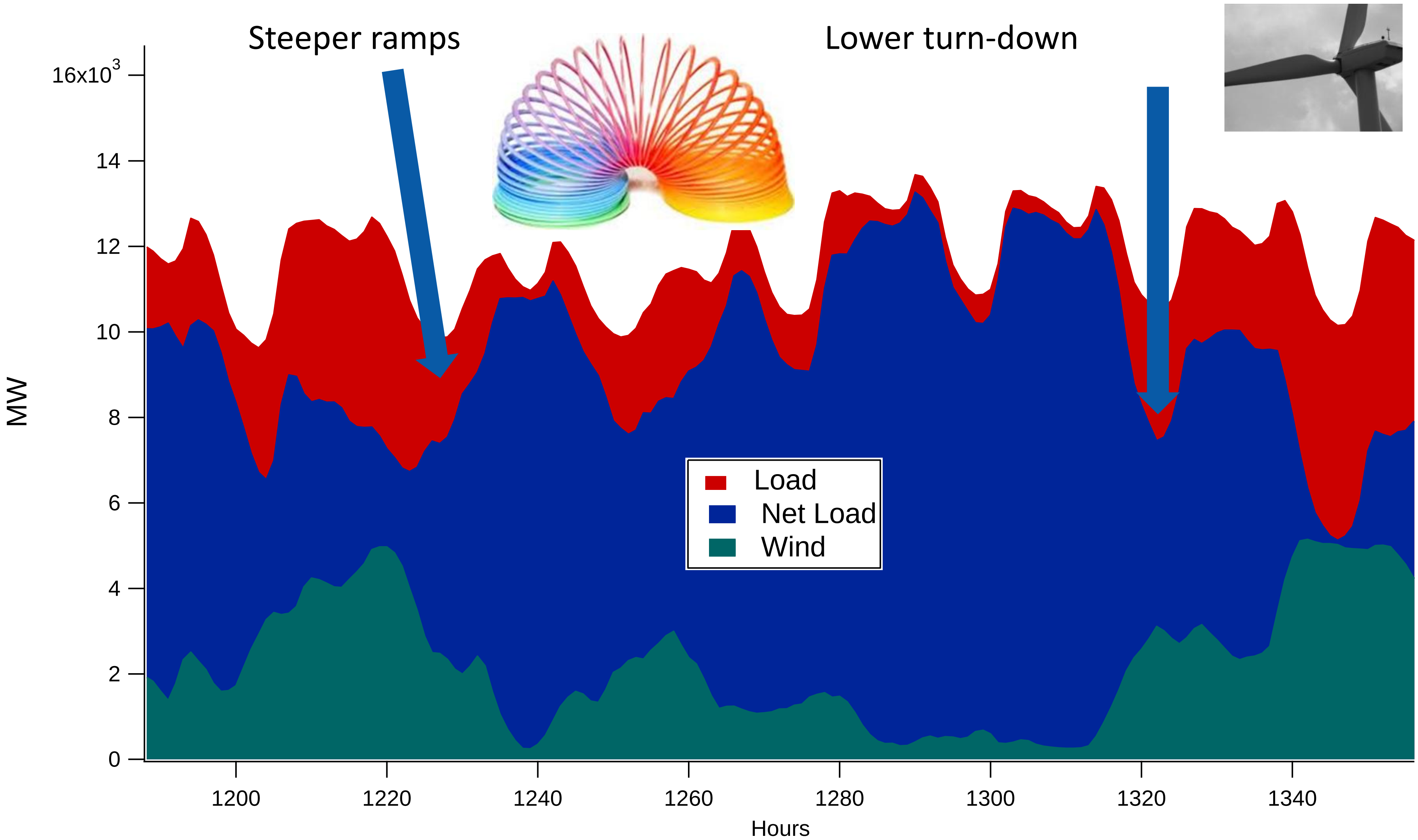
The Vatican Sept 28th 2003

Supply demand balance & Voltage Control



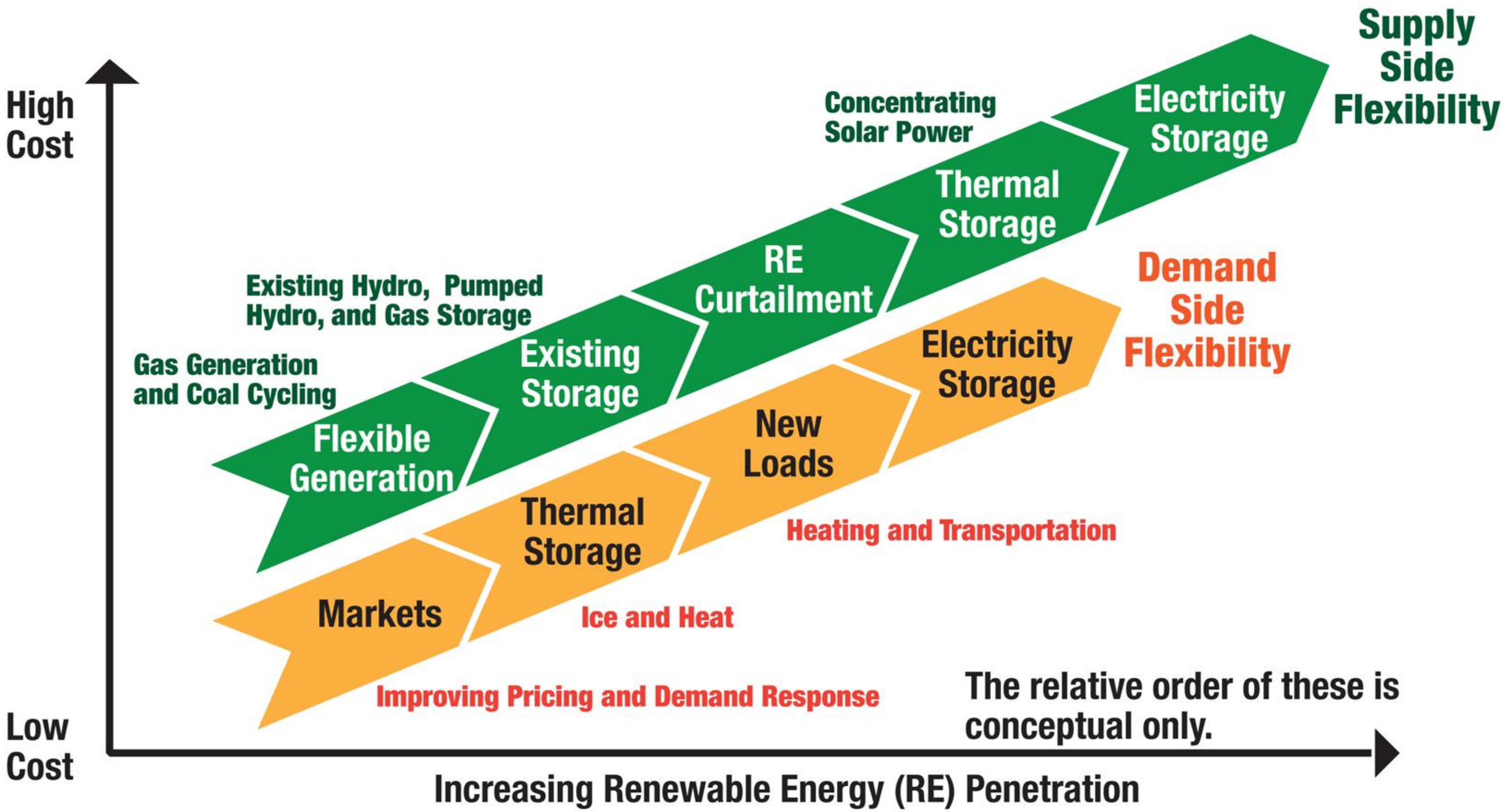


With Variable Renewables More Flexibility is Needed



Source: Michael Milligan , NREL

System Flexibility Supply Curve



How do we choose the optimum mix of flexibility resources?

Key Take Away

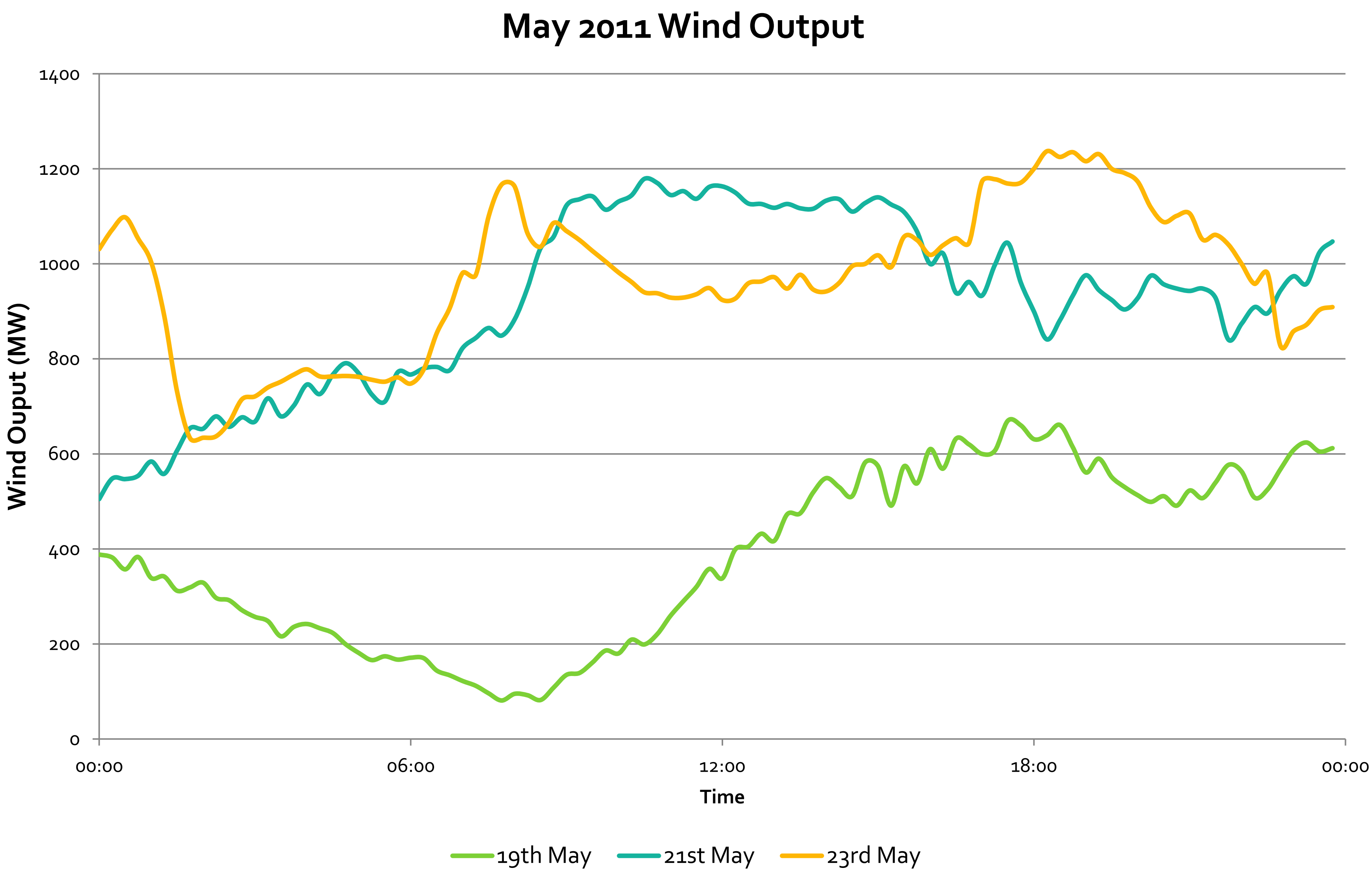
- It is about **reliability** and **cost**

  - Reliability is supply demand balance of real (frequency control) and reactive (voltage control) power.

  - Pick the cheapest cost solutions from the set of possible solutions, but cost is difficult to define.

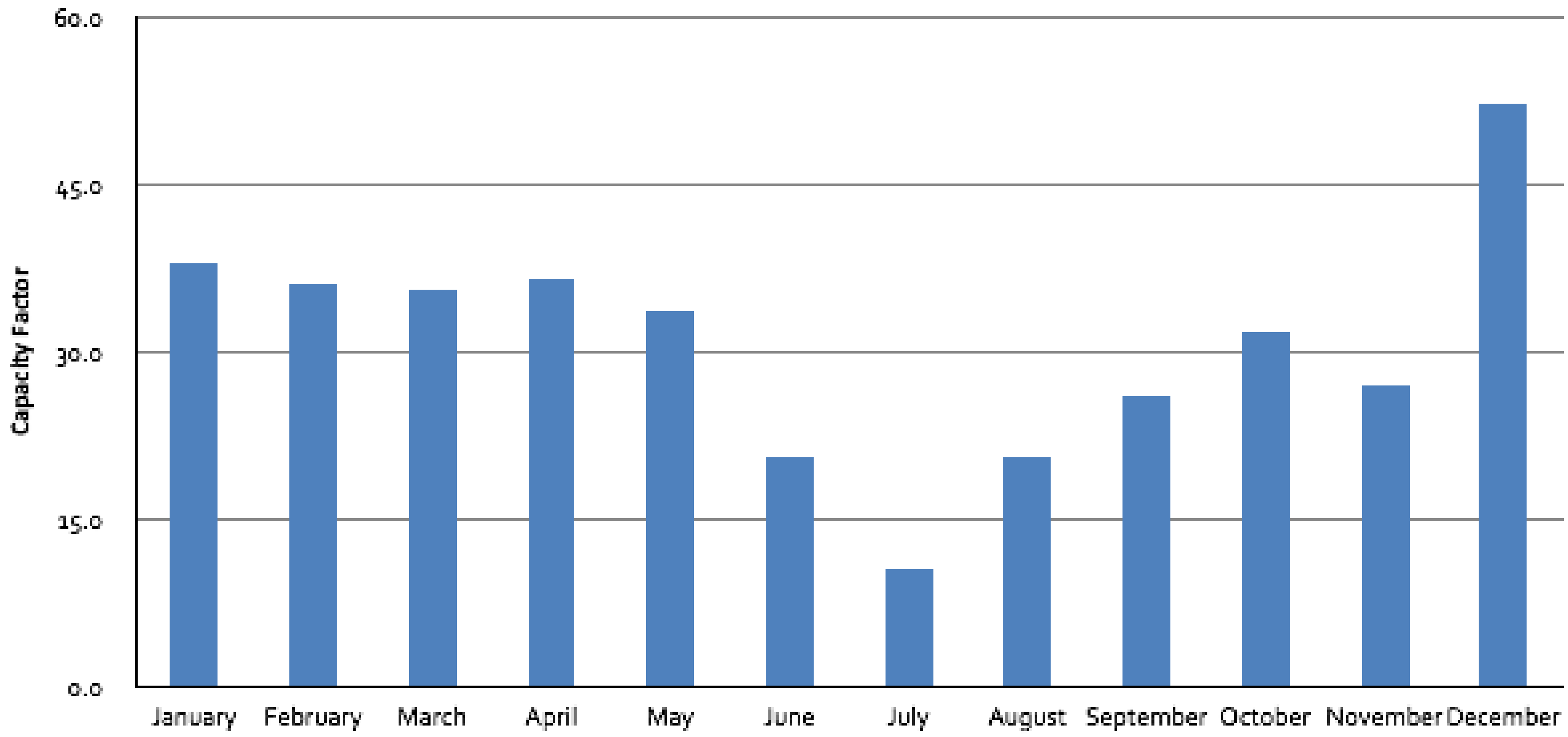
Variable renewable resource characteristics

Wind Generation Hourly Variability



Source: EirGrid

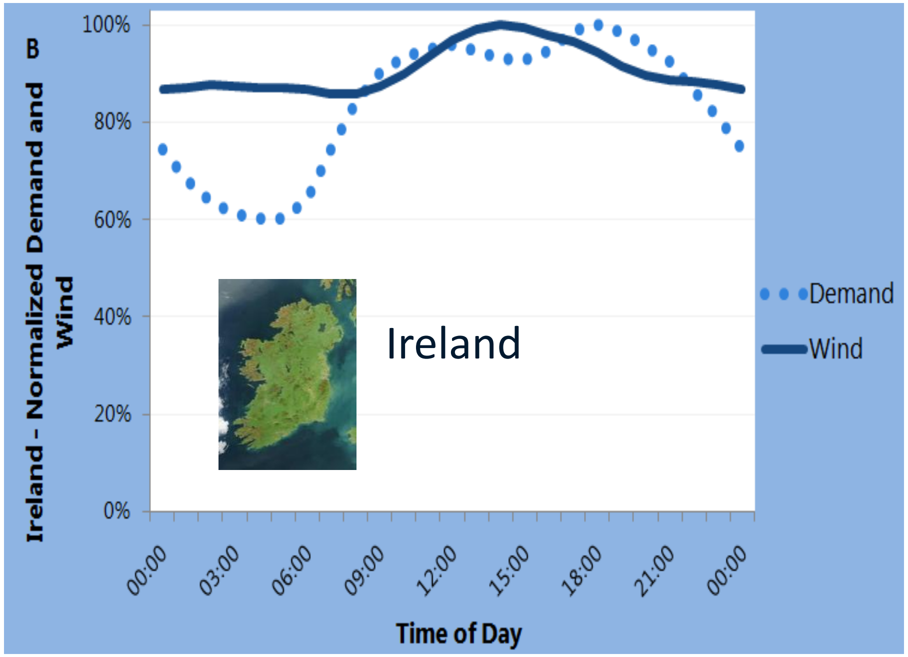
All Island Wind Capacity Factor 2013

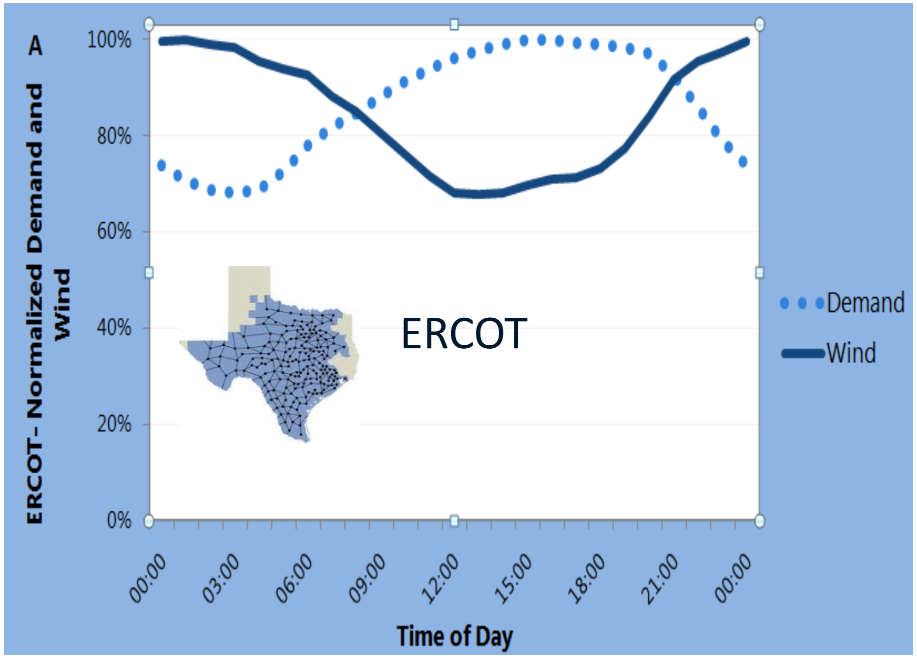


Note: All values used are based on 15 min historical SCADA values

Renewable energy and load (demand) characteristics

Dance partners





AEMO, Australian Energy Market Operator, "Wind Integration In Electricity Grids: International Practice And Experience" Work Package 1, 2011.
http://www.aemo.com.au/~/media/Files/Other/planning/0400-0049%20pdf.pdf

Key Take Away

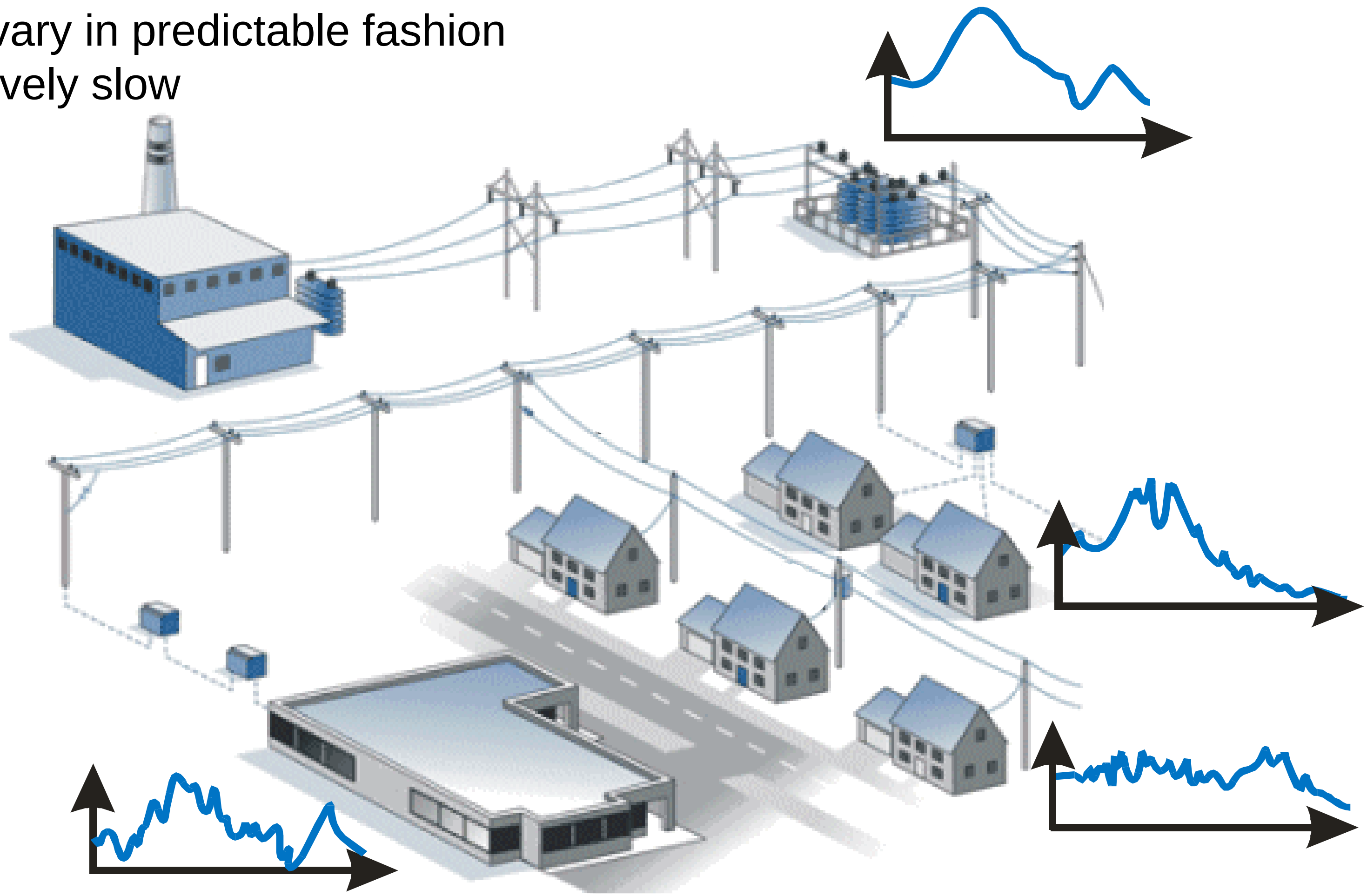
- Variable at all time scales
  - In general supply demand balance with variable renewables more problematic.
  - The resource characteristics sometimes beneficial sometimes not.

Transmission

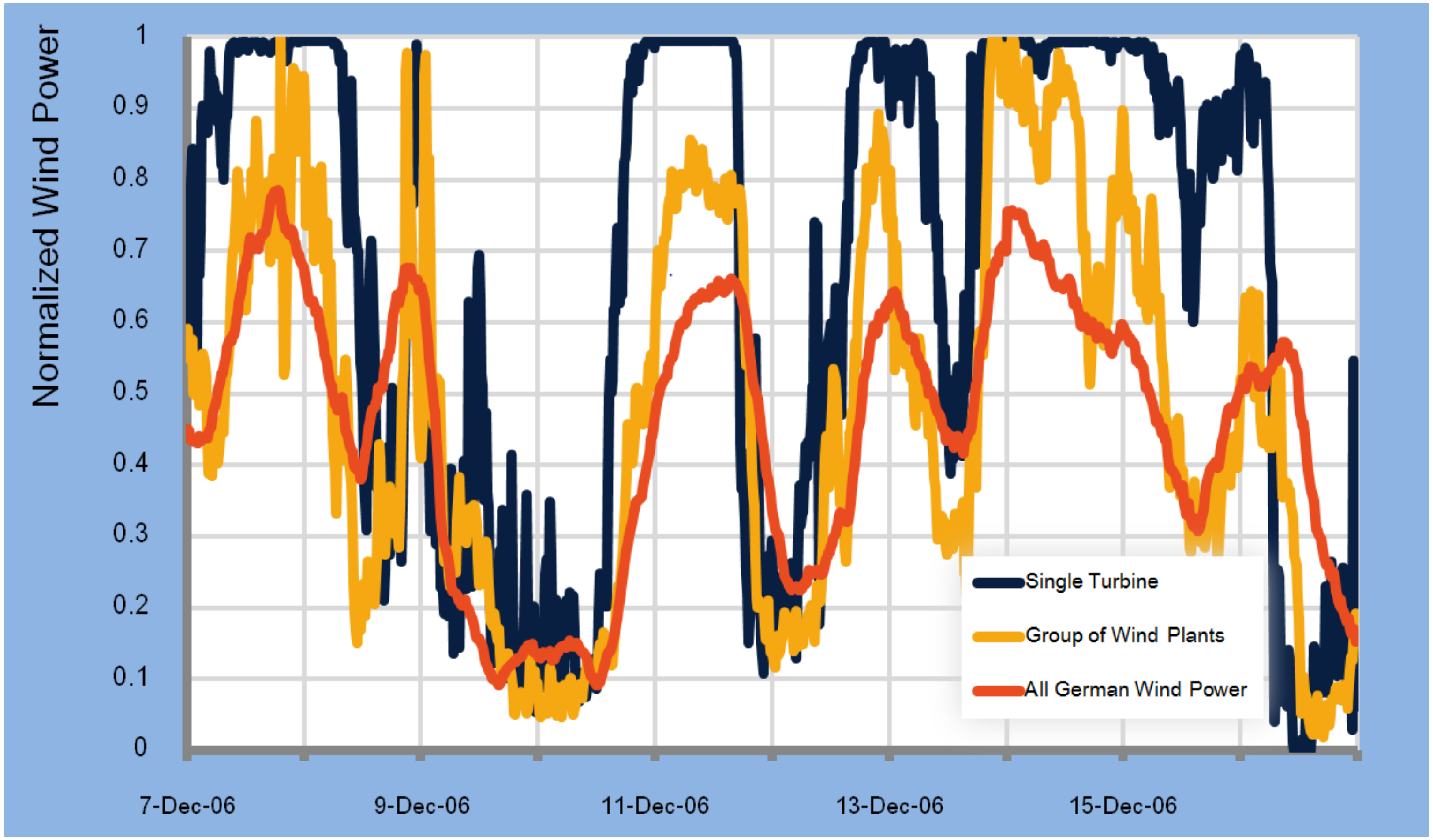

happytoast

Network helps aggregation

Individual loads may be random in nature
Pattern emerges at distribution transformer
Lumped loads vary in predictable fashion
Variations relatively slow



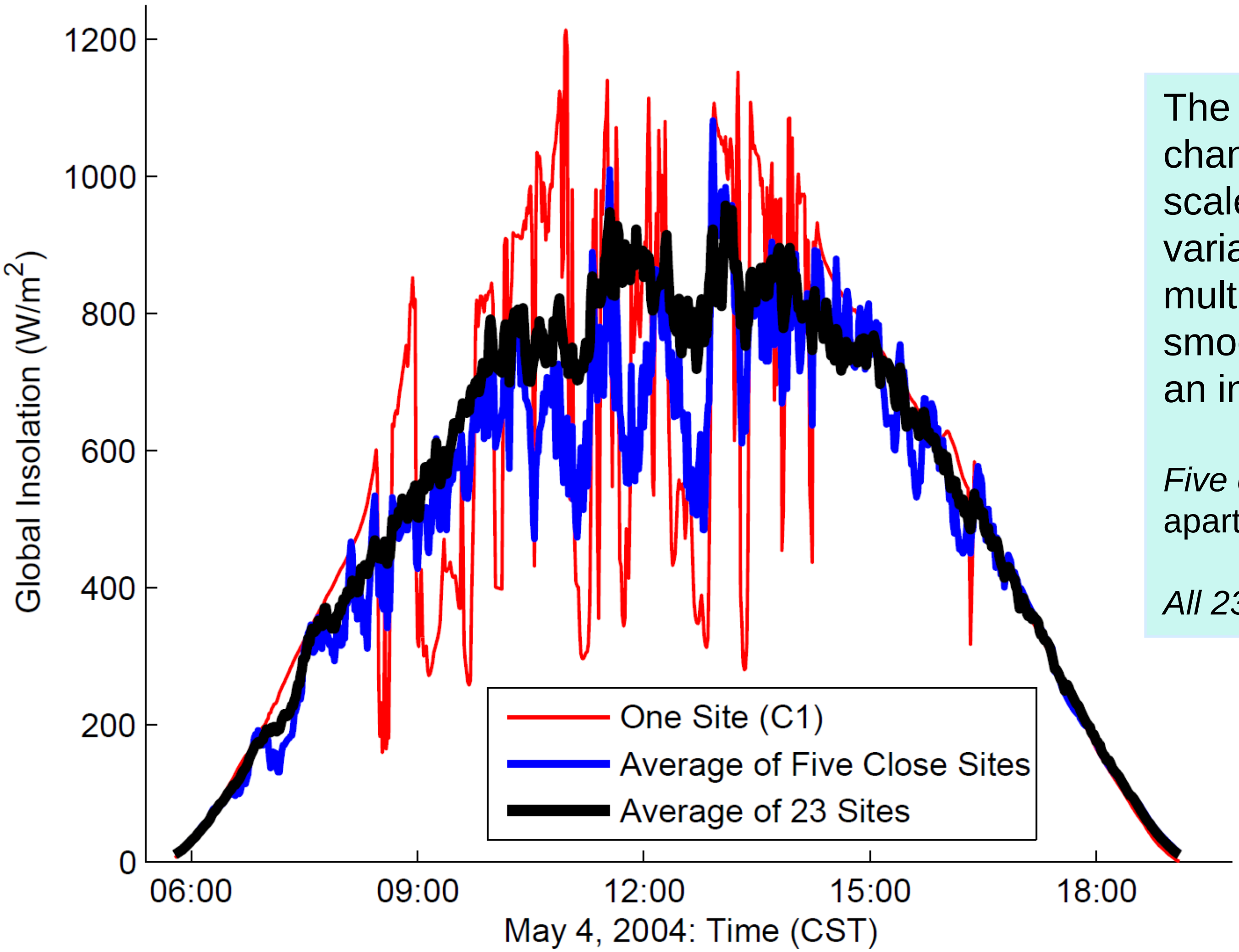
Aggregation wind



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, R., Z. Yang, M. Hand, O. Hohmeyer, D. Infield, P. Hjuler Jensen, V. Nikolaev, M. O'Malley, G. Sinden, A. Zervos, 2011: Wind Energy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. v. Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. http://srren.ipcc-wg3.de/report/IPCC_SRREN_Ch07

Aggregation of solar



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.

Five closest sites: 50 – 170 km apart

All 23 sites: 20 – 440 km apart

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.

Source: Andrew Mills, LBL

… and the Level of Wind Curtailment

Estimated Wind Curtailment (GWh and % of potential wind generation)

	2007	2008	2009	2010	2011	2012
Electric Reliability Council of Texas (ERCOT)	109.1 (1.2%)	1,416.6 (8.4%)	3,872.2 (17.1%)	2,066.5 (7.7%)	2,621.5 (8.5%)	1,038.0 (3.7%)
Southwestern Public Service Company (SPS)	N/A	0 (0.0%)	0 (0.0%)	0.9 (0.0%)	0.5 (0.0%)	N/A
Public Service Company of Colorado (PSCo)	N/A	2.5 (0.1%)	19.0 (0.6%)	81.5 (2.2%)	63.9 (1.4%)	N/A
Northern States Power Company (NSP)	N/A	25.4 (0.9%)	42.4 (1.7%)	44.3 (1.7%)	58.7 (1.6%)	120.5 (3.1%)
Midwest Independent System Operator (MISO), less NSP	N/A	N/A	249.6 (2.0%)	779.7 (4.2%)	782.6 (3.4%)	726.2 (2.5%)
Bonneville Power Administration (BPA)	N/A	N/A	N/A	4.6* (0.1%)	128.7* (1.4%)	70.8* (0.7%)
PJM	N/A	N/A	N/A	N/A	N/A	111.6# (1.8%)#
Total Across These Seven Areas:	**109 (1.2%)**	**1,444 (5.7%)**	**4,183 (9.7%)**	**2,978 (4.9%)**	**3,656 (4.9%)**	**2,067 (2.7%)**

*A portion of BPA's curtailment is estimated assuming that each curtailment event lasts for half of the maximum possible hour for each event.

#2012 curtailment numbers for PJM are for June through December only (data for January through May are not available).

- ERCOT numbers represent both forced (non-market) and voluntary (market) curtailment
- All other regions show only forced curtailment

Assuming a 33% capacity factor, the total amount of wind generation curtailed in 2012 within just the territories shown above equates to the annual output of roughly 715 MW of wind power capacity

Wiser and Bollinger (2013), "Wind Technologies Market Report, 2012" US DOE Energy Efficiency and Renewable Energy, http://www1.eere.energy.gov/wind/pdfs/2012_wind_technologies_market_report.pdf

Curtailment in Ireland 2011

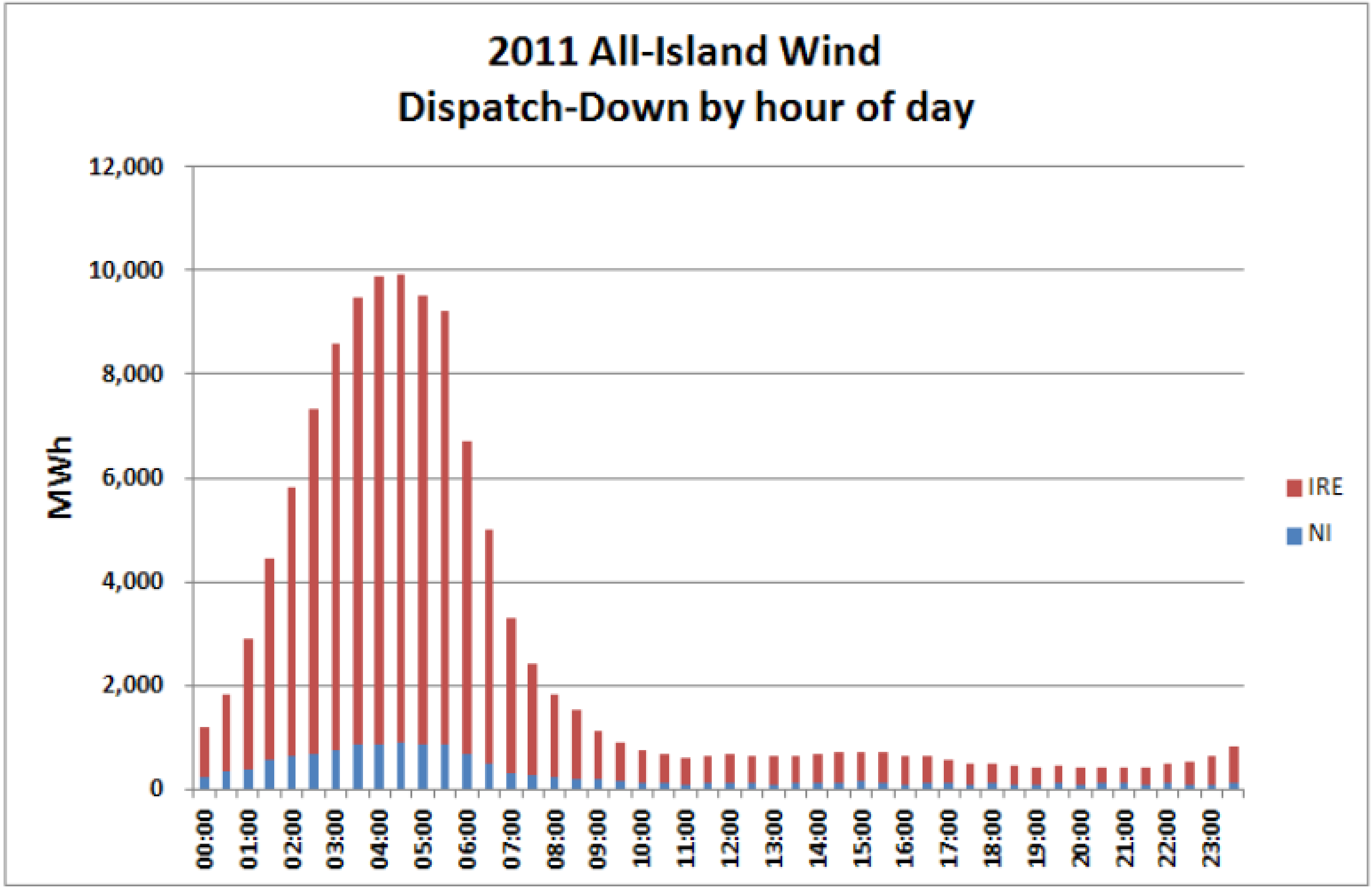


Figure 3 Ireland and Northern Ireland 24 hour clock of dispatch-down of wind 2011

- EirGrid and SONI, 2012; "2011 Curtailment Report"

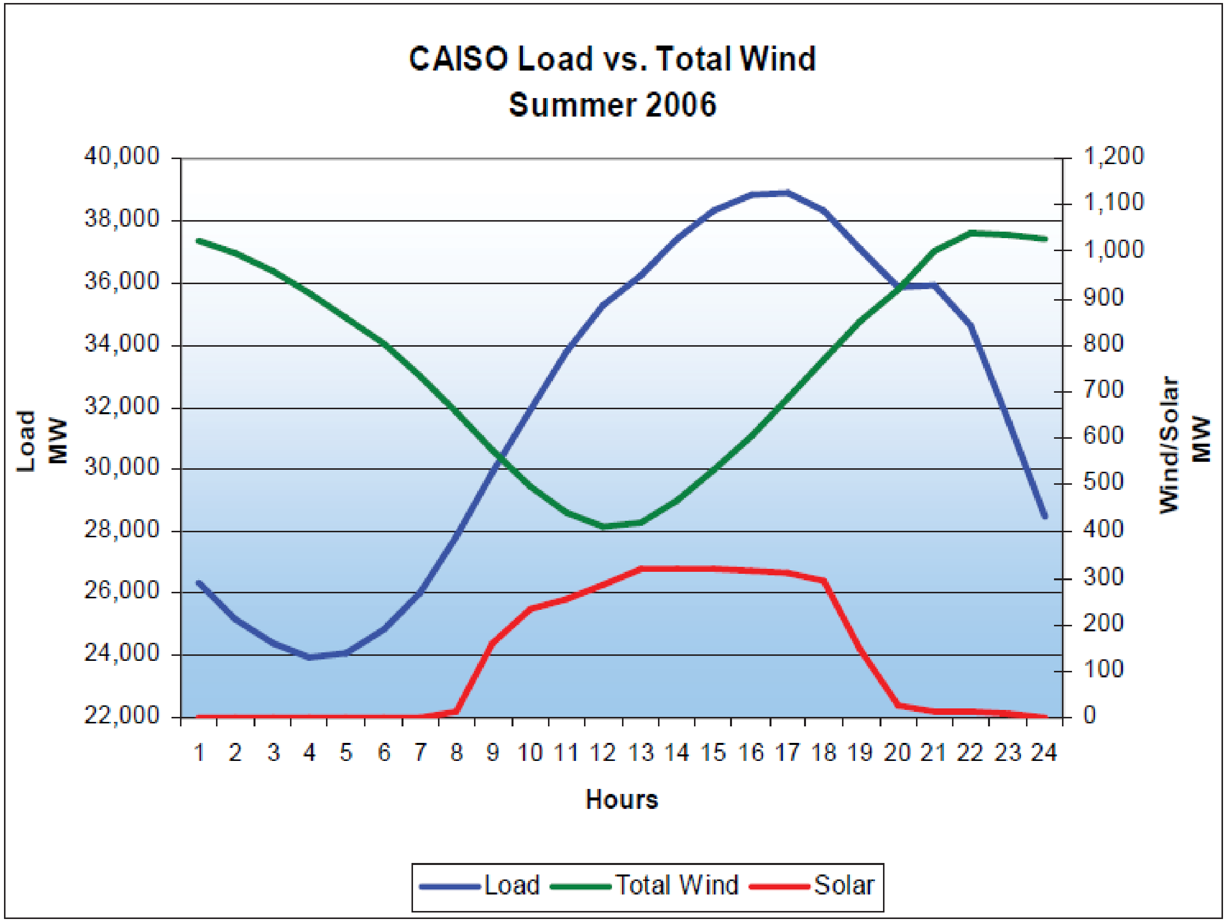
Curtailment in Texas

- Wind curtailment in Texas was 8 % in 2010 and 17 % in 2009 mainly due to lack of transmission (Wiser and Bollinger, 2011). It was this type of high levels of curtailment in the early part of the century that spurred Texas to initiate a proactive scheme to alleviate this problem.

- Competitive Renewable Energy Zone (CREZ) – curtailment in 2012 – 3.7 %

Wiser and Bollinger (2011), "Wind Technologies Market Report" US DOE Energy Efficiency and Renewable Energy
http://www1.eere.energy.gov/wind/pdfs/2011_wind_technologies_market_report.pdf

Aggregation of Sources Daily



Actual System Load, Wind Generation and Solar Generation for Summer 2006

California ISO, 2007 Integration of Renewable Resources, Transmission and operating issues and recommendations for integrating renewable resources on the California ISO-controlled Grid
http://www.uwig.org/CAISOIntRenewablesNov2007.pdf

Key Take Away

- Transmission is the key integration asset
  - Enables aggregation
  - Allows the sharing of “flexibility” etc.
  - Fundamental to reducing curtailment

Thermal plant flexibility

Can Thermal Power Plant Skip ?

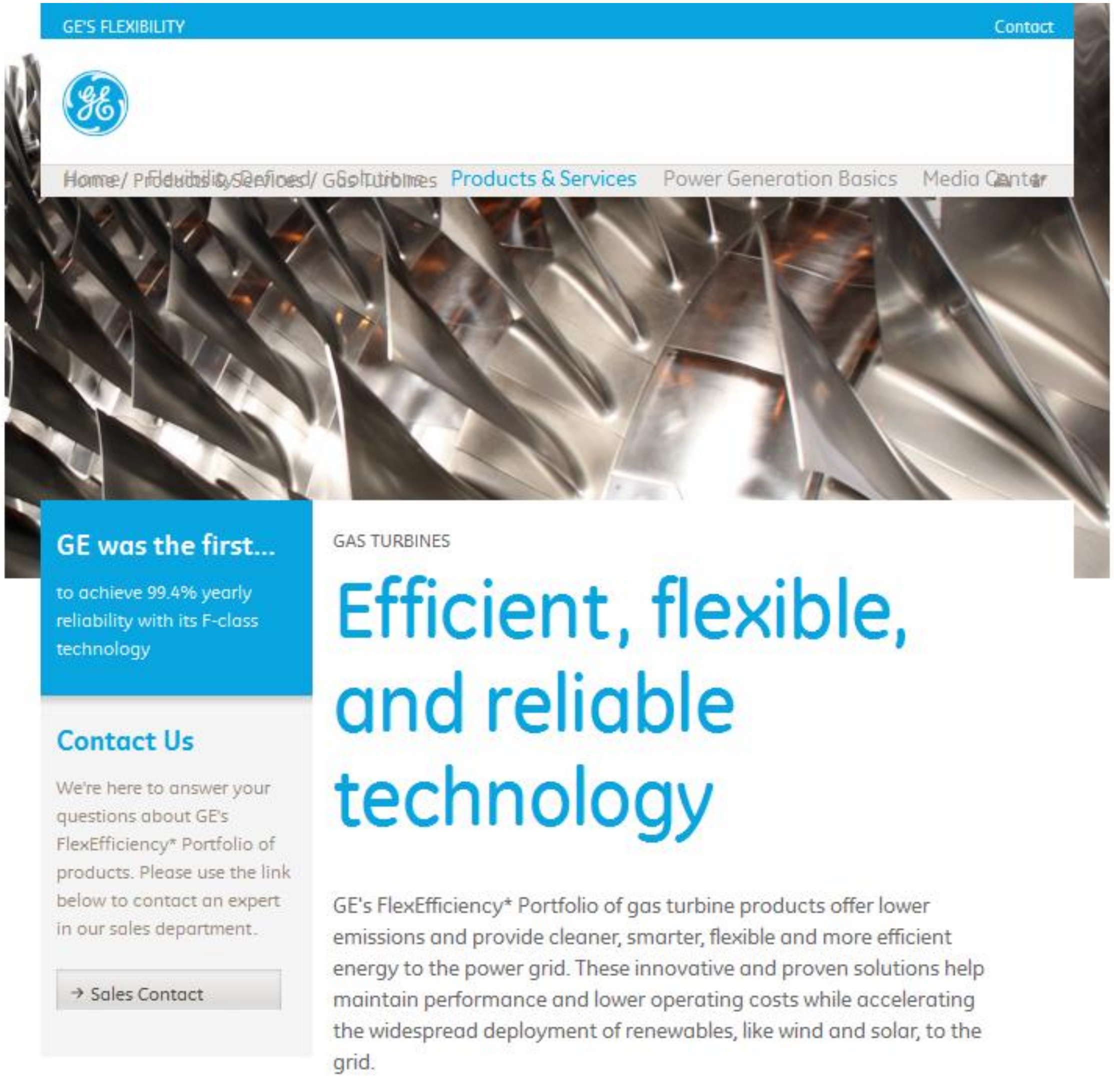
Table 3.2: **The load following ability of dispatchable power plants in comparison**

	Start-up time	Maximal change in 30 sec	Maximum ramp rate (%/min)
Open cycle gas turbine (OCGT)	10-20 min	20-30%	20%/min
Combined cycle gas turbine (CCGT)	30-60 min	10-20%	5-10%/min
Coal plant	1-10 hours	5-10%	1-5%/min
Nuclear power plant	2 hours - 2 days	up to 5%	1-5%/min

Source: EC JRC, 2010 and NEA, 2011a.

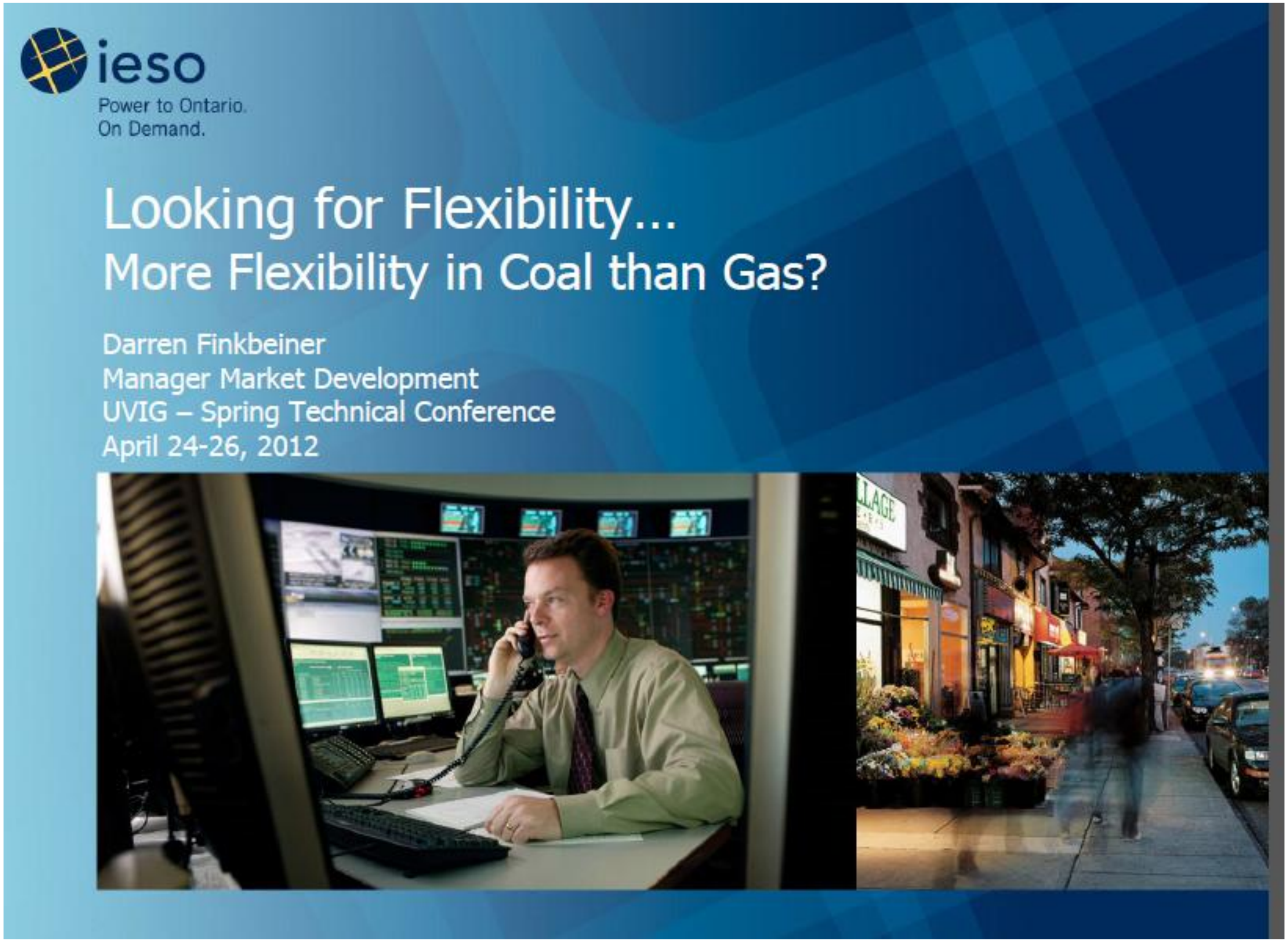
NEA 2012 “Nuclear Energy and Renewables: System Effects in Low-carbon Electricity Systems” Nuclear Energy Agency ISBN 978-92-64-18851-8

Flexible Gas Plant



http://www.ge-flexibility.com/products-and-services/gas-turbines/index.html

Flexible Coal plant ?

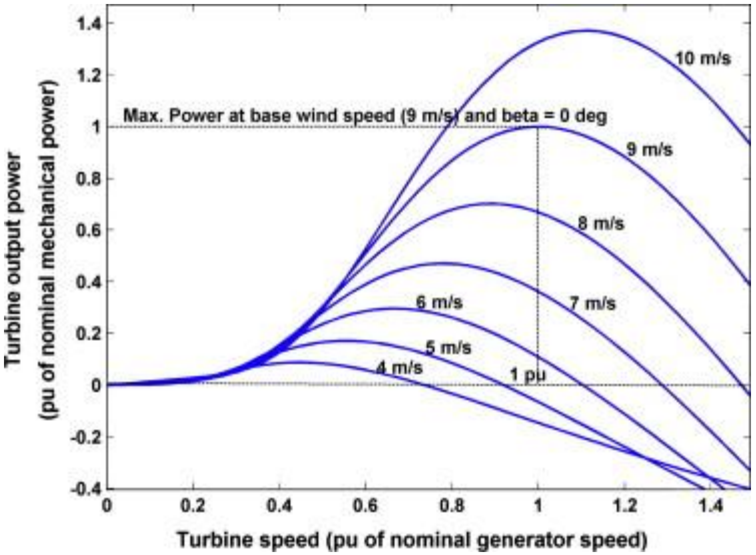


Darren Finkbeiner, IESO, Canada, "Looking for Flexibility... More Flexibility in Coal than Gas?", UVIG – Spring Technical Conference, San Diego, April 24-26, 2012.

Hydro plant

Key Take Away

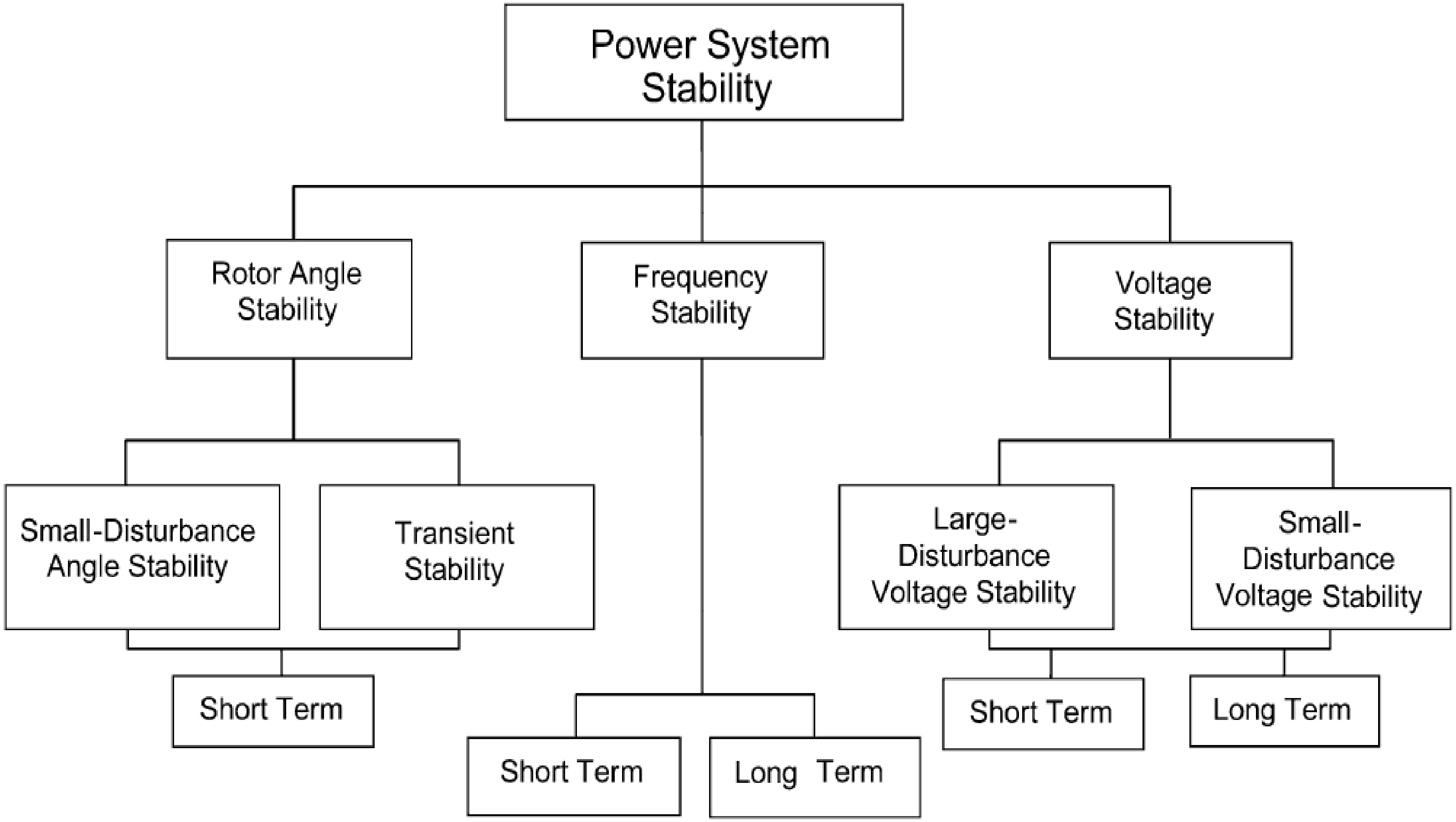
- Thermal power plant can be flexible at a cost
  - Gas tends to be more flexible
  - Coal and nuclear less so
  - Hydro also potentially flexible



Renewable energy generator & stability

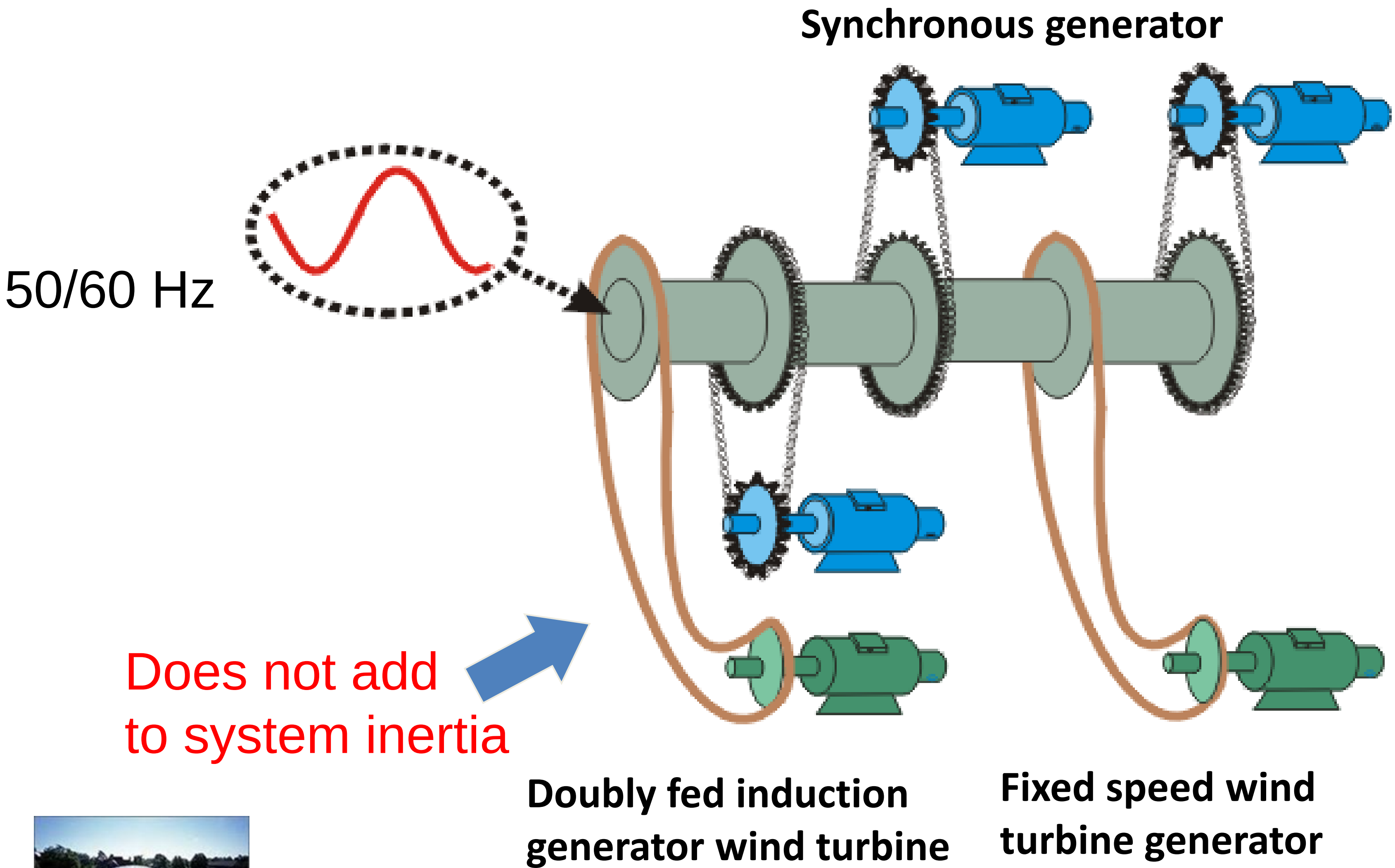
Classification of power system stability

"Power system stability is essentially a single problem"

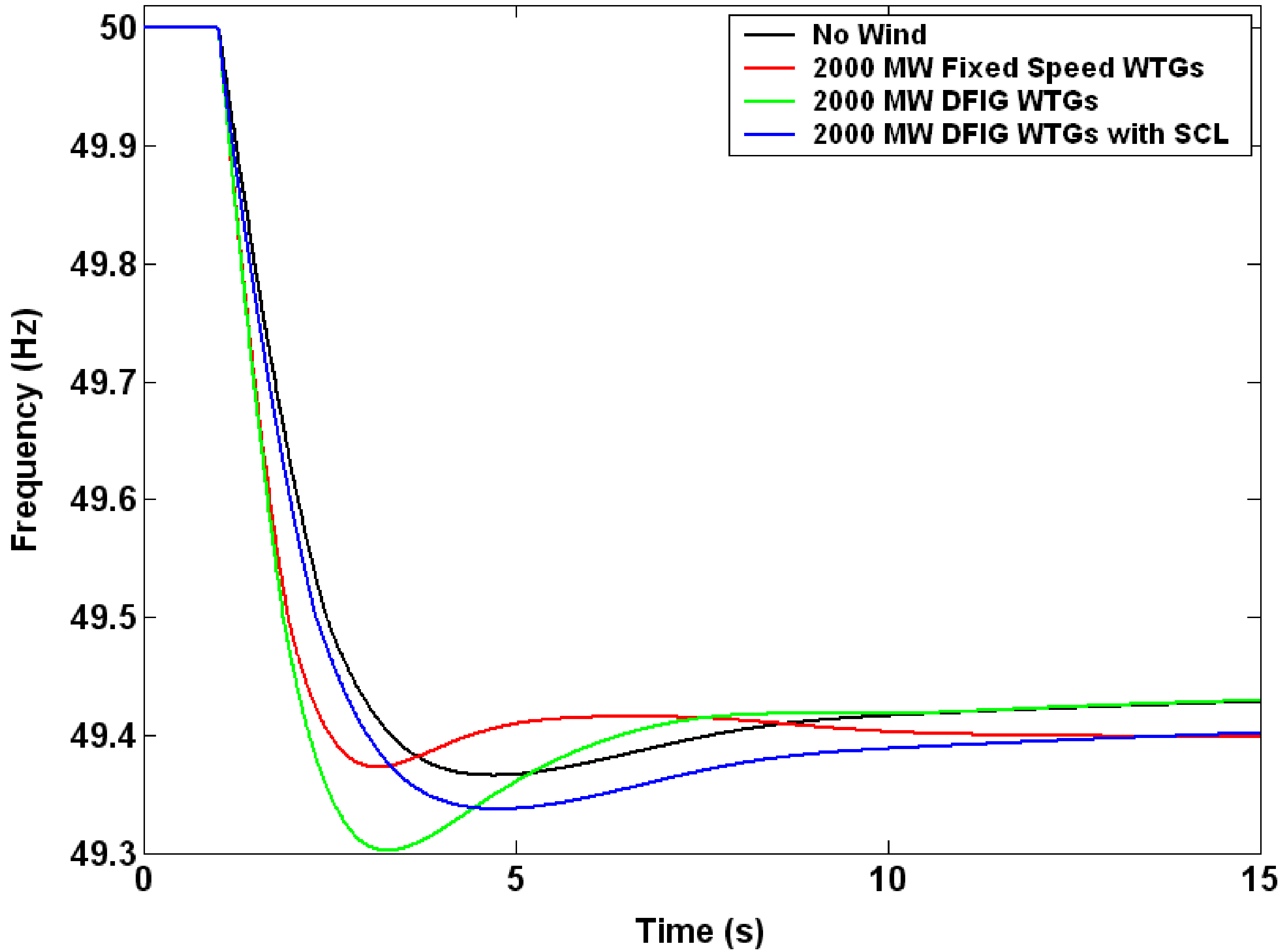


Prabha Kundur, John Paserba, Venkat Ajjarapu, Göran Andersson, Anjan Bose, Claudio Canizares, Nikos Hatziargyriou, David Hill, Alex Stankovic, Carson Taylor, Thierry Van Cutsem and Vijay Vittal. "Definition and Classification of Power System Stability" IEEE/CIGRE Joint Task Force on Stability Terms and Definitions, *IEEE transactions on Power Systems*, Vol. 19, pp. 1387 – 1401, 2004.

Adding non synchronous generation

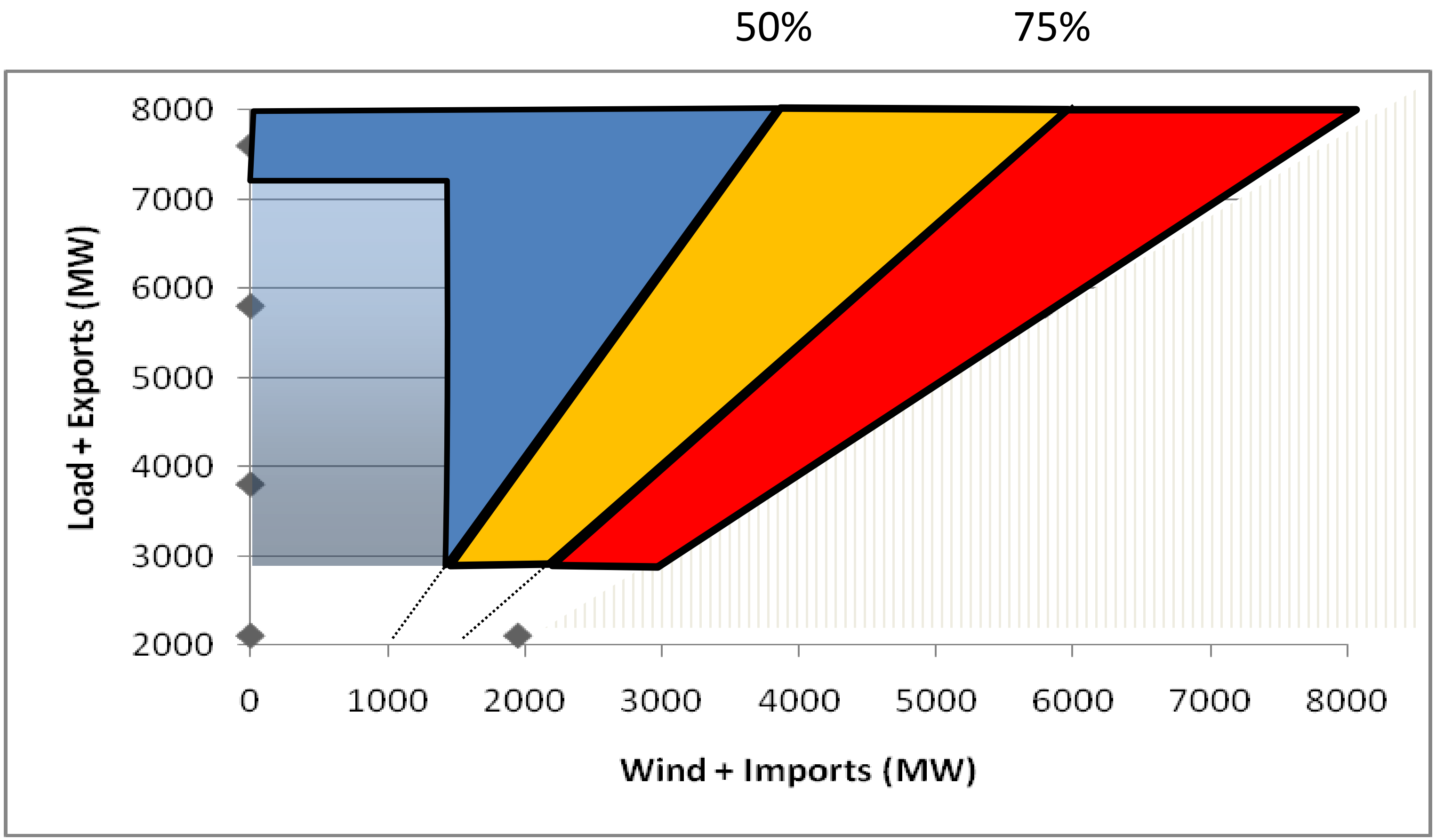


Frequency Response



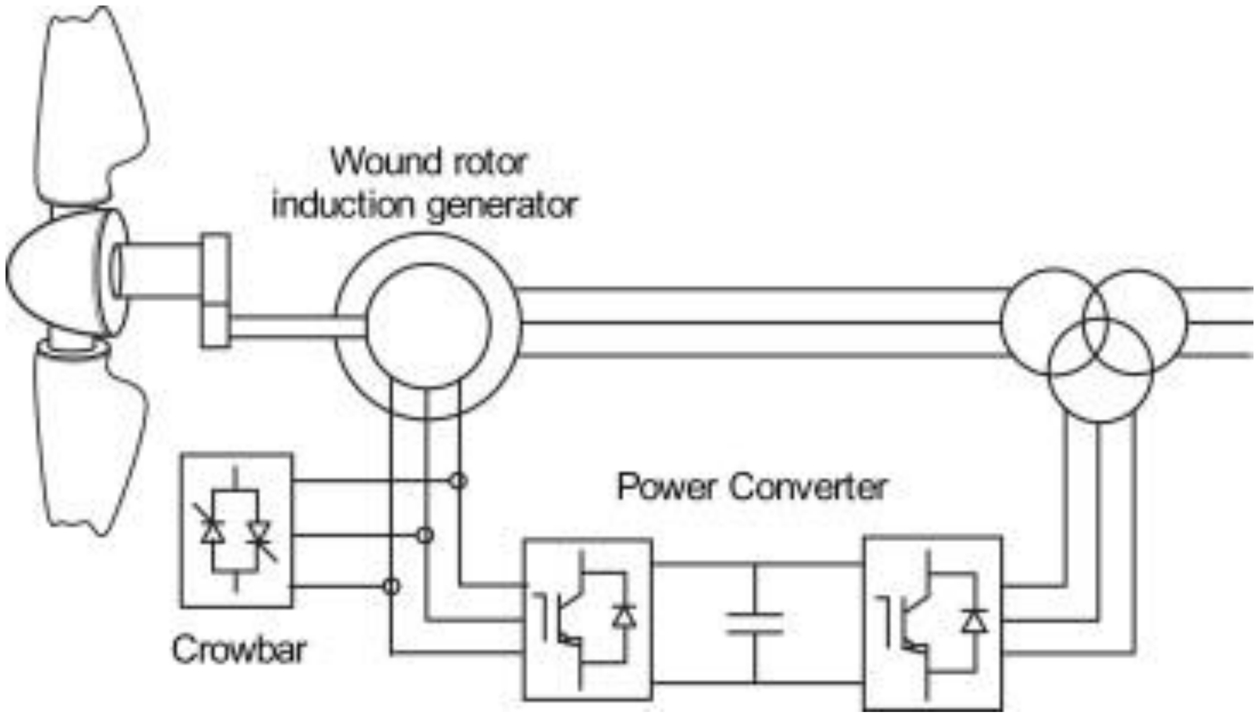
Lalor, G., Mullane, A., and O'Malley, M.J., "Frequency Control and Wind Turbine Technologies", *IEEE Transactions on Power Systems*", Vol. 20, pp. 1903 – 1913, 2005.

Real Time Operational Limits



Maximum Allowable Real Time Wind Level

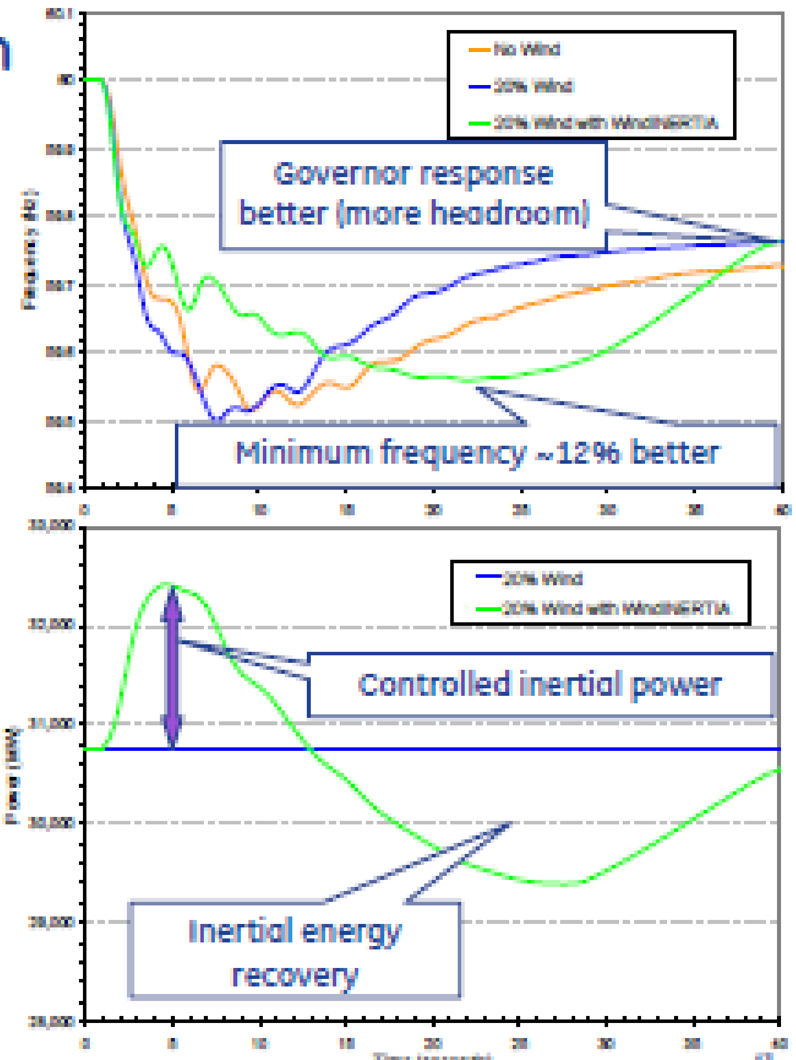
Modern wind and solar PV generators are very controllable



Emulated inertial response

Inertial Response from Wind Generation

- Inertial response reduces and delays minimum frequency
- Margin above UFLS increases by about 40mHz
- Response in this case is overly aggressive: Inertia is now another control variable that can be tuned.



GE imagination at work

Key Take Away

- Renewable energy generators can impact on stability both negatively and positively

- Modern power electronics has enhanced the controllability (frequency and voltage) of renewable energy generators

Storage

Storage Applications

Storage Technologies	Discharge Time / Duration	Storage Application by Response Timeframe									
		Hours					Minutes			Seconds	
		Energy Arbitrage	Generation Capacity Deferral	(T &D) Investment Deferral	Congestion Management	Voltage Support	Black Start	Spinning Reserve	Renewable Ramp Reduction	Regulation	Power Quality
Pumped Hydro	Hours	M	M	M	M	M	M	M	M	M	
CAES	Hours	C	C	C	C	C	C	C	C		
Flywheel	Minutes						D	D	D	D	D
Super Capacitor	Seconds										D
Lead Acid Battery	Hours										C
Advanced Lead Acid Battery	Hours						D	D	D	D	C
NaS Battery	Hours						C		C	C	C
NiCd Battery	Minutes									D	C
Flow Battery	Hours					R	R	R	R	R	R
Li-Ion Battery	Minutes									D	D

Technology Maturity Key : M Mature C Commercial D Demonstration R R & D

Elzinga, D., Dillon, J., O'Malley, M.J., Lampreia, J., "The role electricity storage in providing electricity system flexibility", in Electricity in a climate constrained world. International Energy Agency, Paris, 2012.

Storage Applications & Competitors

			Discharge Time / Duration	Storage Application by Response Timeframe: Hours — Energy Arbitrage	Hours — Generation Capacity Deferral	Hours — (T &D) Investment Deferral	Hours — Congestion Management	Hours — Voltage Support	Minutes — Black Start	Minutes — Spinning Reserve	Minutes — Renewable Ramp Reduction	Seconds — Regulation	Seconds — Power Quality
Storage Technologies		Pumped Hydro	Hours	M	M	M	M	M	M	M	M	M	
Storage Technologies		CAES	Hours	C	C	C	C	C	C	C	C		
Storage Technologies		Flywheel	Minutes						D	D	D	D	D
Storage Technologies		Super Capacitor	Seconds										D
Storage Technologies		Lead Acid Battery	Hours										C
Storage Technologies		Advanced Lead Acid Battery	Hours						D	D	D	D	C
Storage Technologies		NaS Battery	Hours						C		C	C	C
Storage Technologies		NiCd Battery	Minutes									D	C
Storage Technologies		Flow Battery	Hours					R	R	R	R	R	R
Storage Technologies		Li-Ion Battery	Minutes									D	D
Competing Technologies	Generation	Conventional Generation	>Hours		M	M		M	M	M	M	M	
Competing Technologies	Generation	Generation Re-dispatch	>Hours			M	M						
Competing Technologies	Generation	Hydro Generation	>Hours			M	M	M	M	M	M	M	
Competing Technologies		Demand Response[1]	Hours	M	M					M			
Competing Technologies	Transmission / Interconnection	Interconnection	Hours	M	M	M	M		M	M	M		
Competing Technologies	Transmission / Interconnection	Transmission	>Hours	M	M	M	M	M	M			M	M
Competing Technologies	Transmission / Interconnection	Static Comp. Devices	>Hours			M		M					
Competing Technologies	Transmission / Interconnection	Power Electronics	Seconds										M
Competing Technologies	Operational Measures	Protection Measures	Seconds			M	M						
Competing Technologies	Operational Measures	Dynamic Line Rating	Hours			C	C						
Competing Technologies	Operational Measures	Forecasting	Hours	M									

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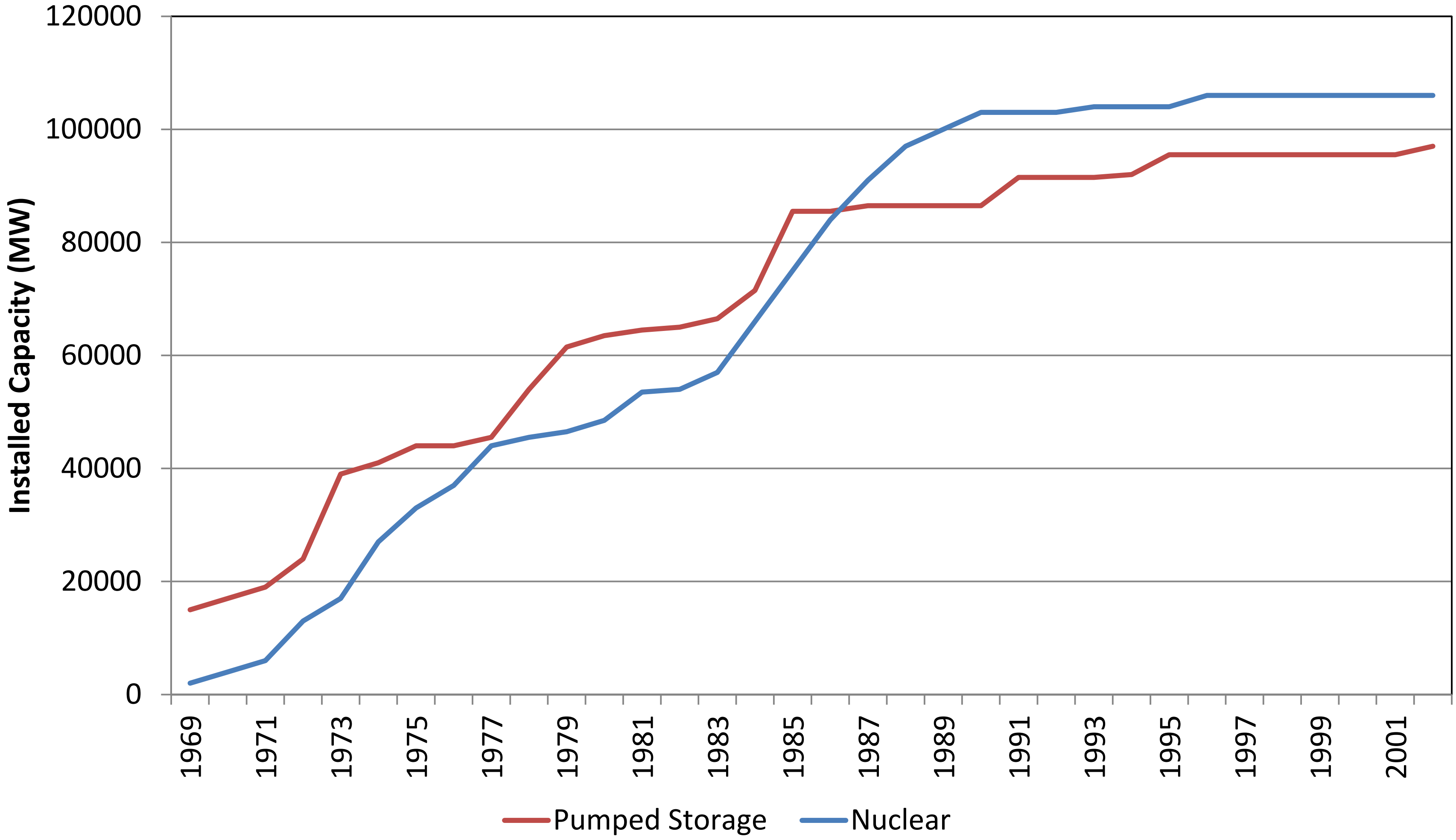
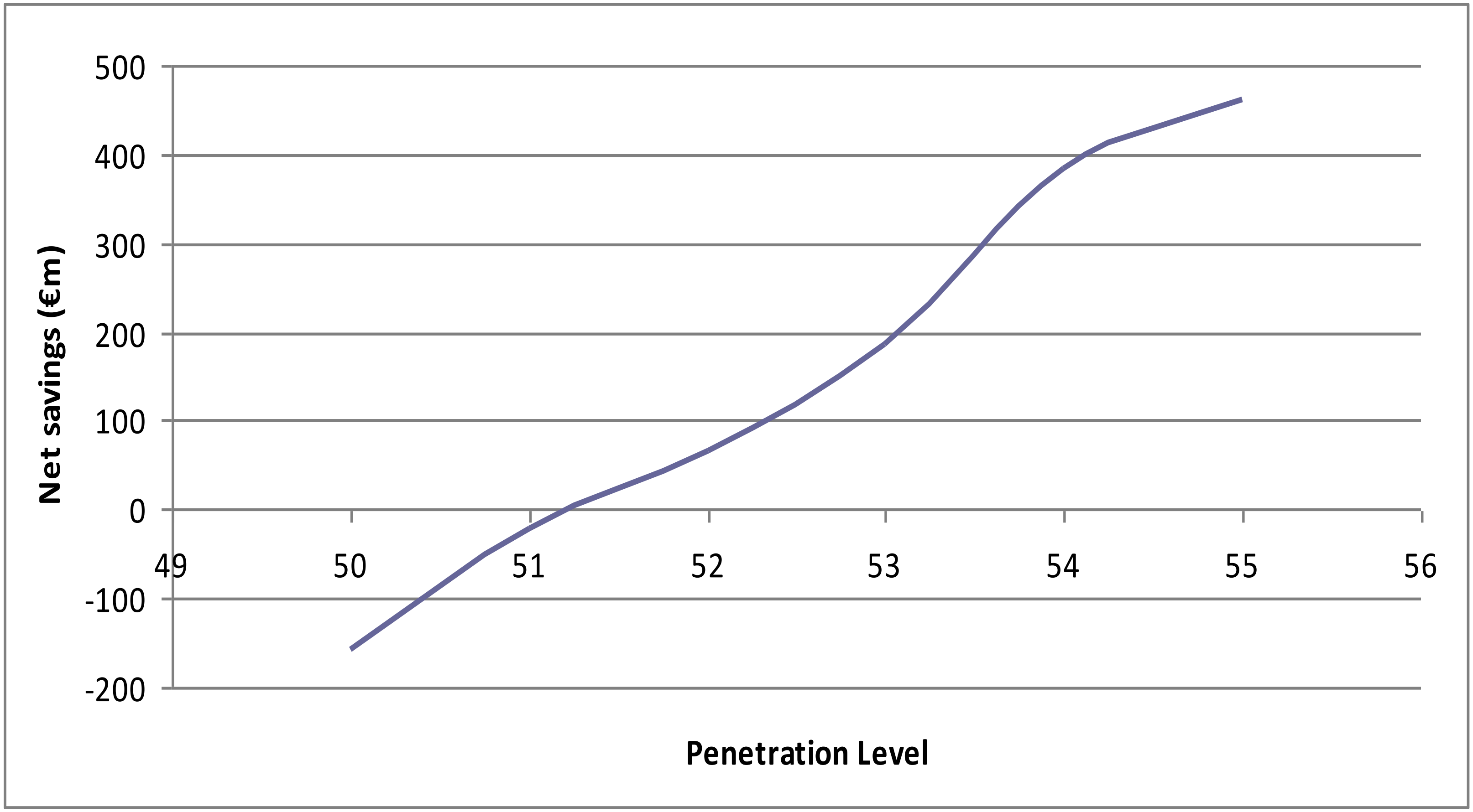
Historical Storage Drivers



Data From OECD Countries only

Business case for storage



Tuohy, A. and O'Malley, M.J., "Pumped Storage in Systems with Very High Wind Penetration", E*nergy Policy*, Vol. 39, pp. 1965-1974, 2011.

Key Take Away – Storage

- Storage can supply multiple services
  - Energy arbitrage
  - Ancillary services
  - The opportunity for these services increases with variable renewable energy
  - Storage has competitors for all these opportunities and is generally more costly

Demand (consumer) Response

Empowering consumers through energy management techniques such as demand response could save $17 billion annually.

http://www.mckinsey.com/client_service/electric_power_and_natural_gas/latest_thinking/mckinsey_on_smart_grid

Demand Response with renewables

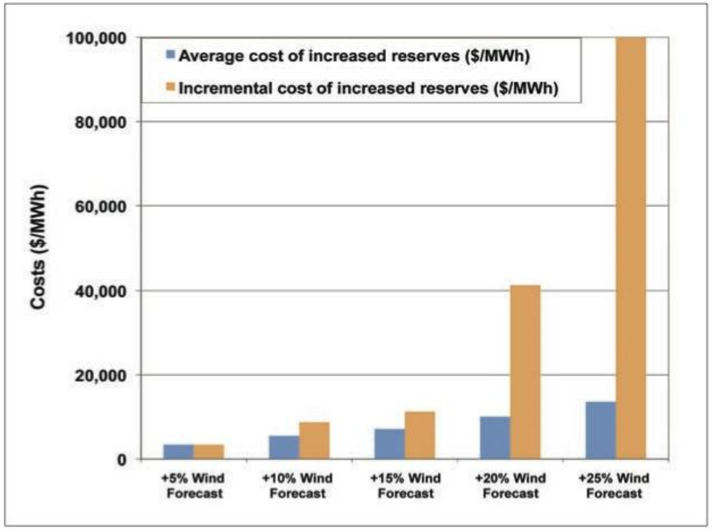


Figure 12 – The cost of increasing spinning reserves increases with higher percentages of spin. The incremental cost increases sharply at higher percentages of spin, indicating that the cost of reducing those final reserve shortfalls is prohibitively high. *The five bars show the effect of increasing spinning reserve by 5, 10, 15, 20, and 25% of the day-ahead wind forecast.*

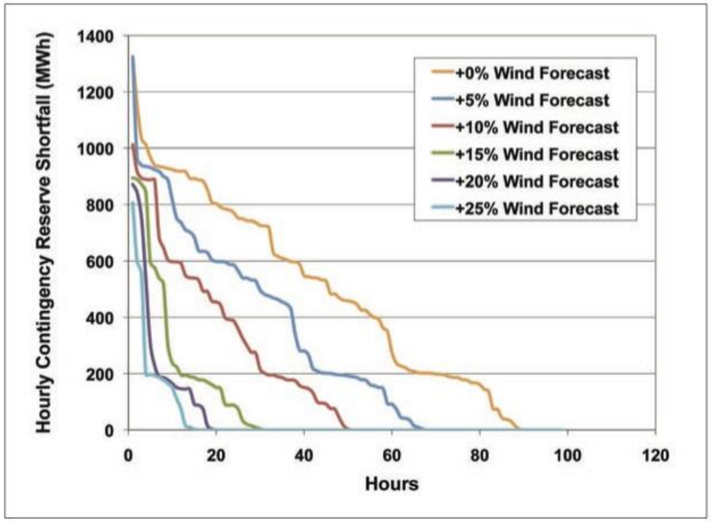
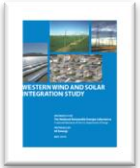


Figure 13 – A demand response program which requires load to participate in the 89 hours of the year that there are contingency reserve shortfalls is more cost-effective than increasing spin for each of the 8760 hours of the year. *Hourly contingency reserve-shortfall duration curves for the In-Area 30% case with a SOA forecast with no additional spinning reserves, and then with spinning reserves increased by 5, 10, 15, 20, and 25% of the day-ahead wind forecast.*

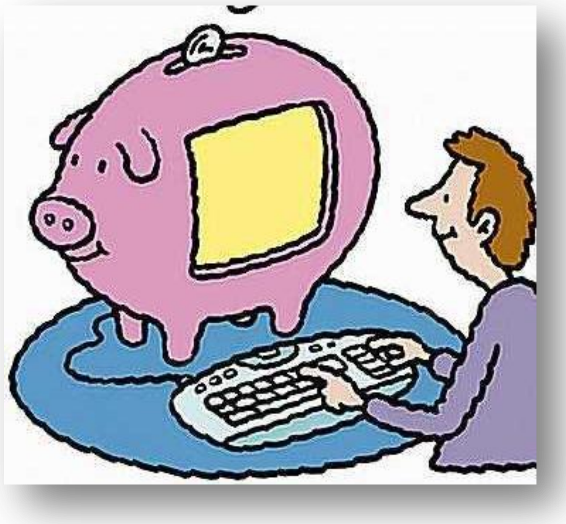
High wind and solar displace thermal units leading to a shortfall in contingency reserves; demand response may be more cost-effective than committing additional units for 89 hours of the year.

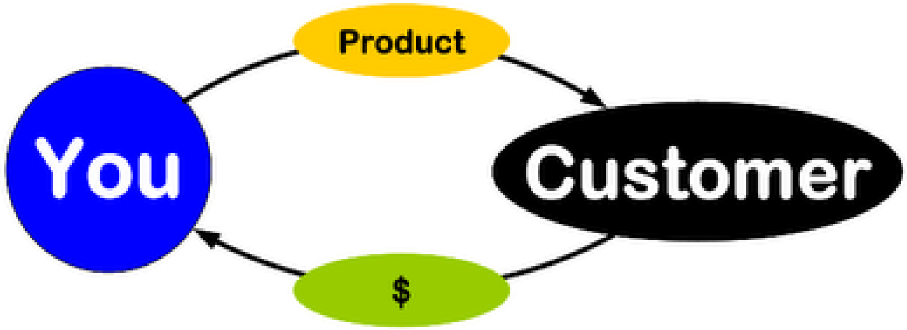


Western Wind and Solar Integration Study, NREL, GE (2010)
http://www.uwig.org/wwsis_executive_summary.pdf

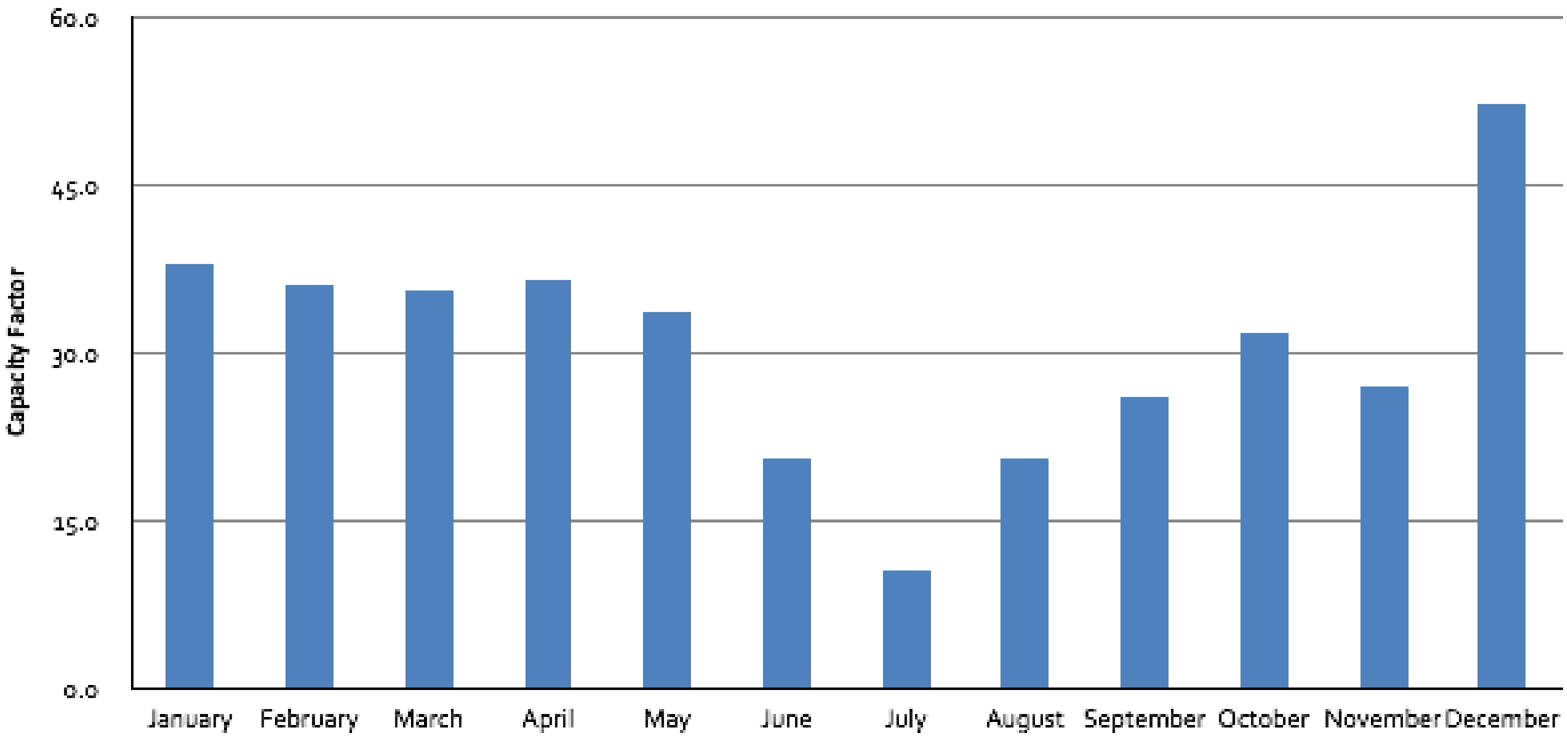
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Business model



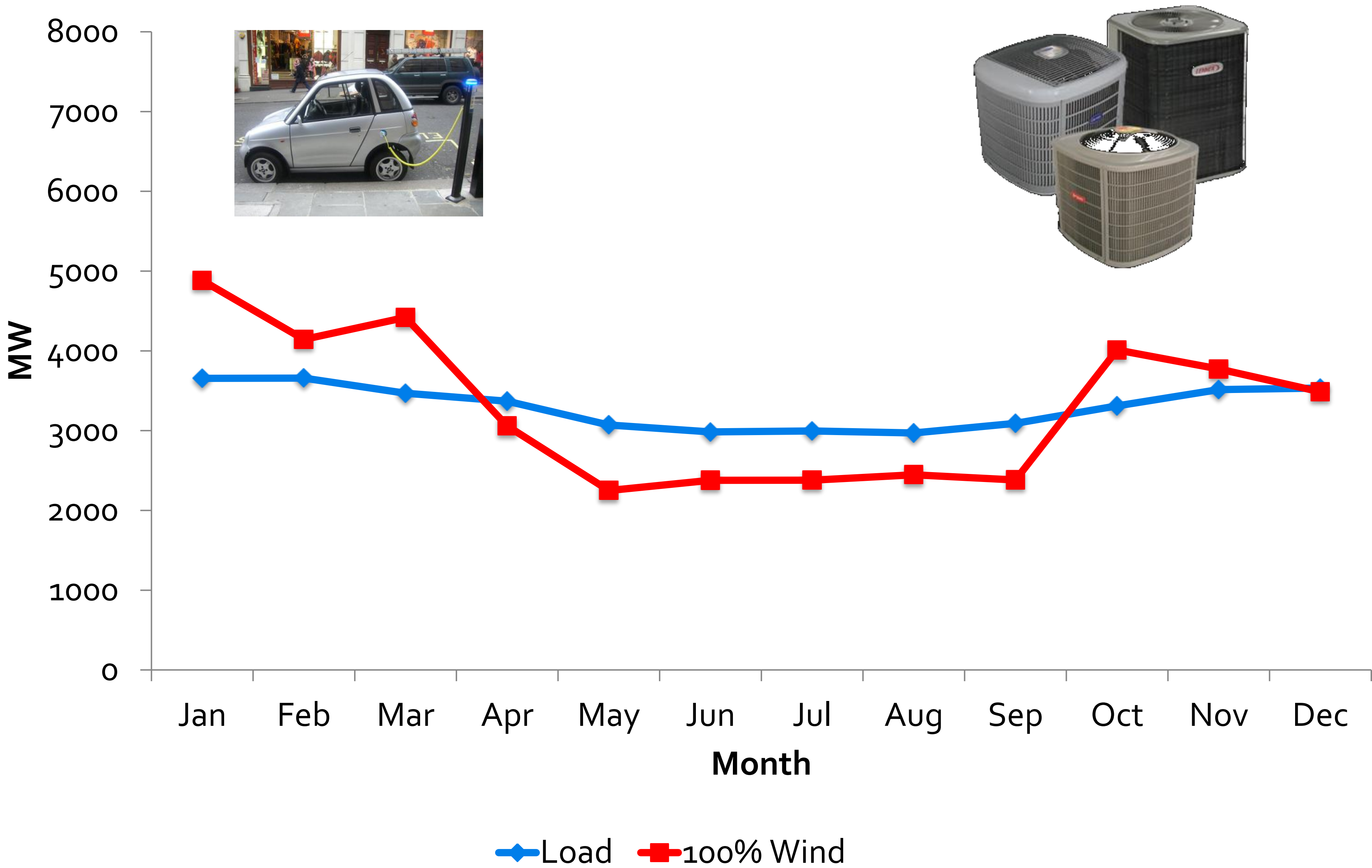


All Island Wind Capacity Factor 2013



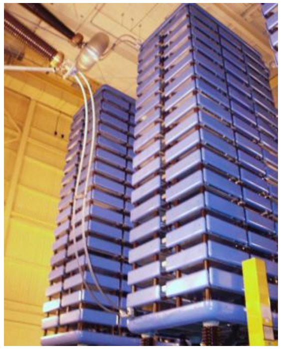
Note: All values used are based on 15 min historical SCADA values

100 % Wind we will have to change how we live



Key Take Away

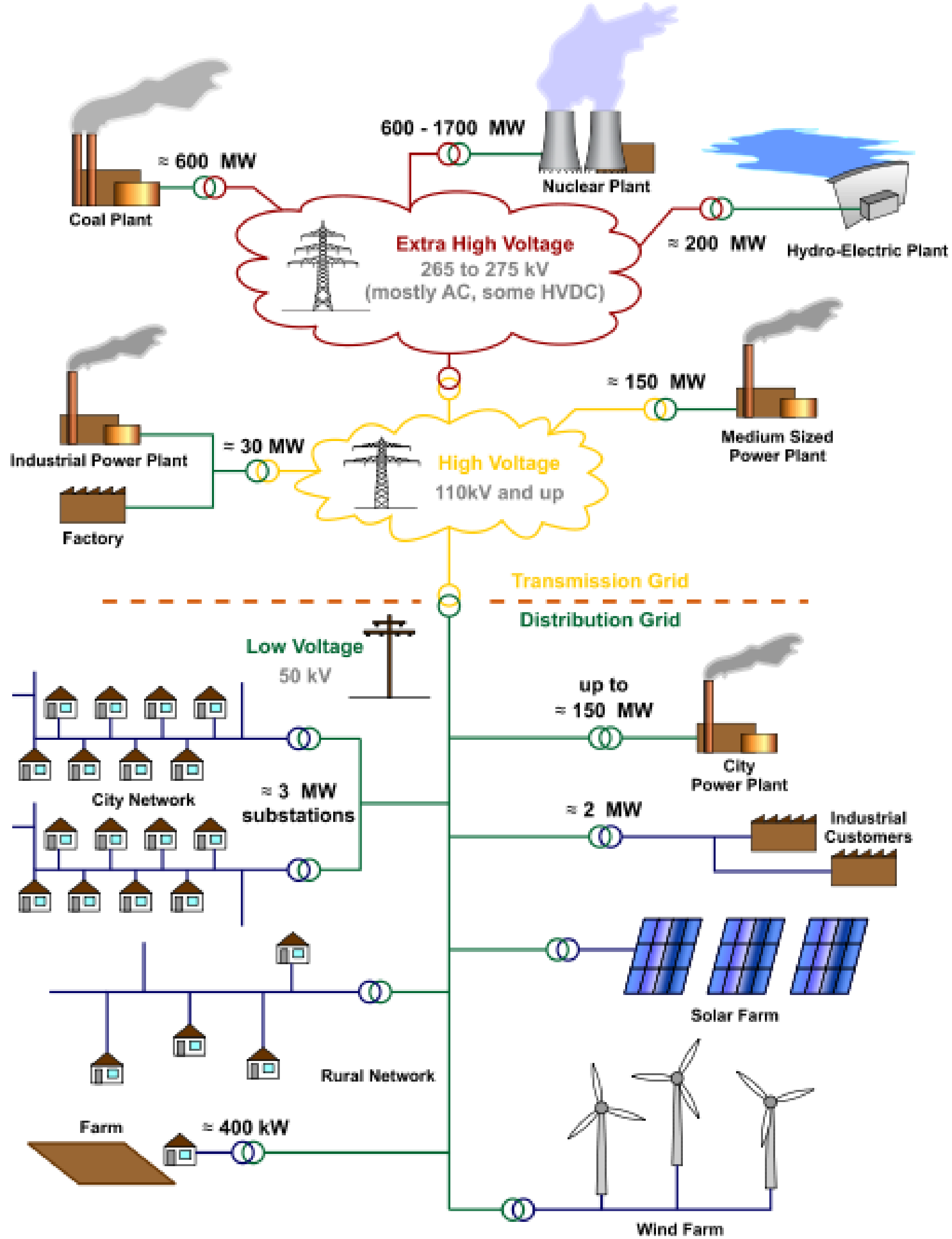
- Demand response is an important potential integration resource
- Demand response and storage unlikely to address variability at longer time scales



New technologies

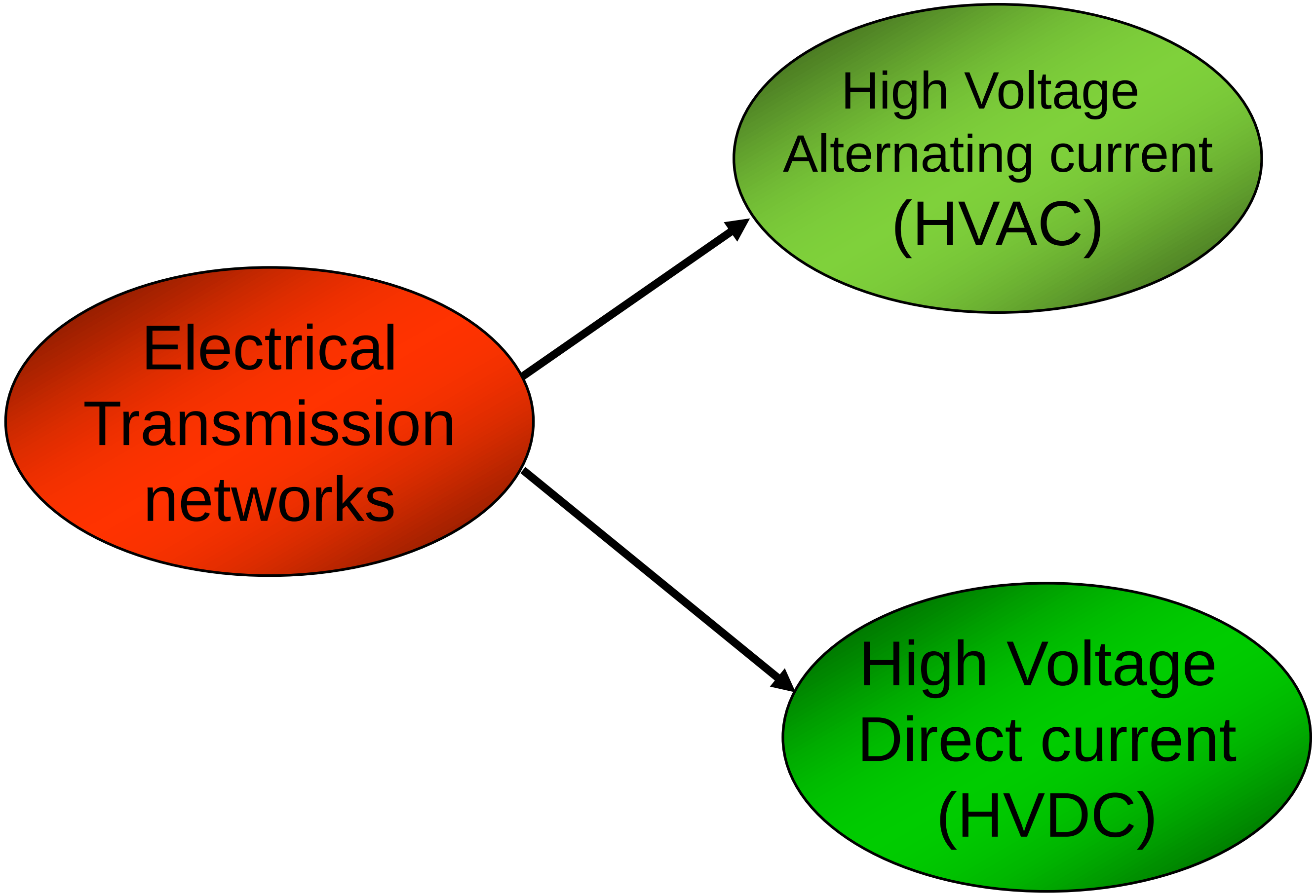
Power Electronics Applications

- Flexible AC Transmission Systems (FACTS)
- High Voltage DC (HVDC)
  - Classic
  - Light (VSC) – more controllable
- Connection of Distributed Generation
- Variable renewables
  - Photovolatics
  - Wind Turbines
- Loads – AC-DC conversion for most electronic equipment.



Source: Terence O'Donnell, UCD

Electrical Transmission Systems

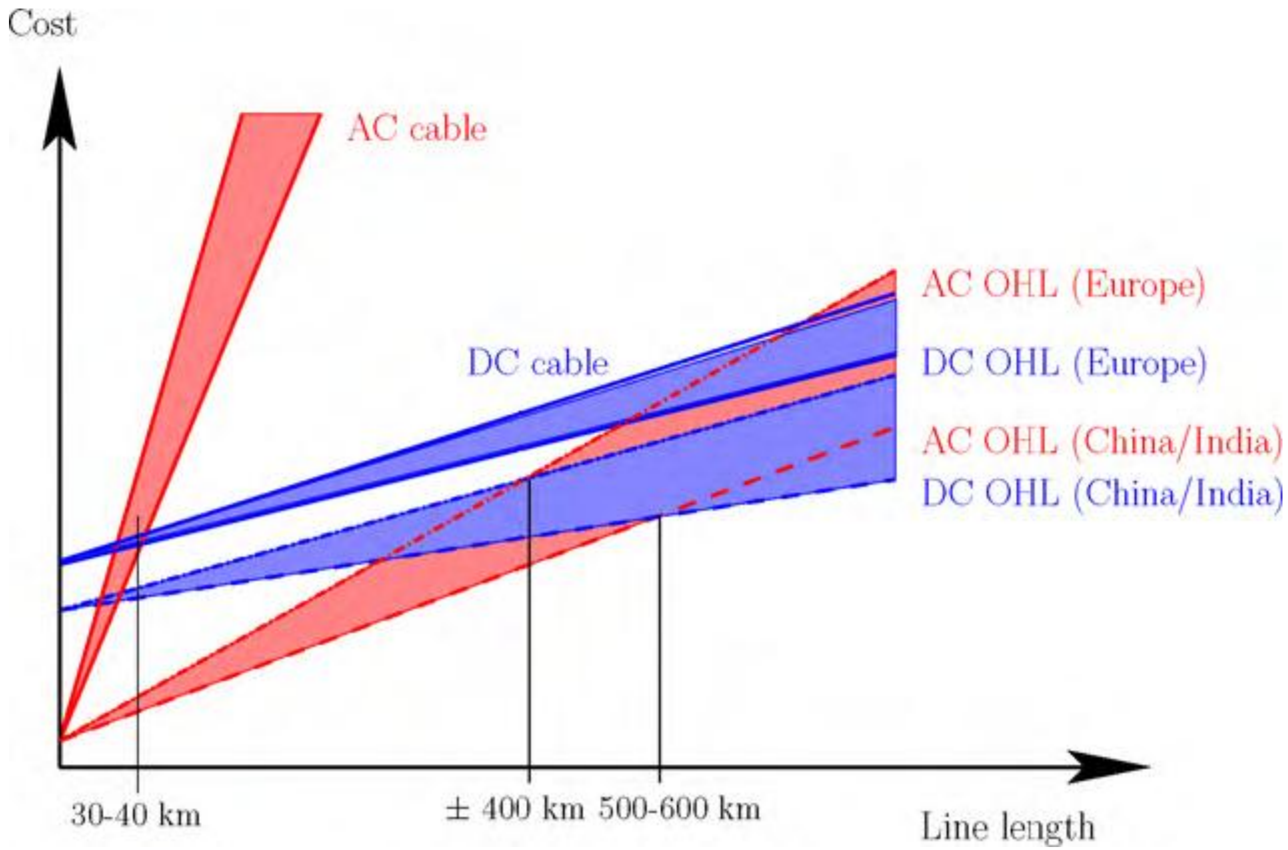


- Overhead lines
- Sea-cables (short)
- Underground cables (short)
- Meshed grids

- Overhead lines
- Sea-cables
- Underground cables
- Point to point not meshed

AC vs. DC

- Cost comparison AC vs. DC



"Multi-terminal VSC HVDC for the European supergrid: Obstacles", D. Van Hertem, M. Ghandhari / Renewable and Sustainable Energy Reviews 14 (2010) 3156–3163

Technology (Smart Grids) Solutions

- Avoid construction of new lines
- Dynamic Line Rating (DLR)
  - Real time measurements (temperature, wind speed) are used to derive more accurate capacities of transmission lines
  - 25%-30% increases in line capacity 90% of the time
- Special Protection Schemes (SPS)
  - Automatic corrective actions rather than conservative preventive control
  - Increase in system risk associated with the complexity of the scheme

Source: Janusz Bialek

Key Take Away

- Power electronics and DC are growing in importance
- HVDC is typically for long distance point to point energy transfers and can be very controllable
- Other “smart grid” technologies can make the grid more flexible and increase its capacity

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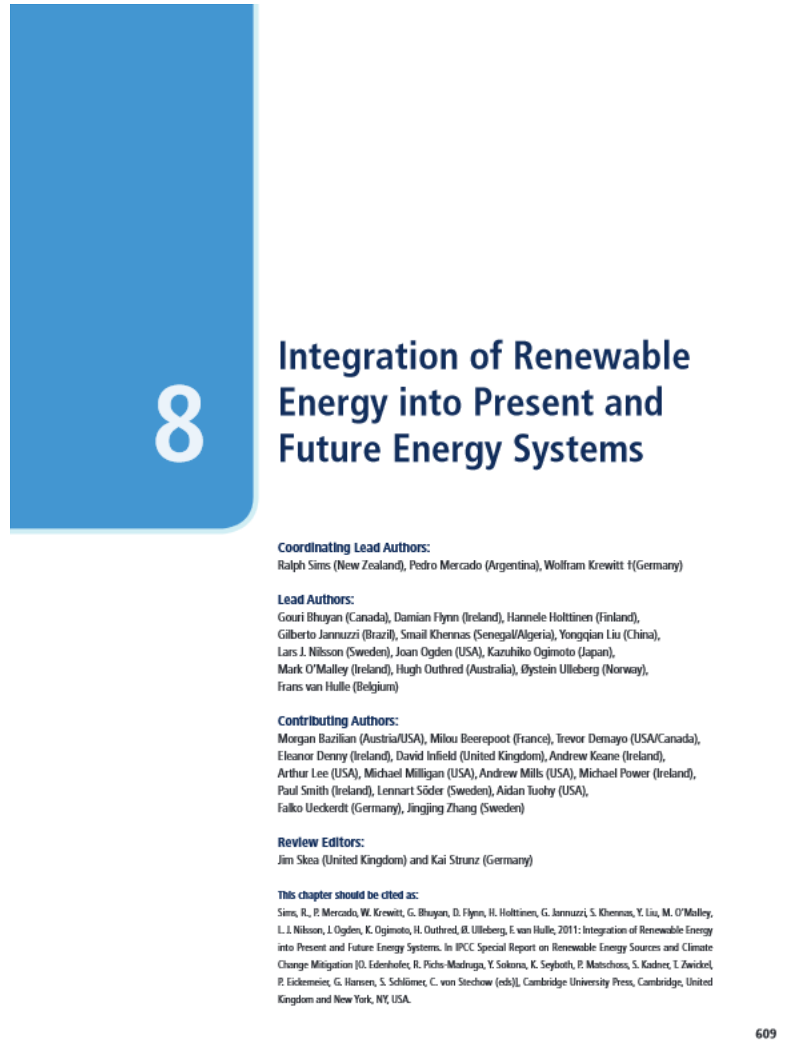

8

Integration of Renewable Energy into Present and Future Energy Systems

Coordinating Lead Authors:
Ralph Sims (New Zealand), Pedro Mercado (Argentina), Wolfram Krewitt †(Germany)

Lead Authors:
Gouri Bhuyan (Canada), Damian Flynn (Ireland), Hannele Holttinen (Finland), Gilberto Jannuzzi (Brazil), Smail Khennas (Senegal/Algeria), Yongqian Liu (China), Lars J. Nilsson (Sweden), Joan Ogden (USA), Kazuhiko Ogimoto (Japan), Mark O'Malley (Ireland), Hugh Outhred (Australia), Øystein Ulleberg (Norway), Frans van Hulle (Belgium)

Contributing Authors:
Morgan Bazilian (Austria/USA), Milou Beerepoot (France), Trevor Demayo (USA/Canada), Eleanor Denny (Ireland), David Infield (United Kingdom), Andrew Keane (Ireland), Arthur Lee (USA), Michael Milligan (USA), Andrew Mills (USA), Michael Power (Ireland), Paul Smith (Ireland), Lennart Söder (Sweden), Aidan Tuohy (USA), Falko Ueckerdt (Germany), Jingjing Zhang (Sweden)

Review Editors:
Jim Skea (United Kingdom) and Kai Strunz (Germany)

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