Harvesting Renewable Energy
The Grid Integration Challenge

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IEEE DLP, 19th May 2011

Zagreb

electricity research centre

UCD DUBLIN

Mark O'Malley

- Professor of Electrical Engineering at University College Dublin (UCD)
- Founder and Director of the Electricity Research Centre (http://ee.ucd.ie/erc)
- Royal Irish Academy
- Fellow of the Institute of Electrical and Electronic Engineers (IEEE)
  - IEEE Ethics and Member Conduct Committee.
  - Chair of the IEEE Power and Energy Society Task Force on Capacity Value of Wind
  - Editorial Board of the IEEE Transactions on Power Systems
  - IEEE Power Engineering Society Wind Power Coordinating Committee
  - IEEE distinguished lecturer in the grid integration of renewable energy
- European Academy of Sciences Advisory Council Energy Panel and is the
- North American Electric Reliability Corporation Task Force on Integrating Variable Generation
- International Energy Agency Research Task 25: Design and Operation of Power Systems with Large Amounts of Wind Power
- International Panel on Climate Change Special Report on Renewable Energy Sources and Climate Change Mitigation.
- Wind Integration Studies: All Island Grid Study; Eastern Wind Integration and Transmission Study; Western Wind and Solar Integration Study.

Electricity Research Centre (ERC), Industry Members

Other stakeholders on ERC board:

seai

ESRI

Department of Communications Energy & Natural Resources

Major Funding sources:

erc electricity research centre

sfi

IRCSET

HEA Higher Education Authority An tÚdarás um Ard-Oideachas

Electricity Research Centre (ERC), 2011


Prof. Mark O'Malley


Dr. Ciara O'Connor


Ms. Magdalena Szczepanska


Ms. Rachael O' Hegarty

ERC has four research strands across two institutions, UCD and TCD:

- **Operations**
  Dr. Damian Flynn








- **Networks**
  Dr. Andrew Keane







- **Economics**
  Dr. Eleanor Denny (TCD)






- **Systems**
  Prof. Mark O'Malley





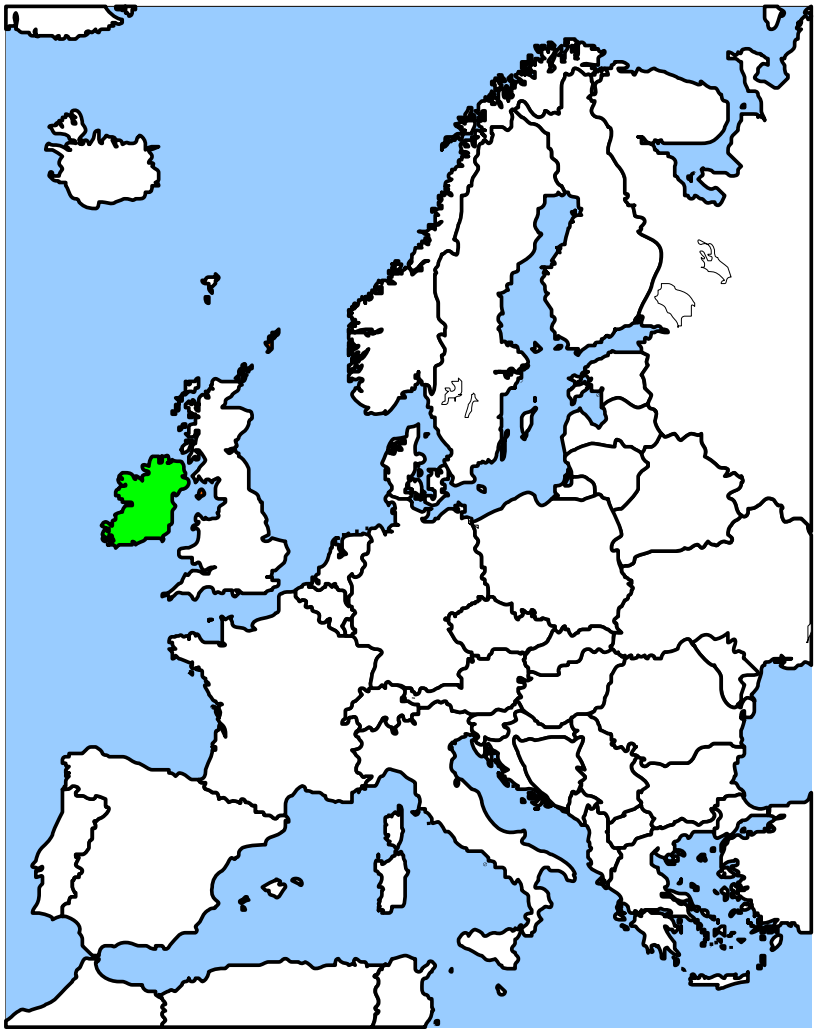




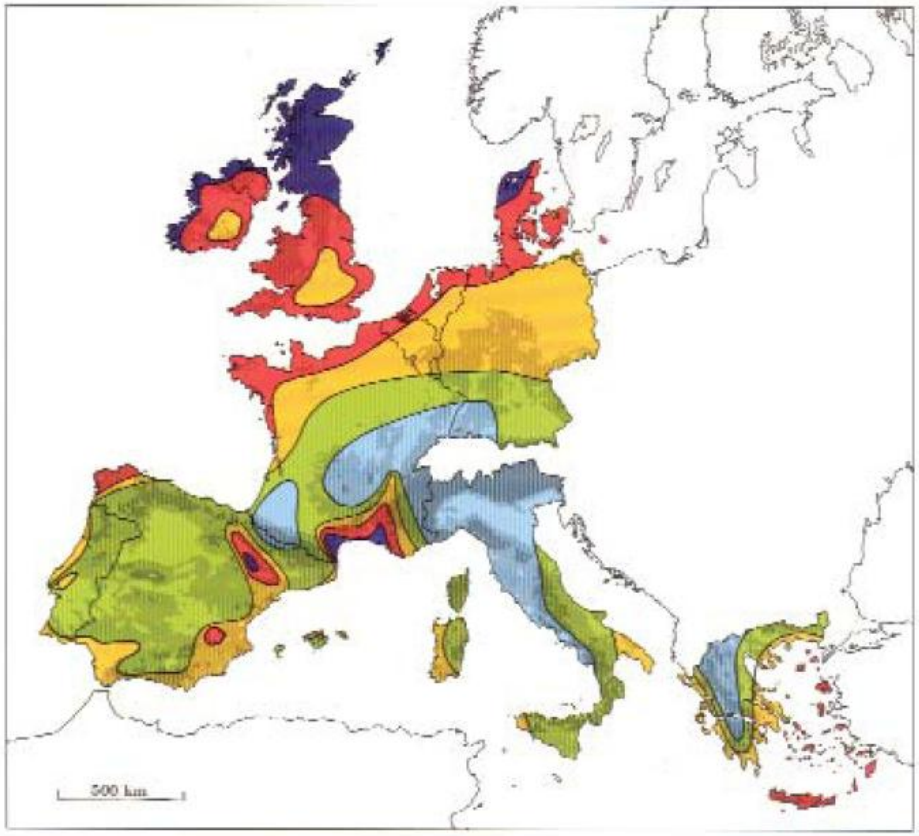
Ireland has a unique renewable resource & technical environment

Ireland: All Island Grid

- Republic of Ireland (RoI) & Northern Ireland
- 9.7 GW Installed
- 1.8 GW Wind (> 10 % energy)
- 450 HVDC to GB
- Max load: 6.5 GW
- Min load: 2.4 GW

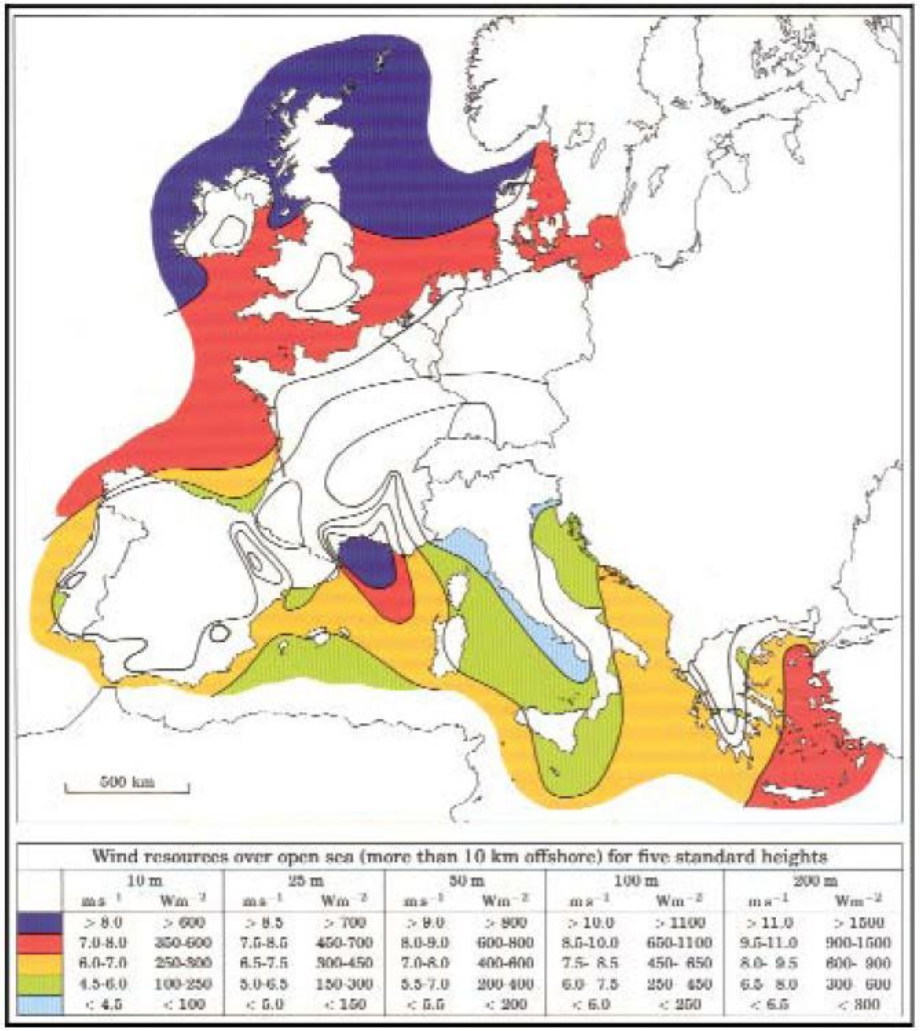


European Wind Resources



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]	
	m s^{-1}	Wm^{-2}	m s^{-1}	Wm^{-2}	m s^{-1}	Wm^{-2}	m s^{-1}	Wm^{-2}	m s^{-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	5.5-7.0	200-400	7.0- 8.5	400- 700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 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	
	m s^{-1}	Wm^{-2}	m s^{-1}	Wm^{-2}	m s^{-1}	Wm^{-2}	m s^{-1}	Wm^{-2}	m s^{-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

Offshore

Sustainable development commission, Wind Power in the UK, 2005

Wind Stats 2009

	Capacity (MW)#	Energy (%)#	Wind capacity factor (%)*	System
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%		
China	26,010^	1%^^		

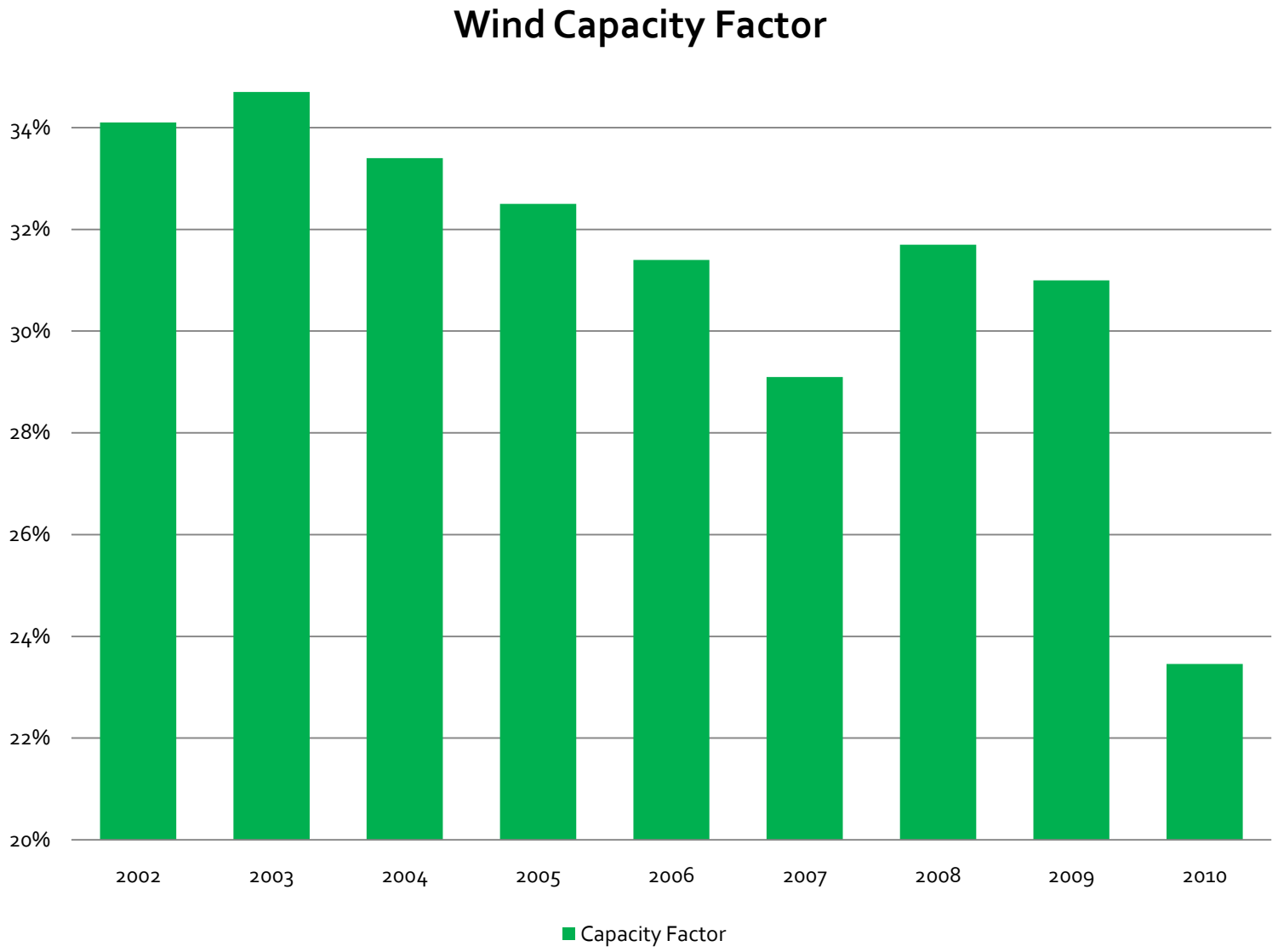
IEA, Wind Energy, Annual Report, 2009

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

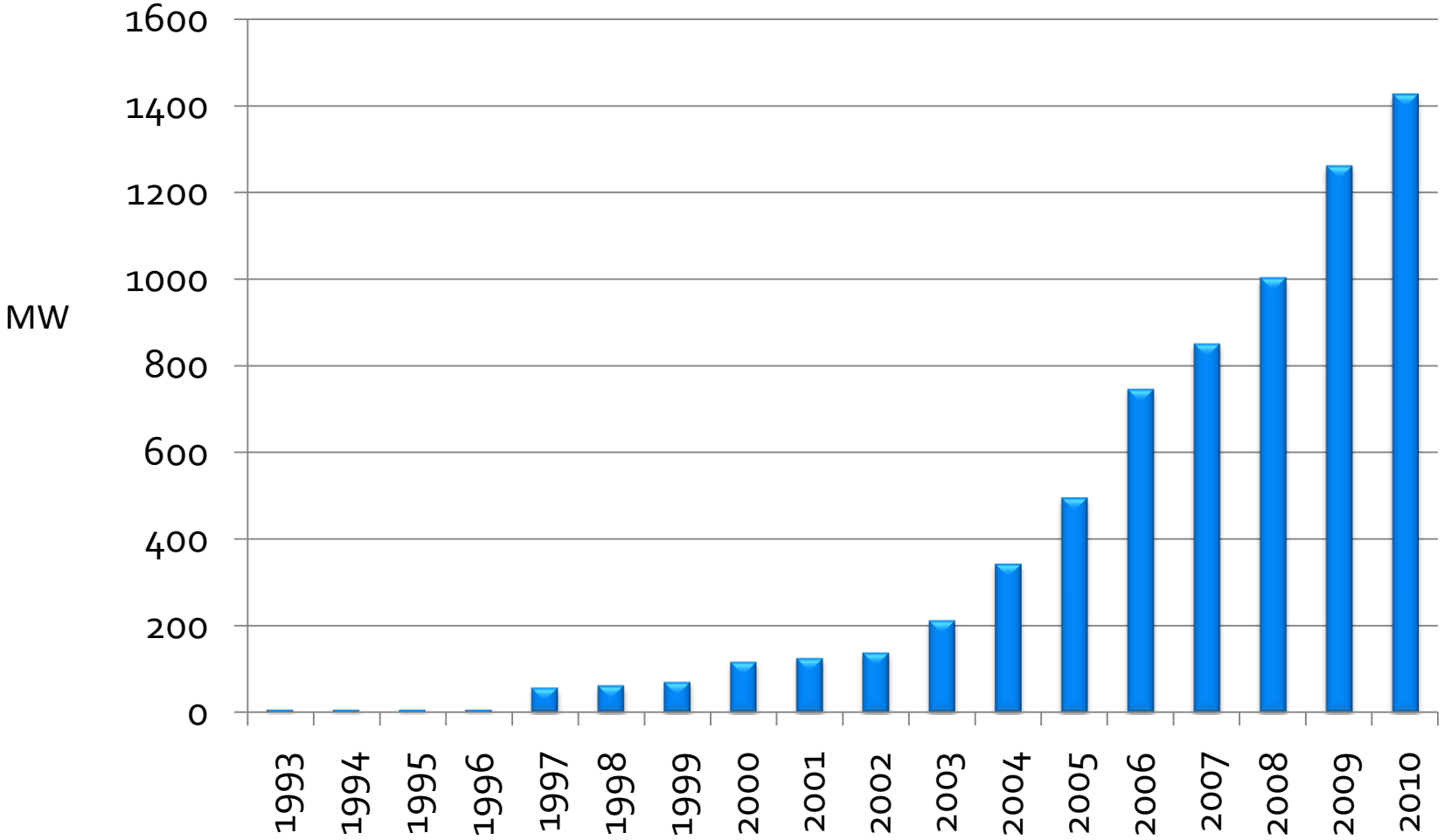
^ World Wind Energy Report 2009, WWEA

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

Capacity factor (Republic of Ireland)

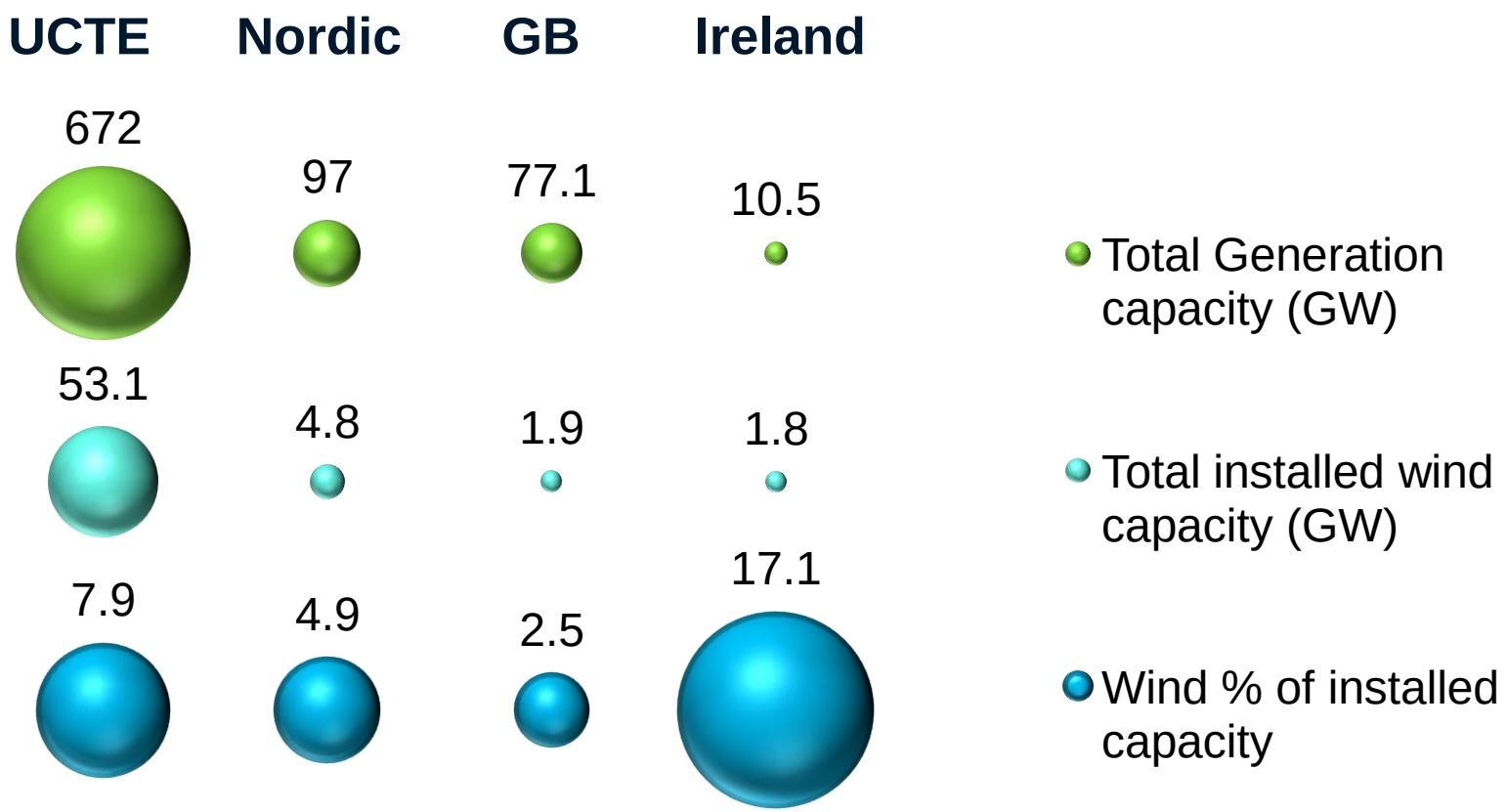


Wind Installed in Republic of Ireland



Source: EirGrid

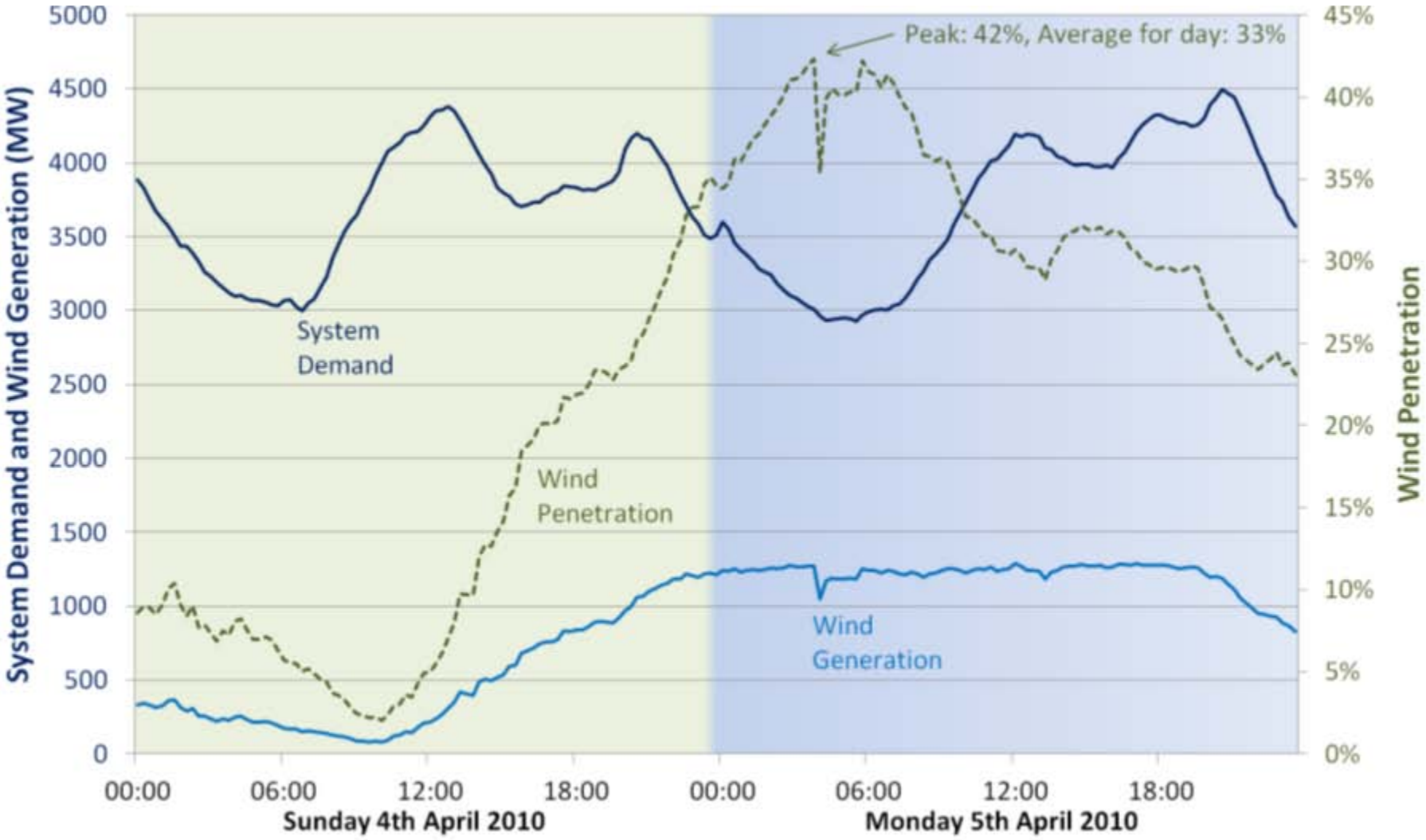
Ireland: Very High Wind Penetration



Figures for end 2008

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

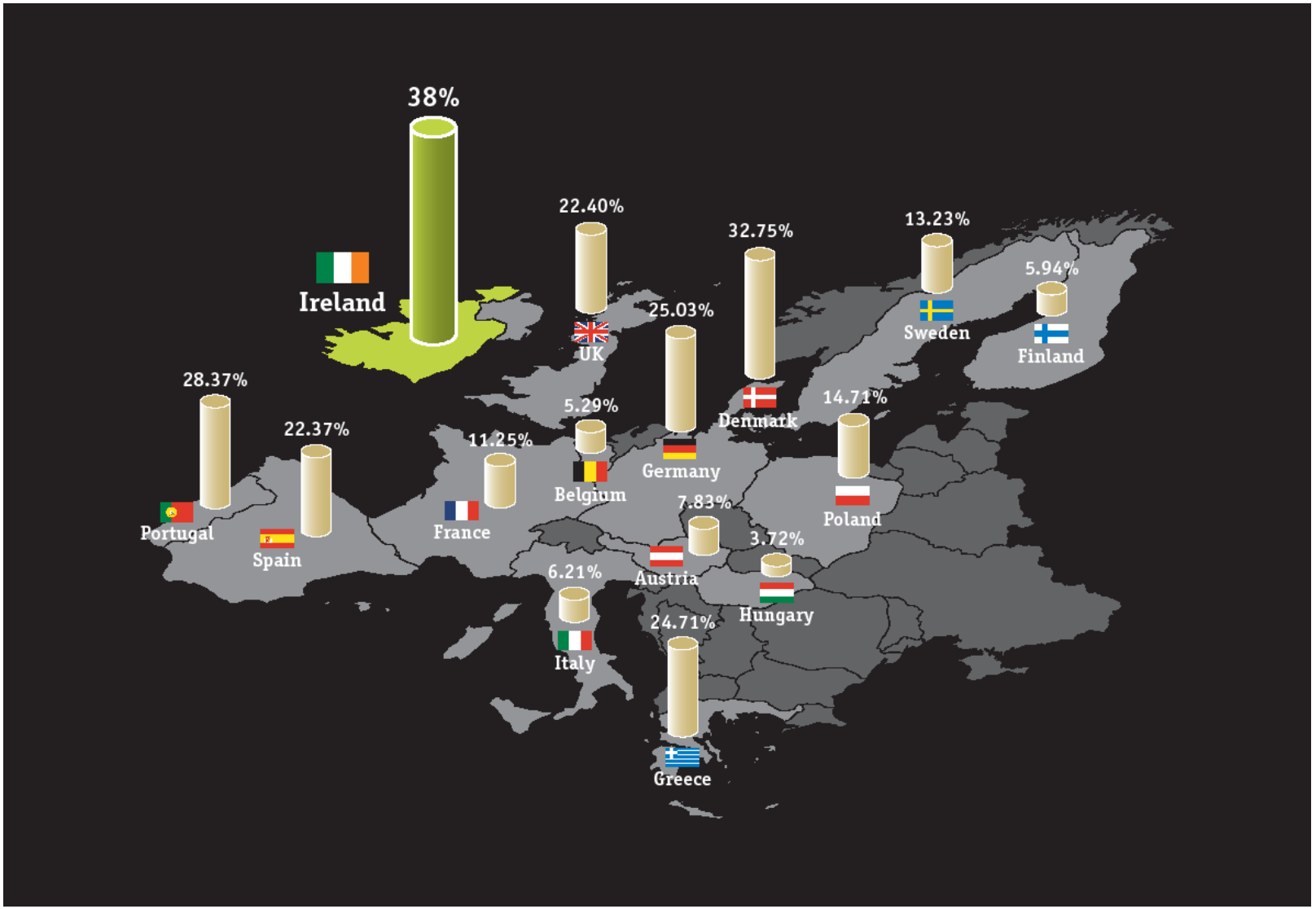
Wind in Republic of Ireland, April 2010



~1 .2 GW wind power change in 18 hours
(2 % to 42 % penetration)

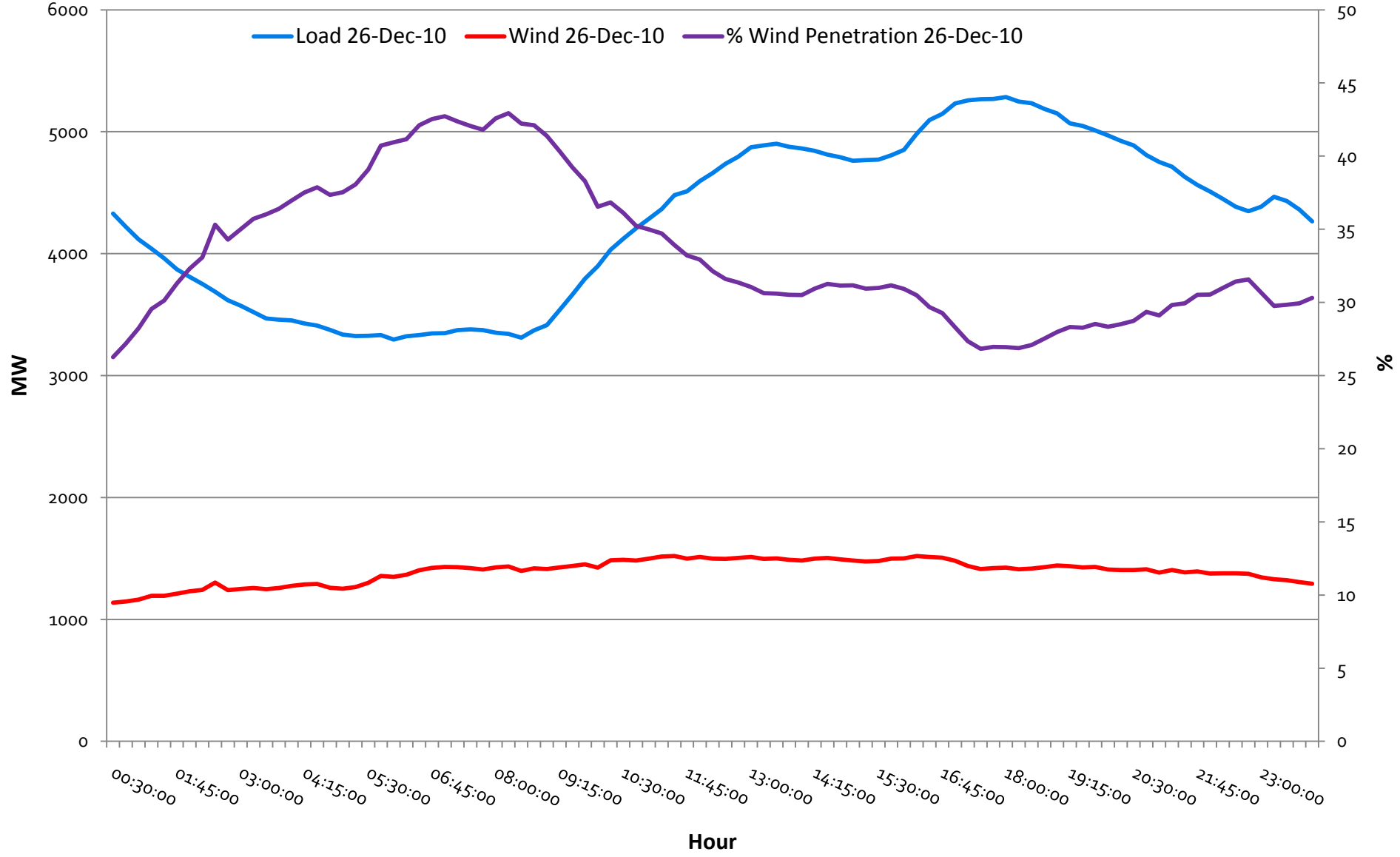
All island data from EirGrid & SONI

EU Targets 20 20 20 - Wind energy as % of electricity

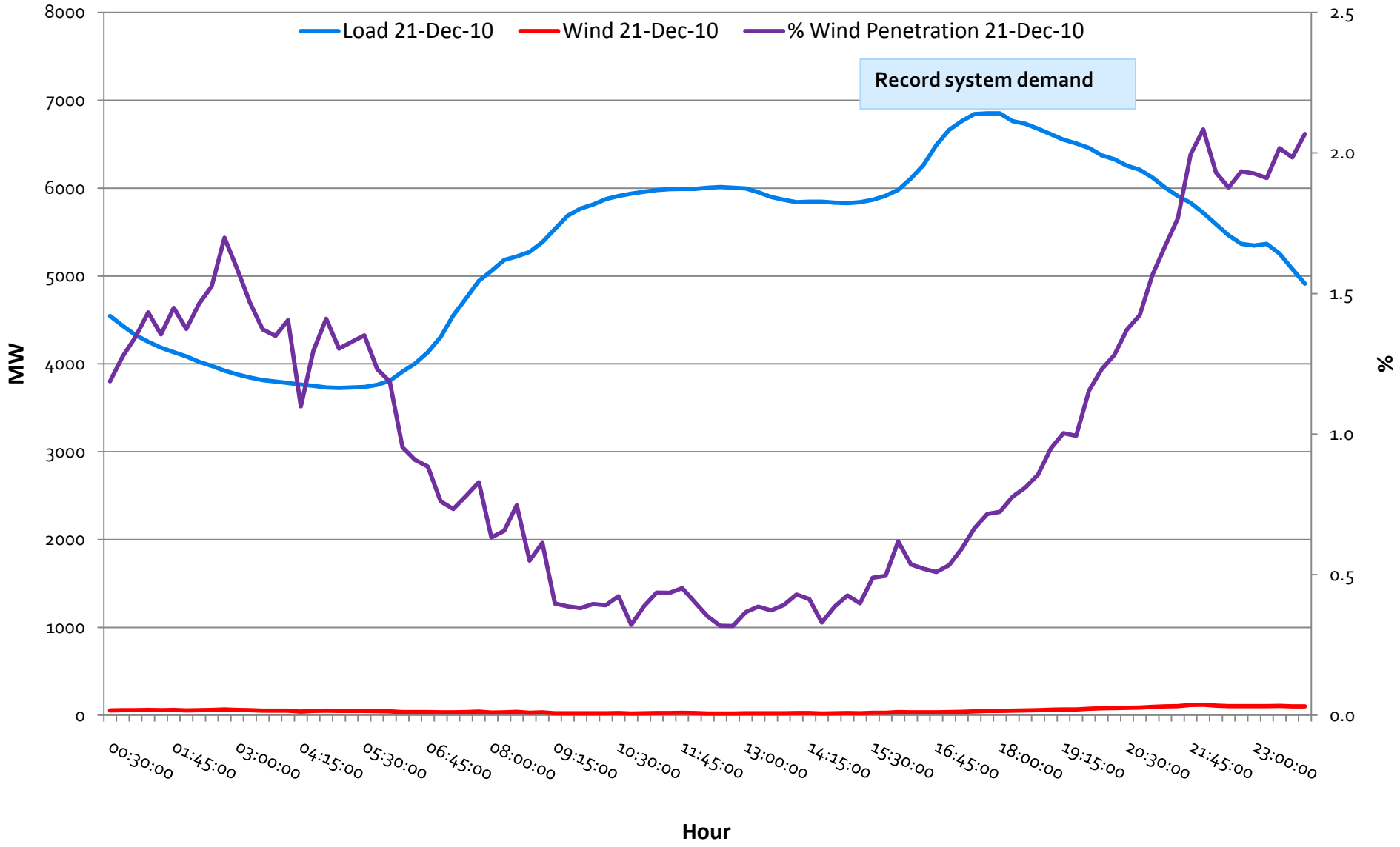


Wind characteristics in Ireland

Ireland – Demand, Wind and Penetration -26 Dec 2010

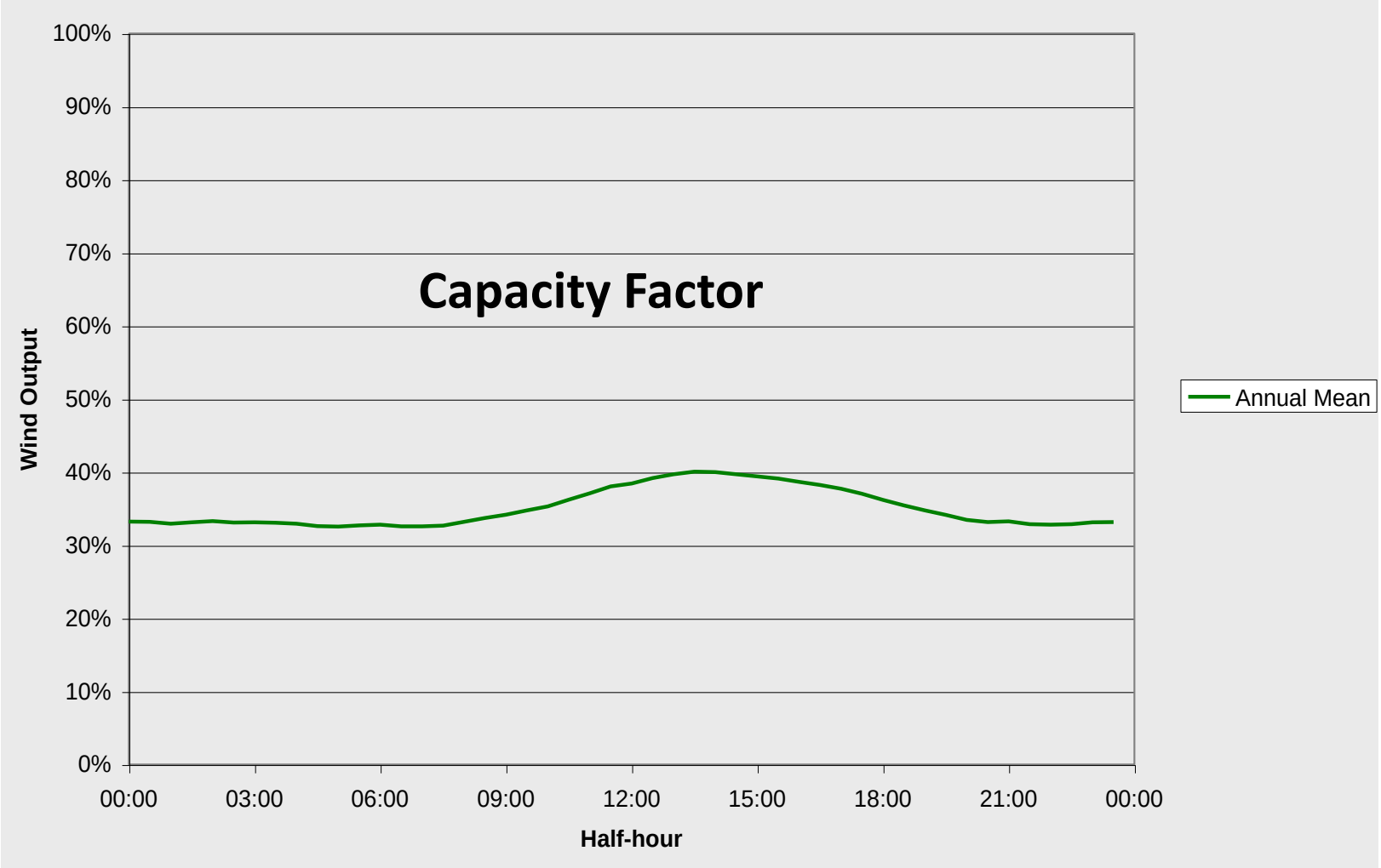


Ireland Wind & Load (21 Dec 2010)

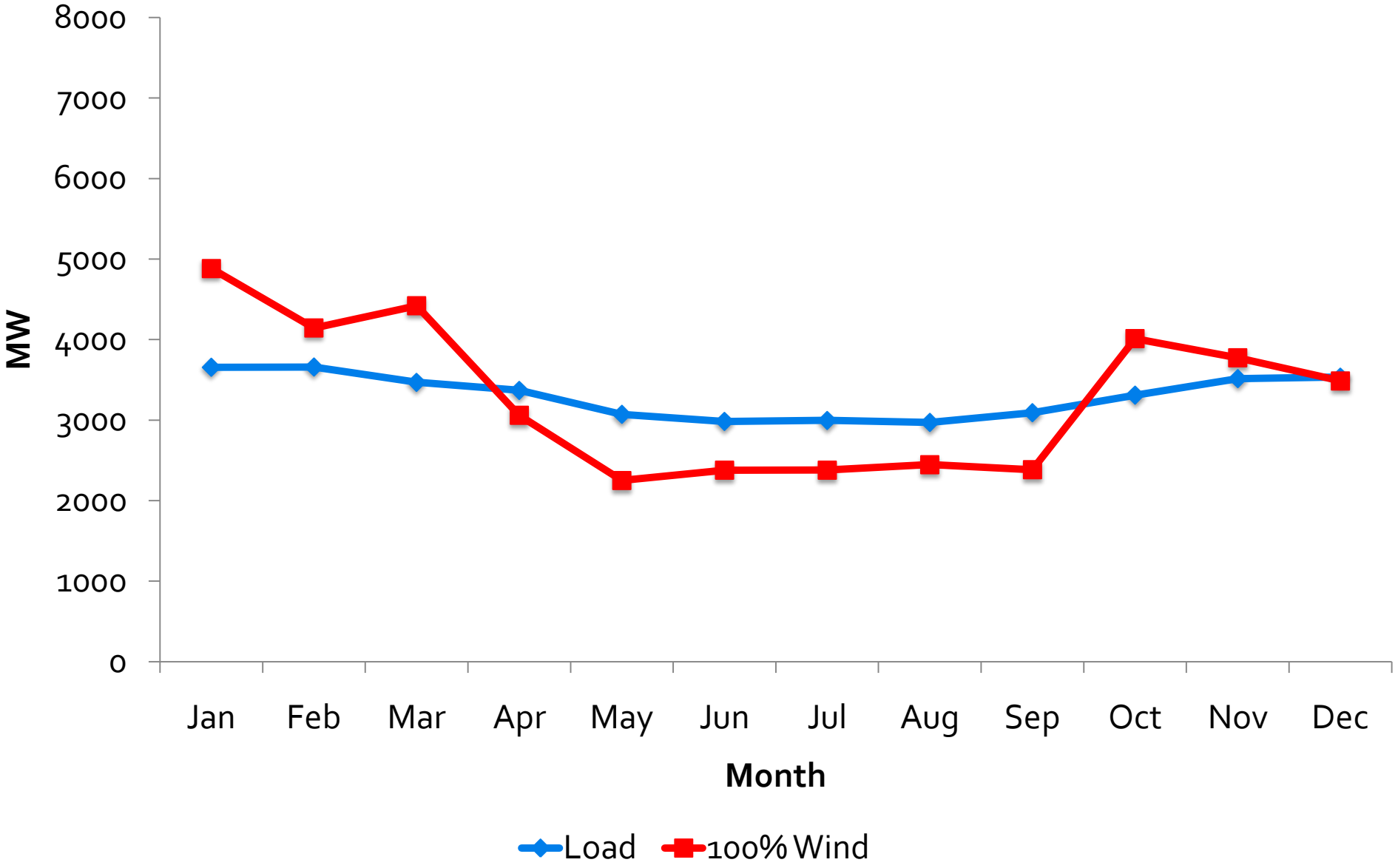


Wind Generation in Ireland

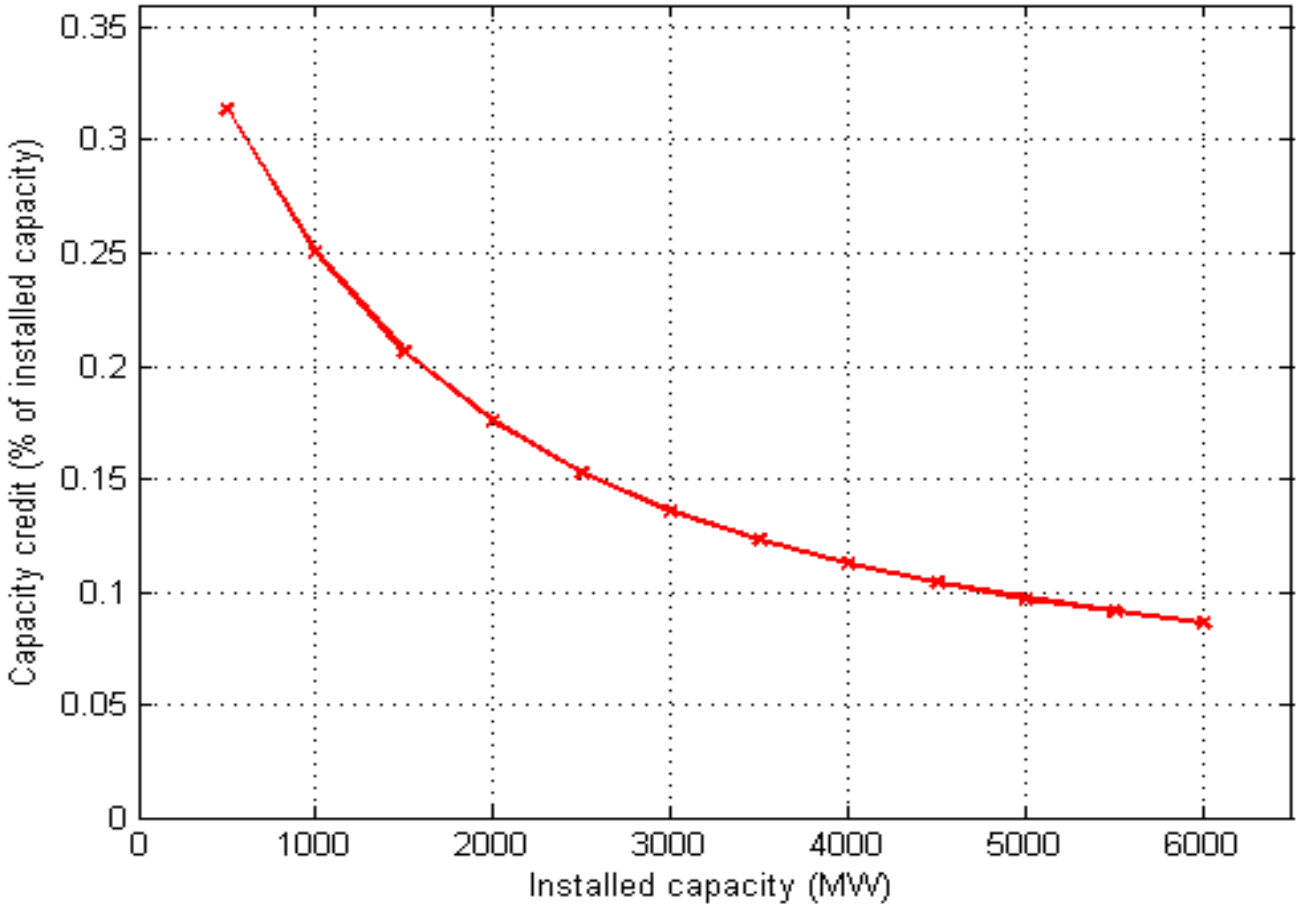
Annual Mean Wind Output



Yearly load & 100 % Wind

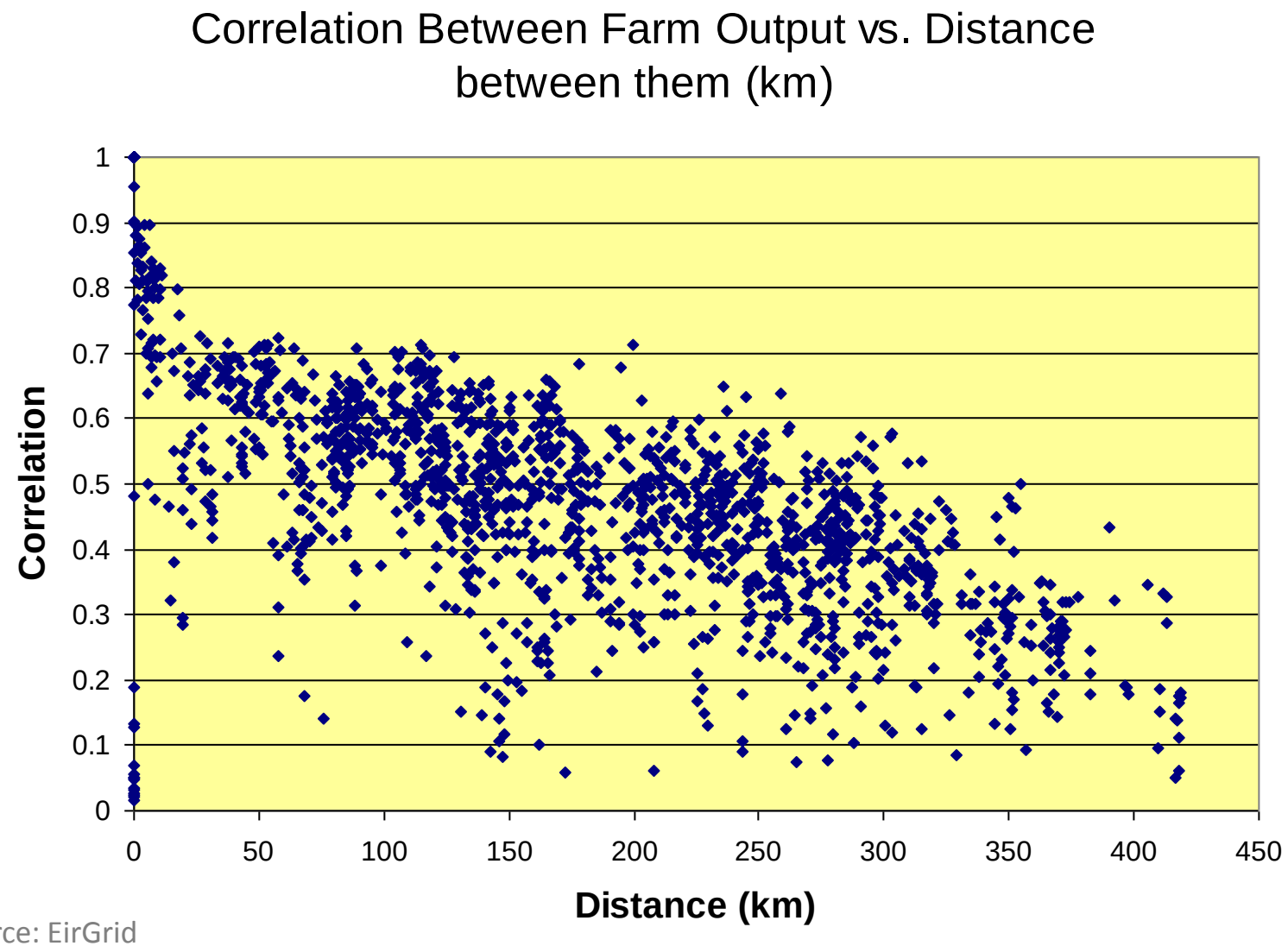


Capacity Credit Ireland



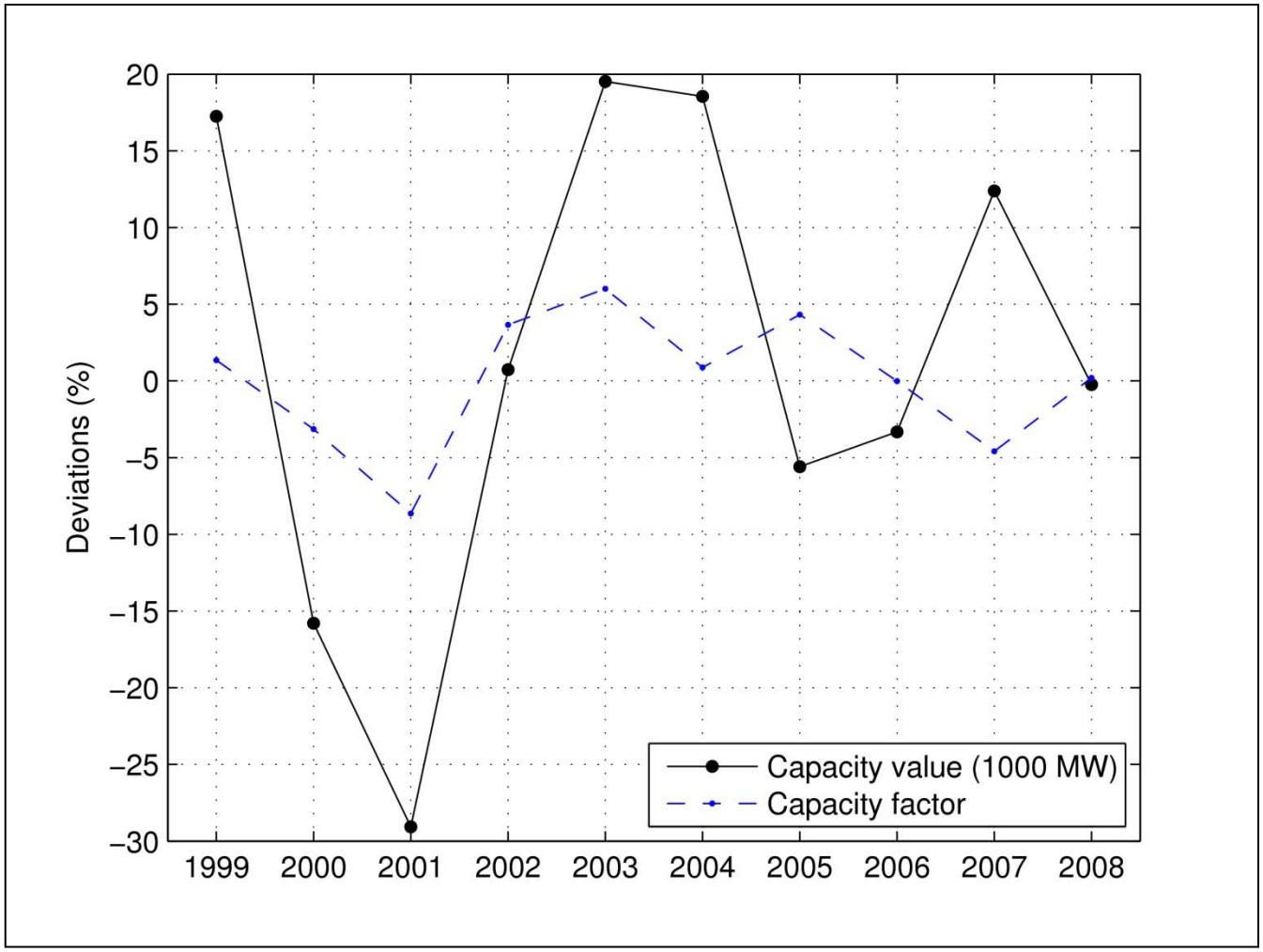
Keane, A., Milligan, M., D'Annuzio, C., Dent, C., Dragoon, K., Hasche, B., Holttinen, Samaan, N., Soder, L. and O'Malley, M.J., "Capacity Value of Wind Power, *IEEE Transactions on Power Systems*, Vol. 26, pp. 564 - 572, 2011.

Correlation Between Wind Farms



Source: EirGrid

Yearly variations

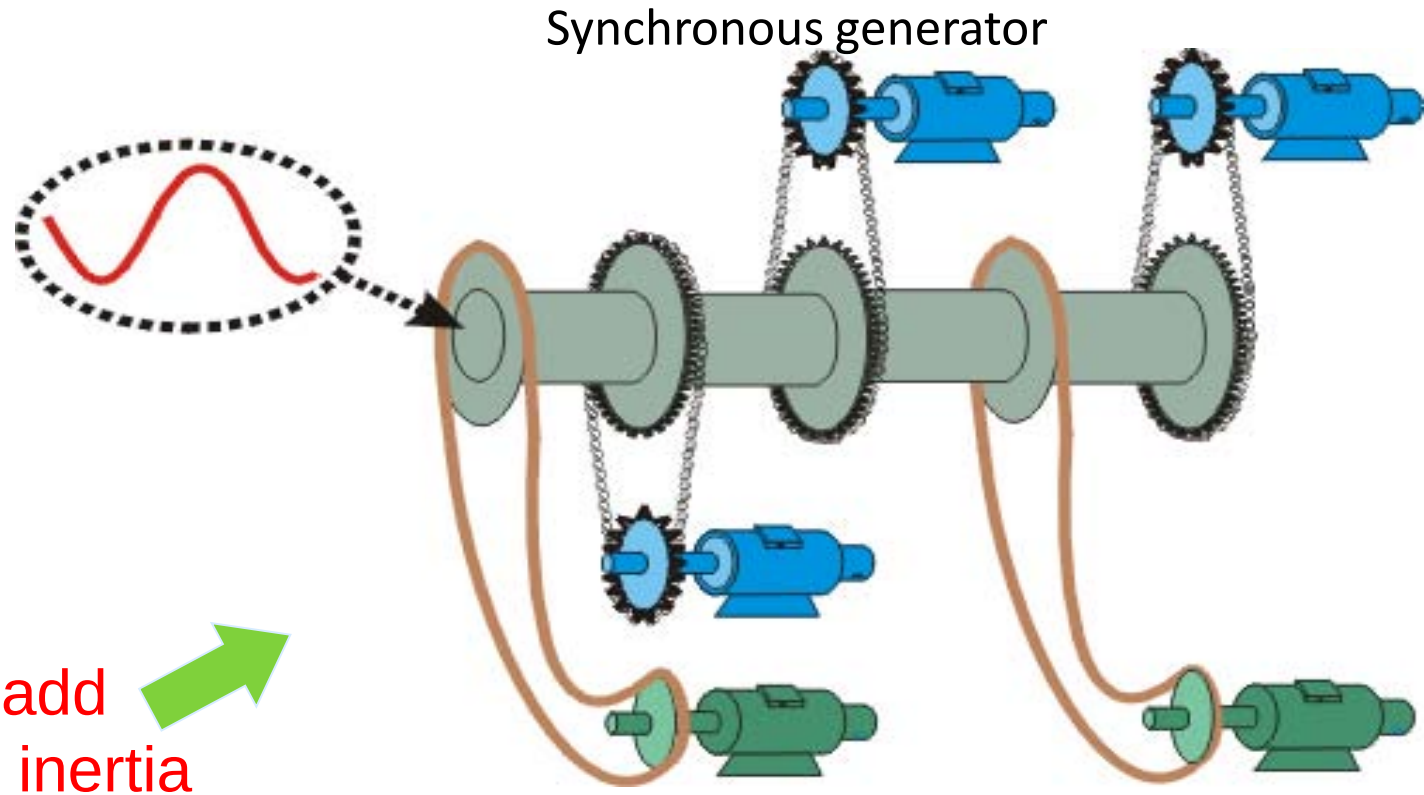


Hasche, B., Keane, A. and O'Malley, M.J. "Capacity credit of wind power: calculation and data requirements", *IEEE Trans. Power Syst.,* Vol. 26, pp. 420 - 430, 2011.

Frequency control & inertia

Frequency control

50/60 Hz

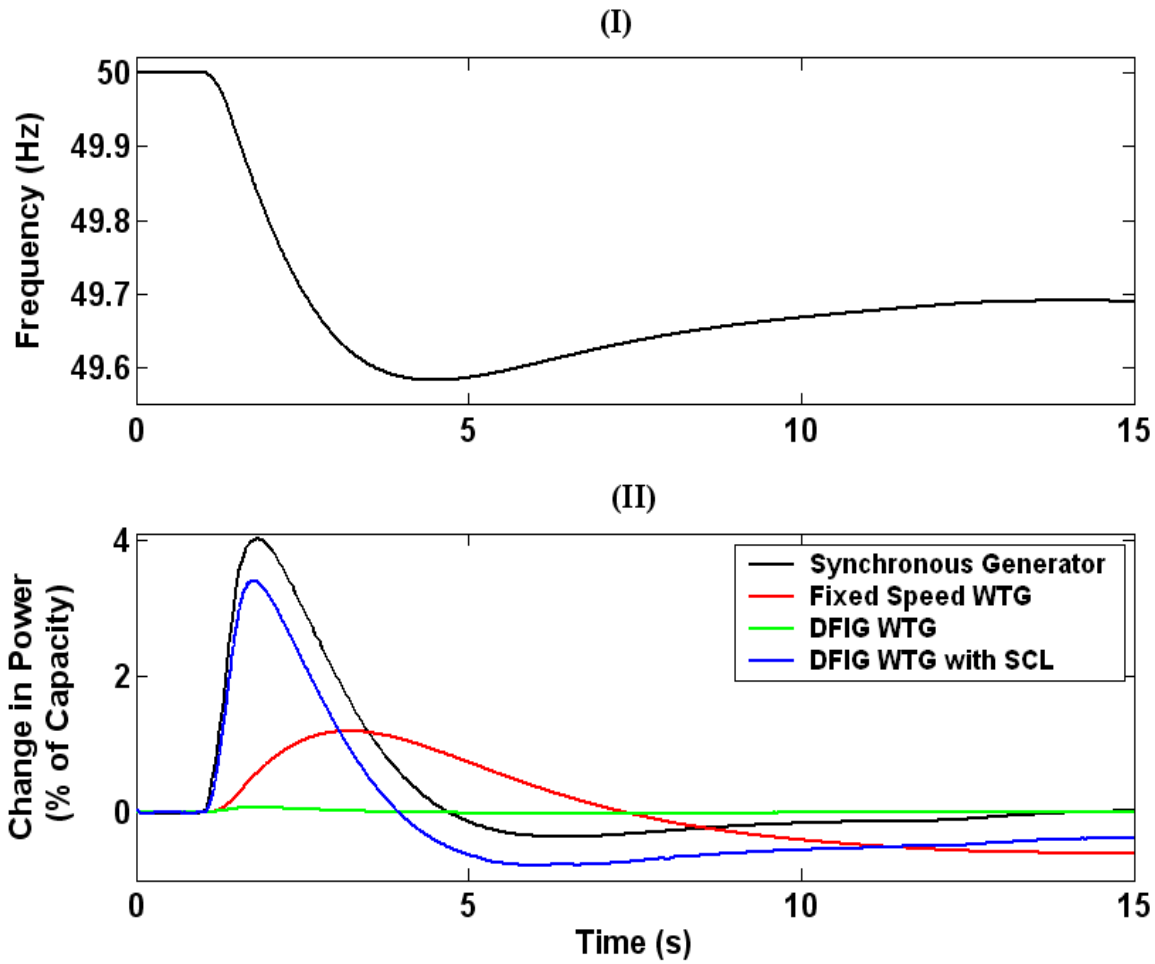


Does not add
to system inertia

Doubly fed induction generator wind turbine

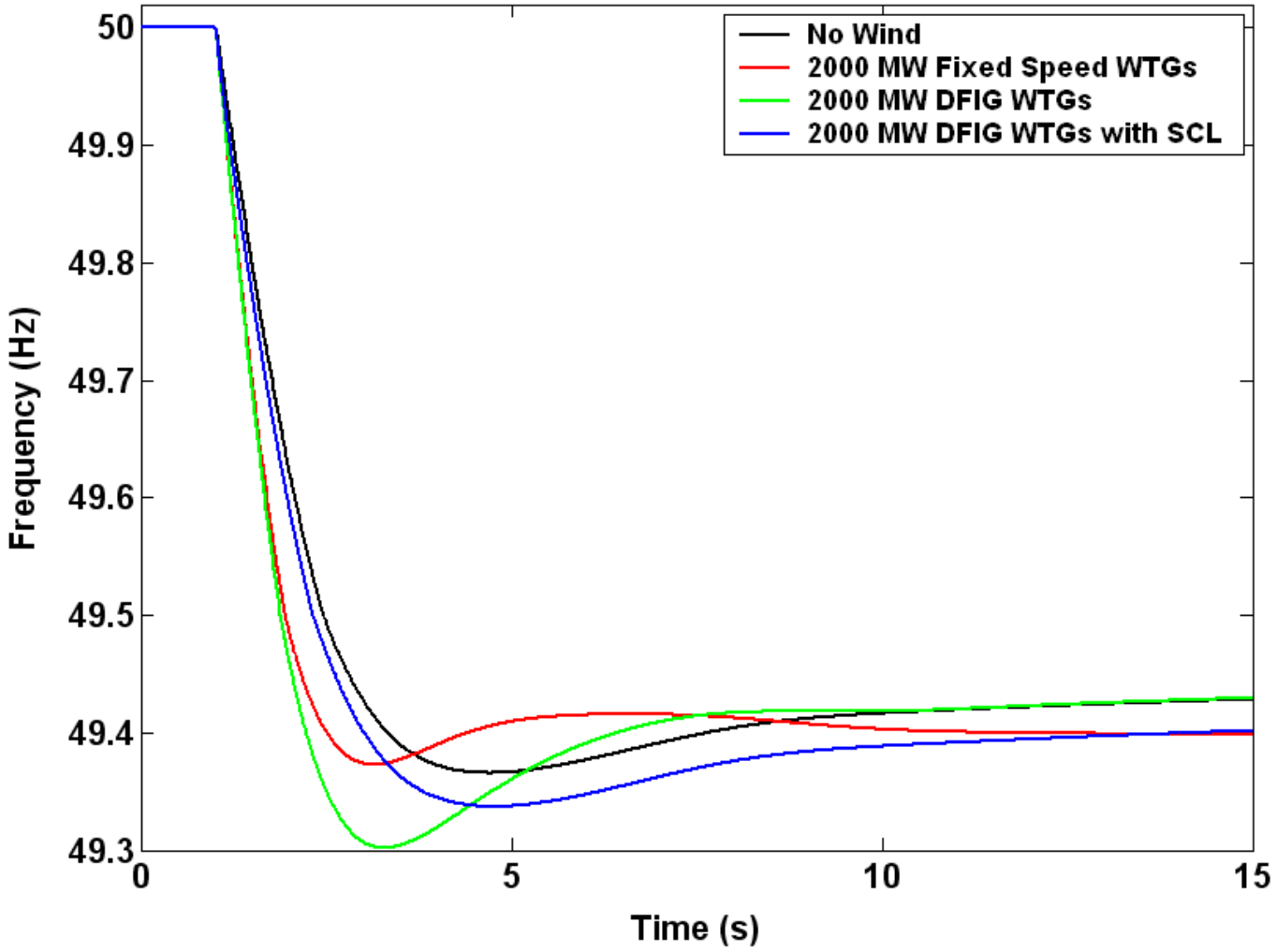
Fixed speed wind turbine generator

Wind Turbine Inertial Response



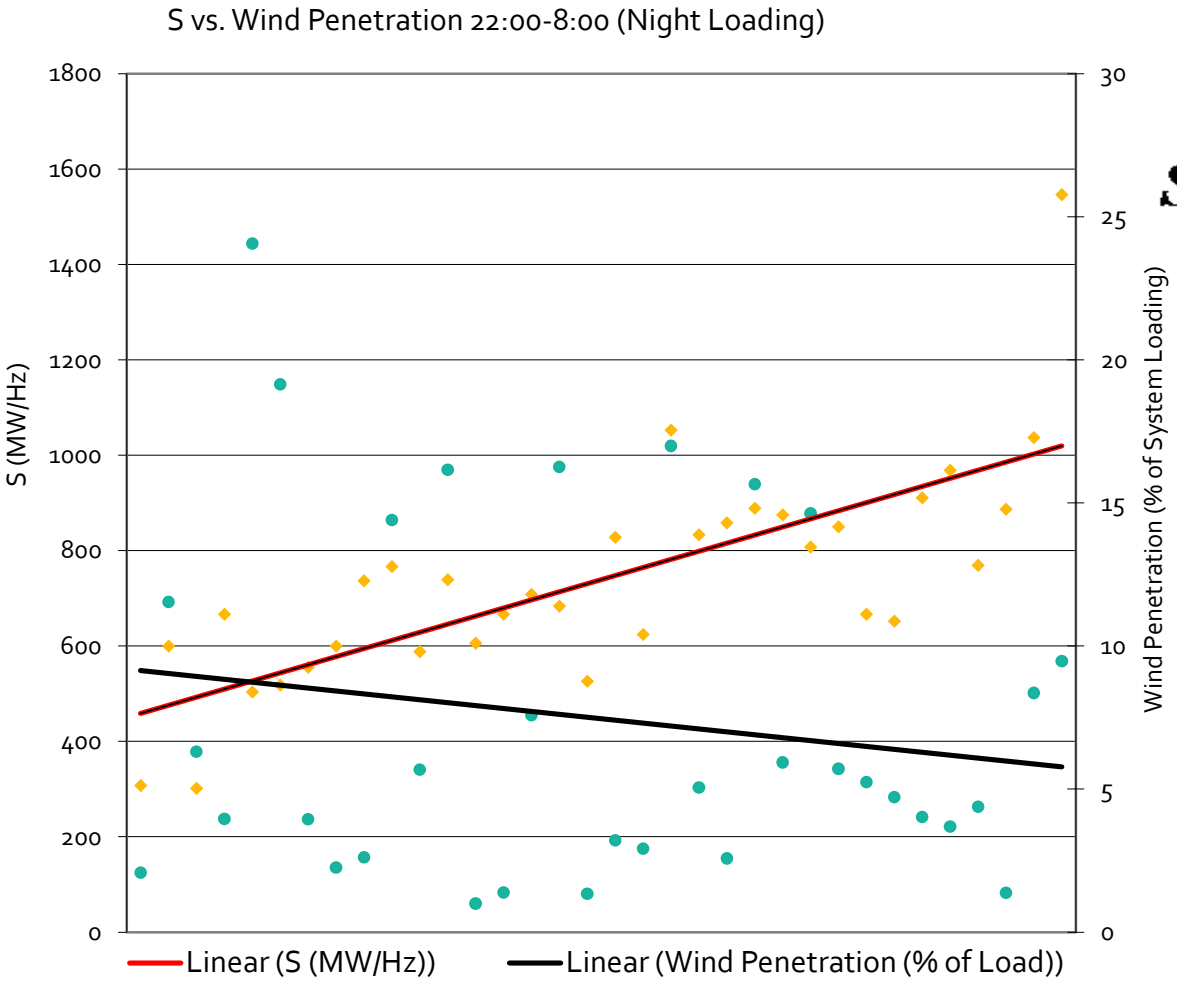
Mullane, A. and O'Malley, M.J., "The inertial-response of induction-machine based wind-turbines", *IEEE Transactions on Power Systems*, Vol. 20, pp. 1496 – 1503, 2005 .

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.

Historical data Ireland



- Frequency response

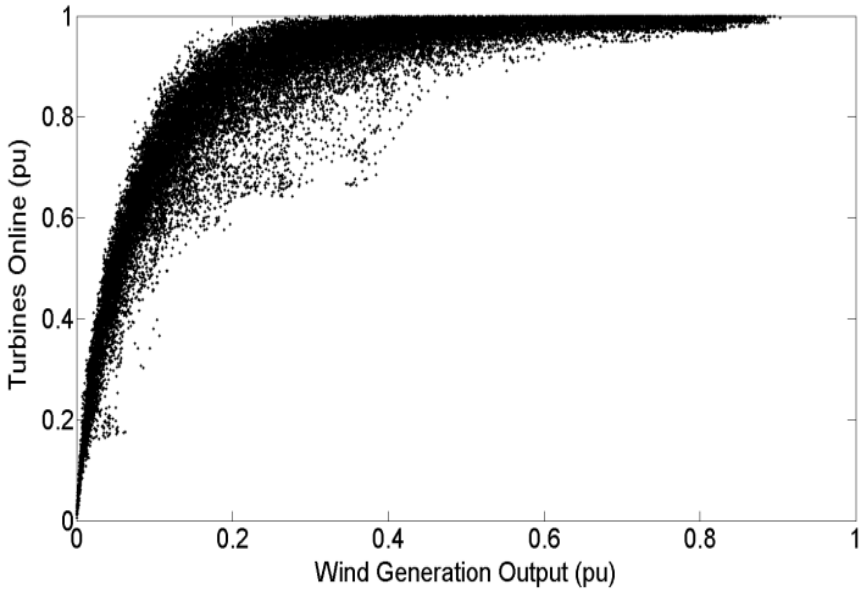
$$S = \left(\frac{MW_{Lost}}{f_{pre\text{-}event} - f_{nadir\,post\text{-}event}} \right)$$

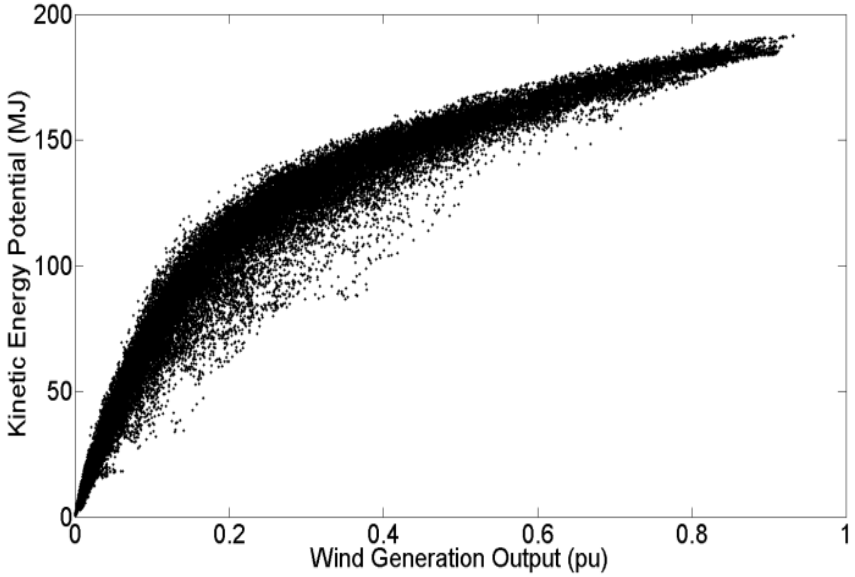
  - Wind penetration increases
  - Stiffness decreases
    - Indicates increased vulnerability to a loss of generation event

- Should there be a market in frequency response ?

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

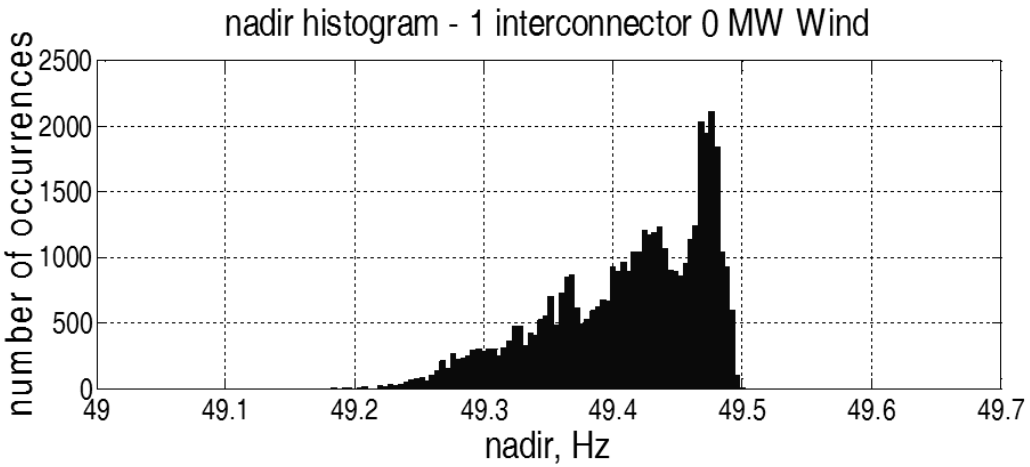
Experimental data: Inertia

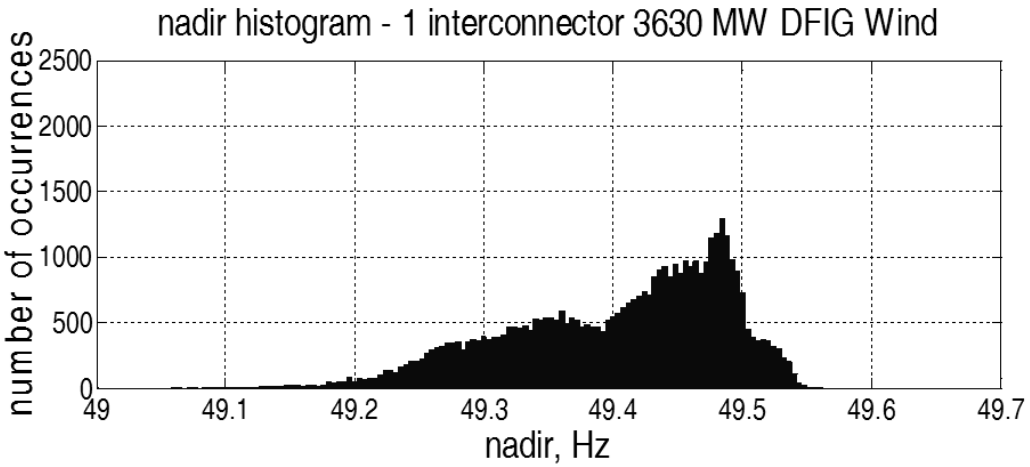




Ruttledge and Flynn, "System-wide inertial response from fixed Speed and variable speed wind turbines", *IEEE PES General Meeting*, Detroit, USA, July, 2011.

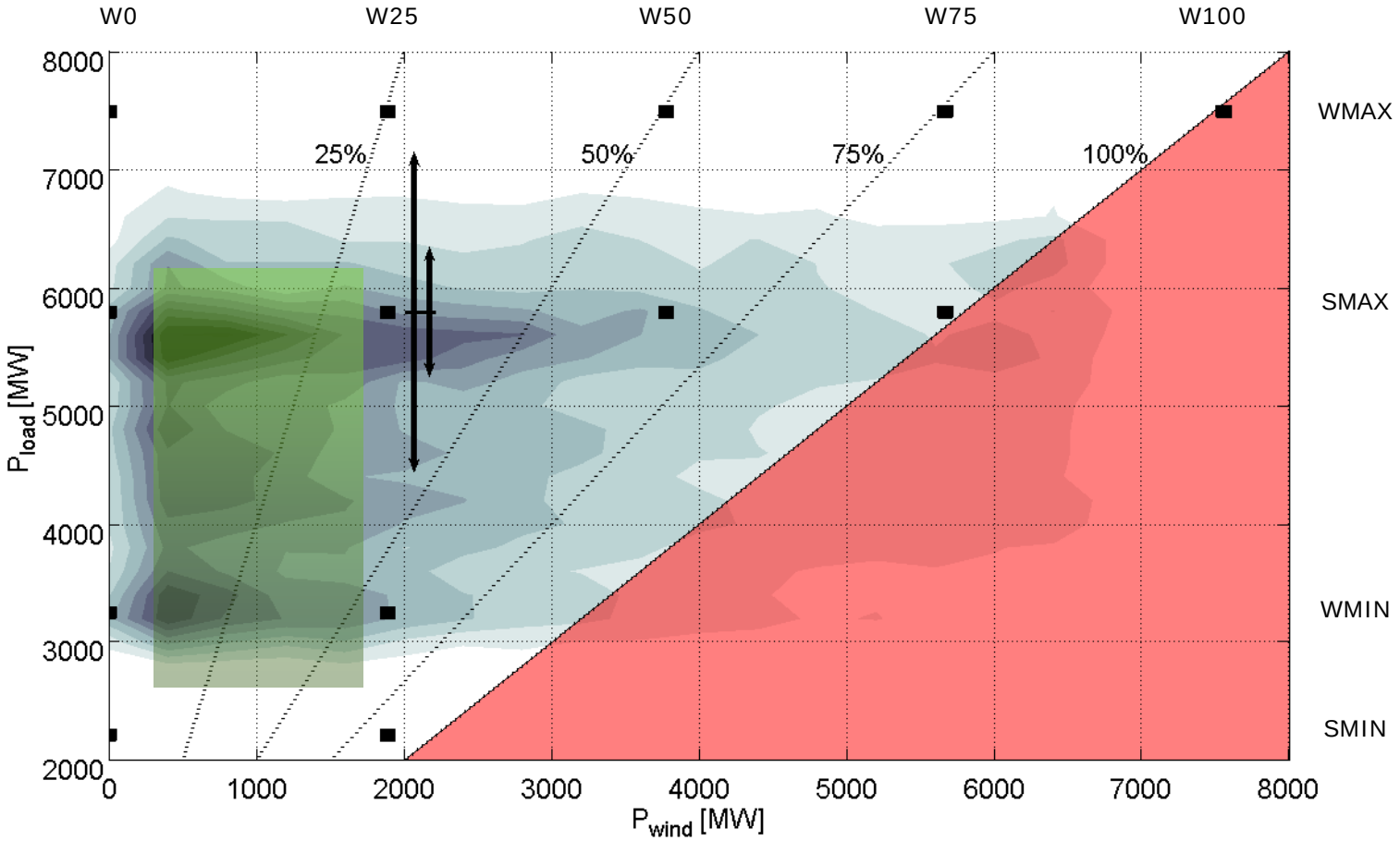
Results: Frequency Nadir





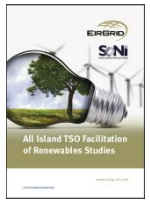
Doherty, R, Mullane, A., Lalor, G., Burke, D., Bryson, A. and O'Malley, M.J. "An Assessment of the Impact of Wind Generation on System Frequency", *IEEE Transactions on Power Systems*, Vol. 25, pp. 452 – 460, 2010.

Operational Boundaries

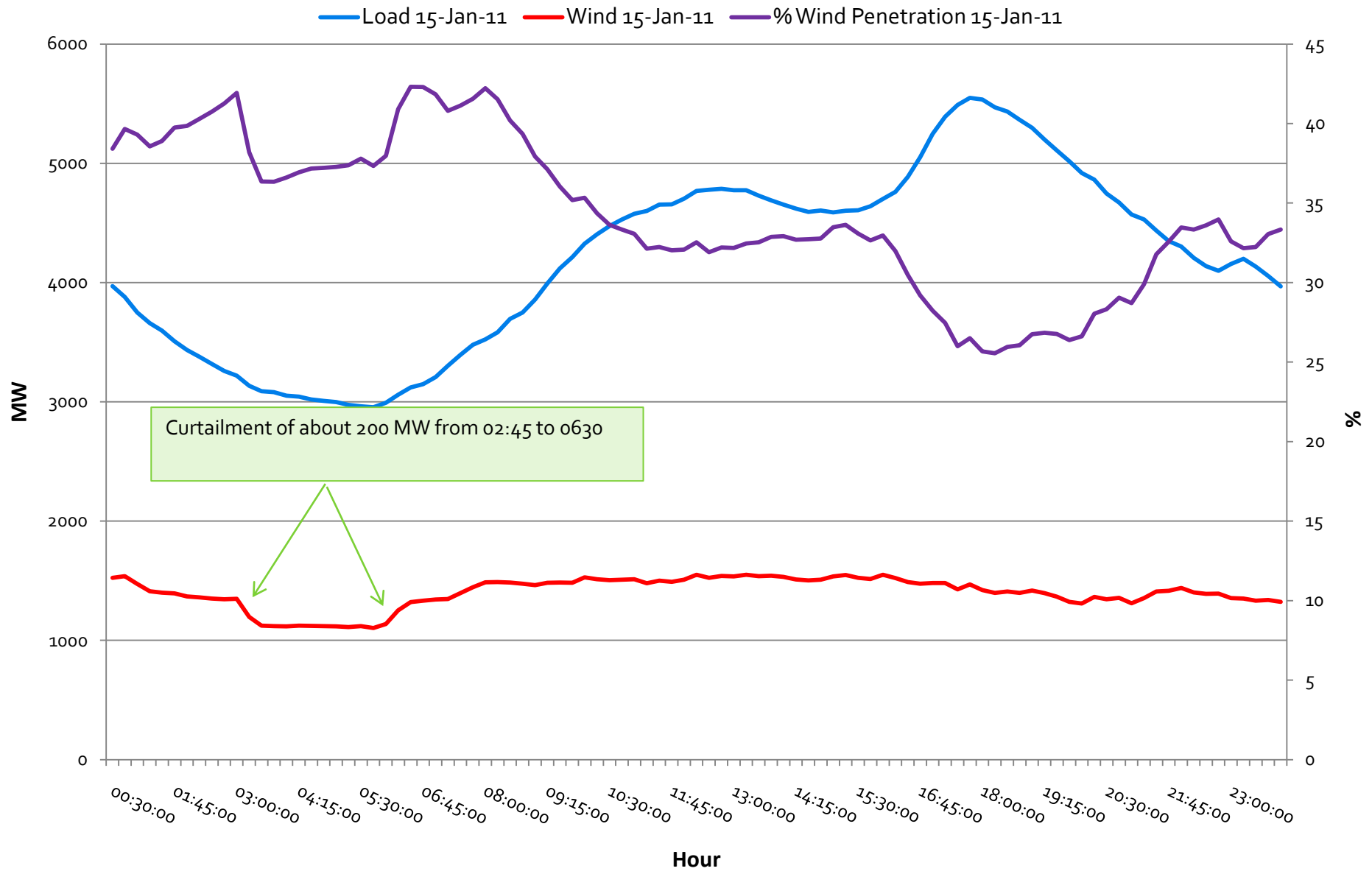


EirGrid, "All Island TSO Facilitation of Renewable Studies", Final Report, 2010 .

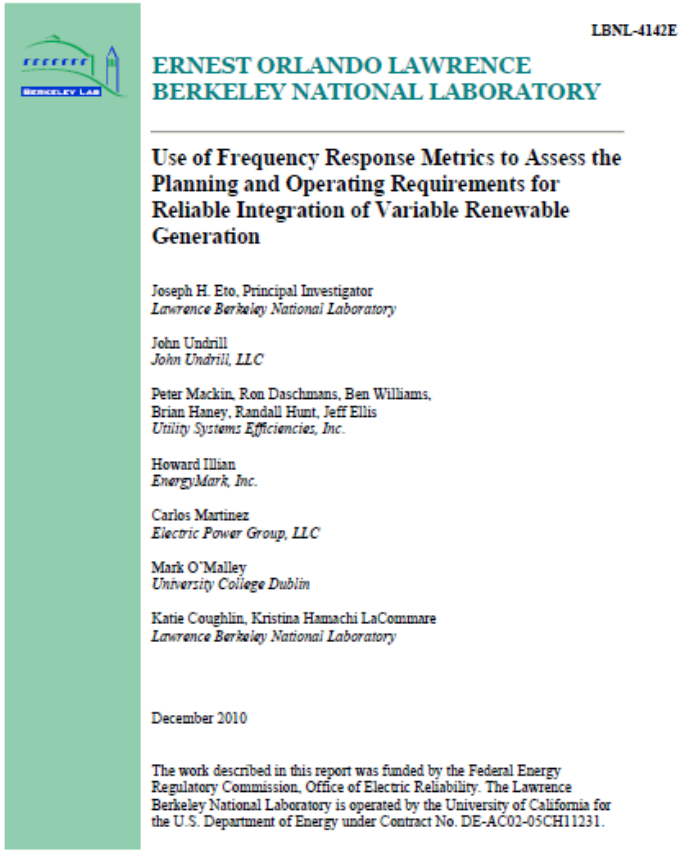
http://www.eirgrid.com/media/Renewable%20Studies%20V3.pdf



Ireland, Wind & Load – 15 Jan 2011



Frequency response USA



LBNL-4142E

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

Use of Frequency Response Metrics to Assess the Planning and Operating Requirements for Reliable Integration of Variable Renewable Generation

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December 2010

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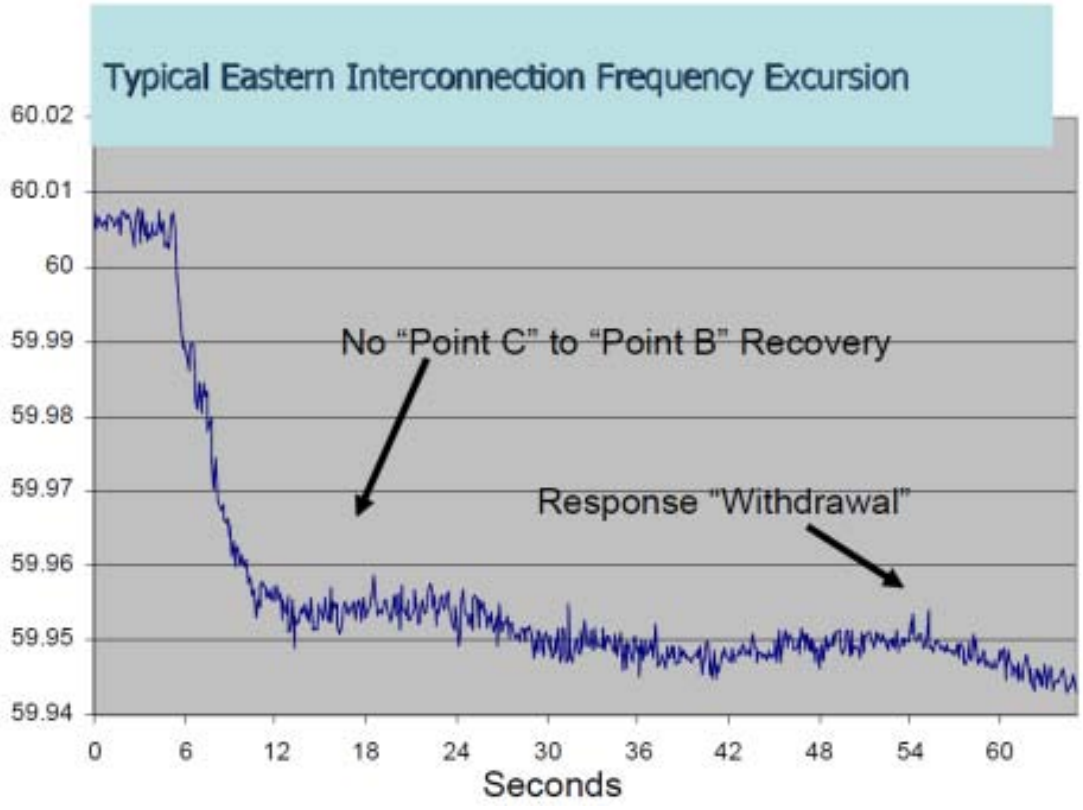
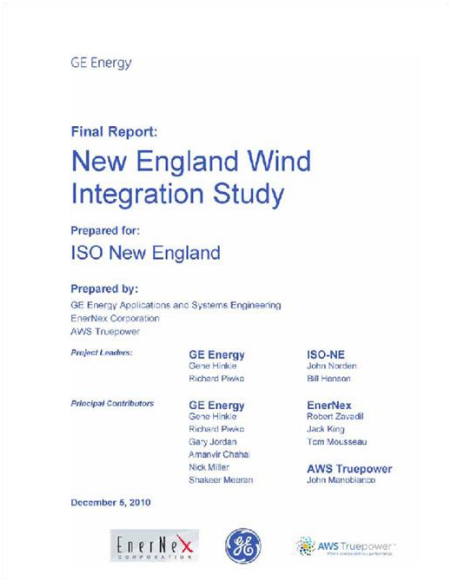
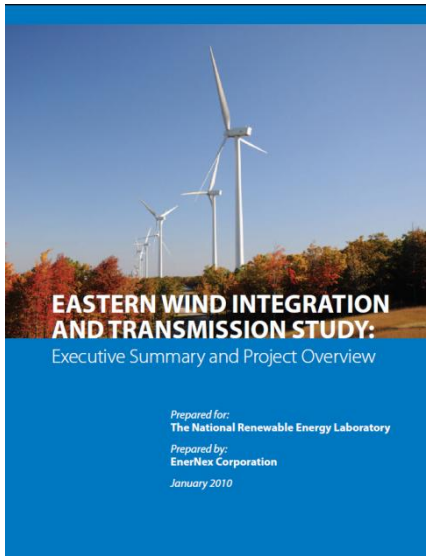


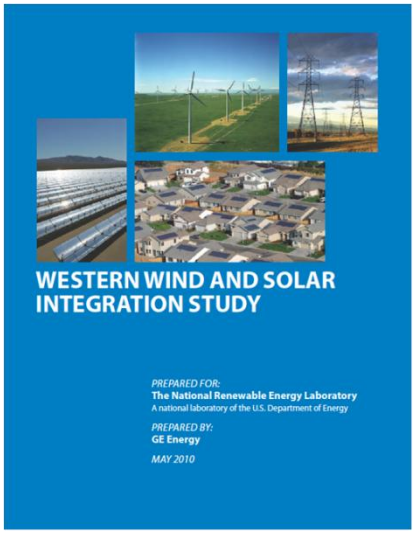
Eto, J., J. Undrill, P. Mackin, R. Daschmans, B. Williams, B. Haney, R. Hunt, J. Ellis, H. Illian, C. Martinez, M. O'Malley, K. Coughlin, and K.H. LaCommare,""Use of Frequency Response Metrics to Assess the Planning and Operating Requirements for Reliable Integration of Variable Renewable Generation", Lawrence Berkley National Laboratory, Berkeley, 2010. http://www.ferc.gov/industries/electric/indus-act/reliability/frequencyresponsemetrics-report.pdf

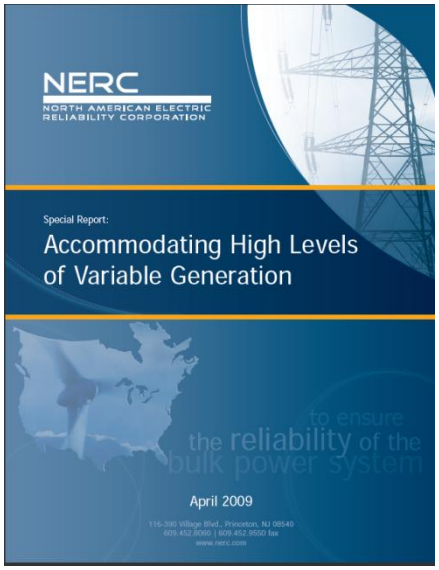
Grid Studies

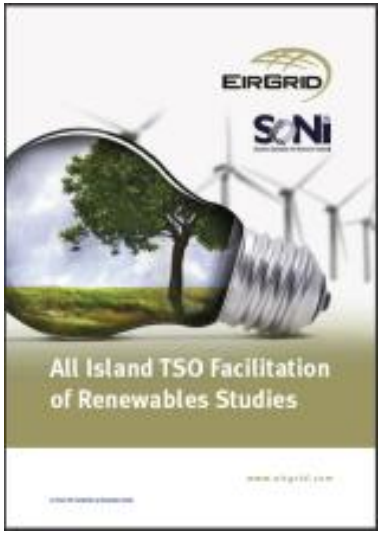
Wind energy integration studies







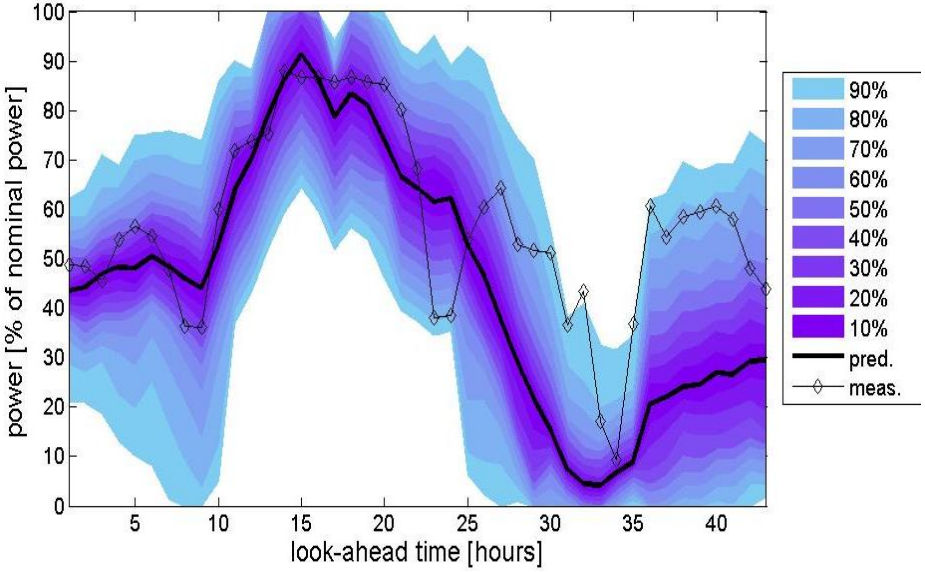


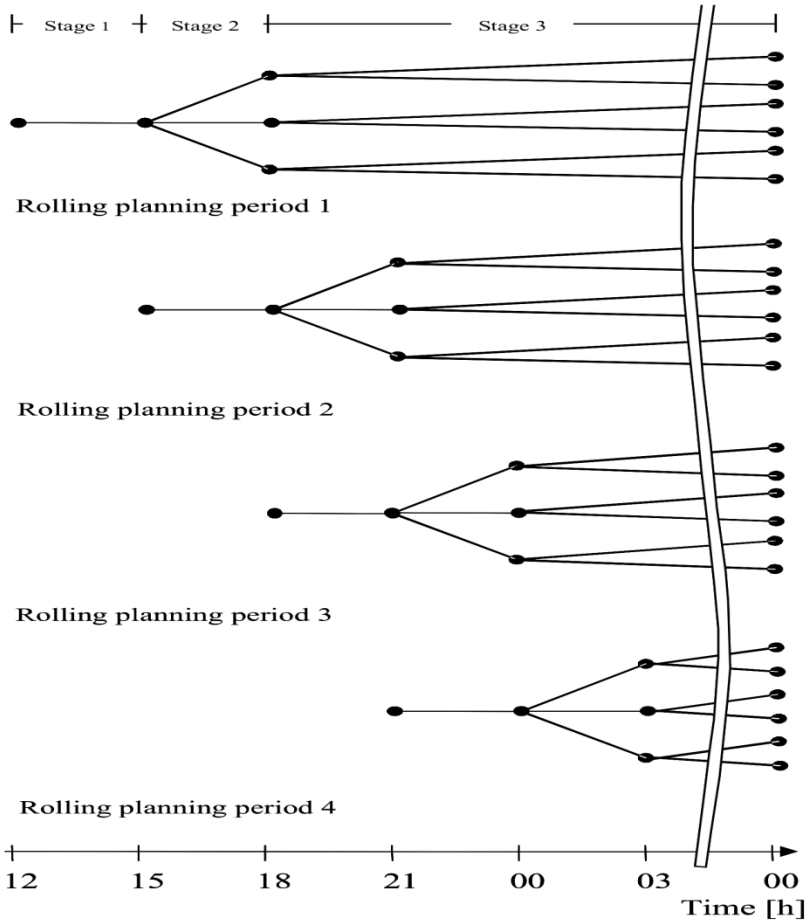


Risø DTU

Stochastic Unit Commitment

Wilmar: Stochastic Unit Commitment

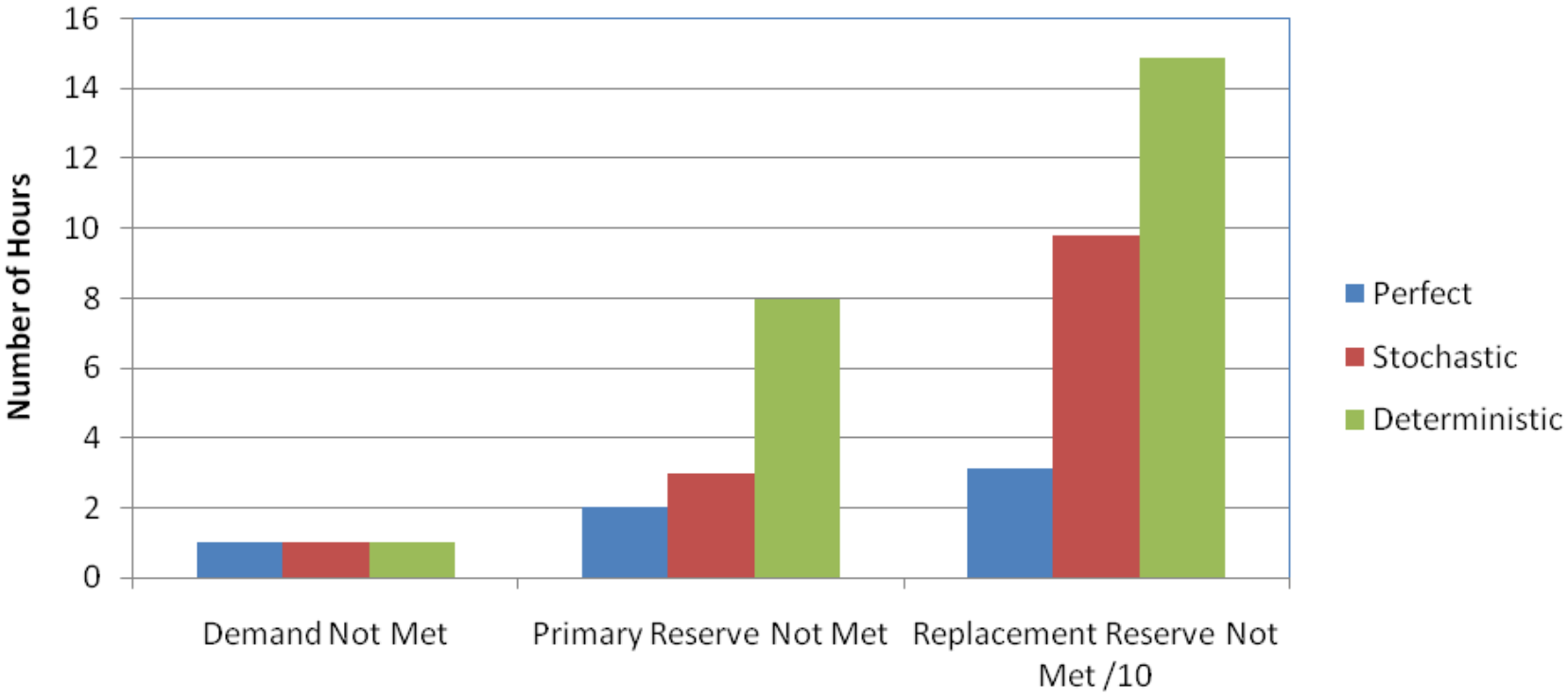




Meibom, P., Barth, R., Hasche, B., Brand, H., Weber, C. and O´Malley, M.J., "Stochastic optimisation model to study the operational impacts of high wind penetrations in Ireland", *IEEE Transactions Power Systems,* in press, 2011.

Performance of Schedules

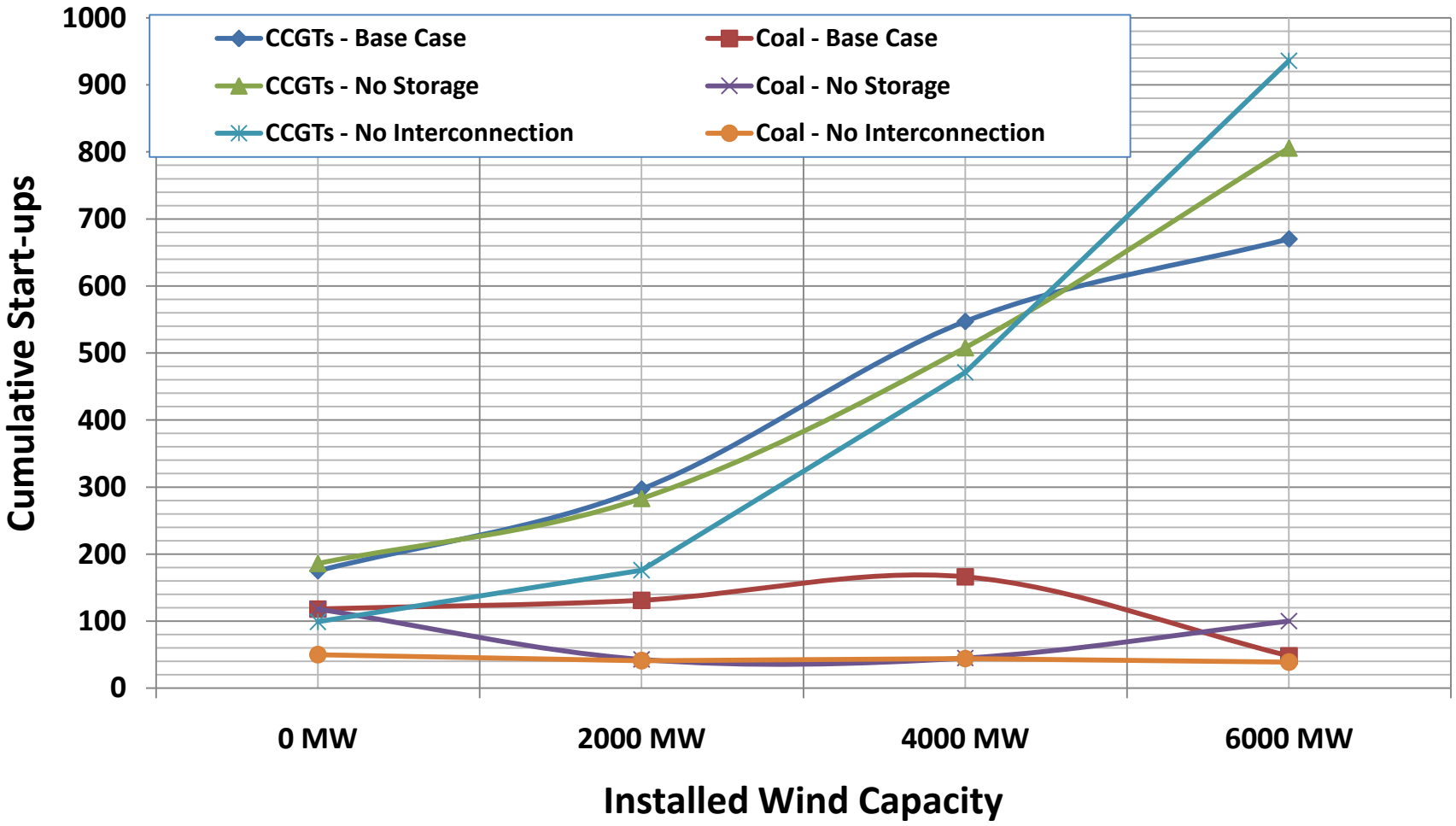
- One hour frequency of rolling commitment



Tuohy, A., Meibom, P., Denny, E., & O'Malley, M., "Unit commitment for Systems with Significant Installed Wind Penetration", *IEEE Transactions on Power Systems* , Vol, 24, pp. 592 – 601, 2009.

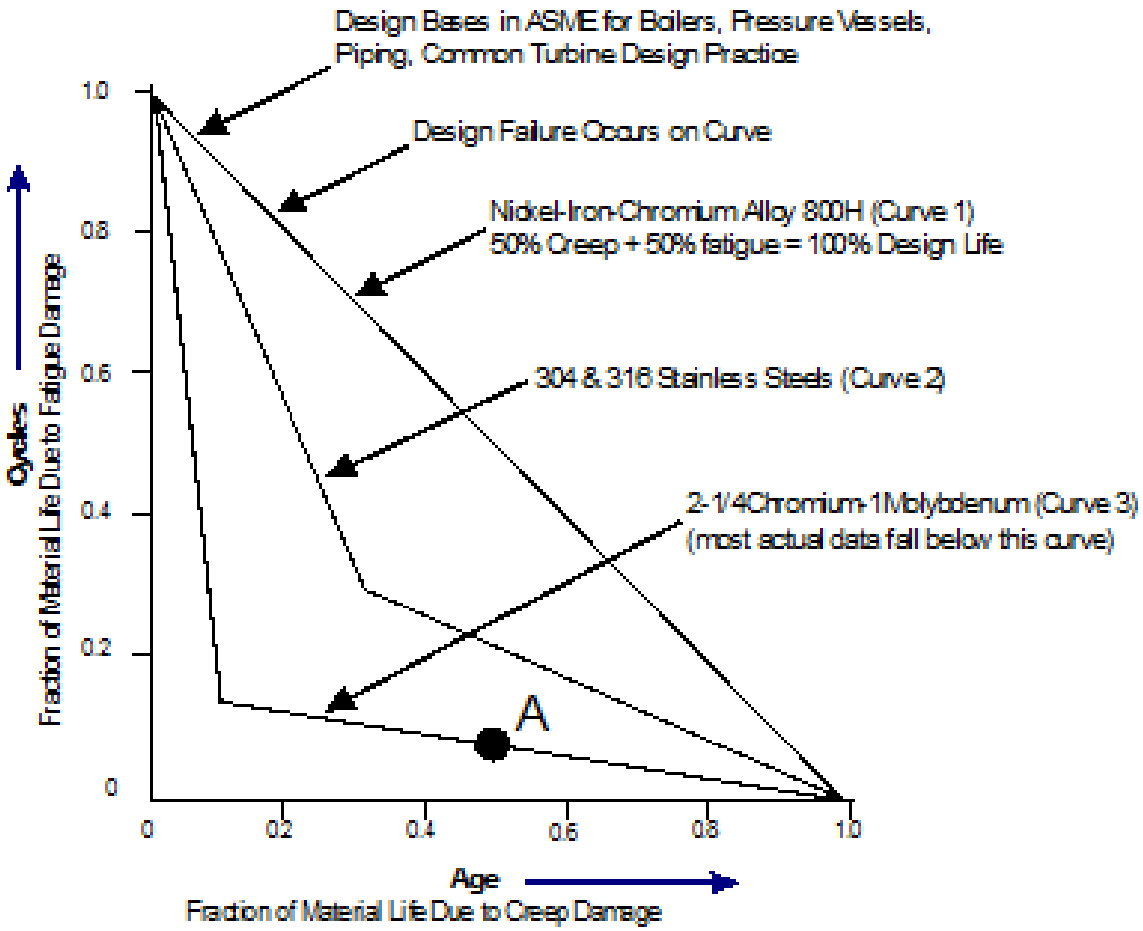
Frequency Control & Cycling

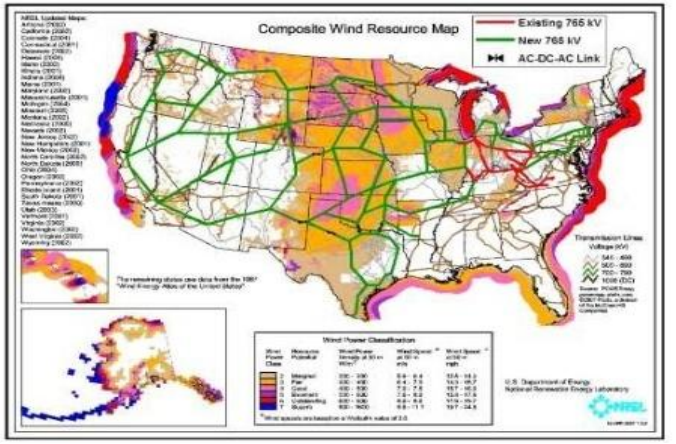
Impact of Wind on Base-load Start-ups



Troy, N., Denny, E. and O'Malley, M.J. "Base load cycling on a system with significant wind penetration", *IEEE Trans. Power Syst.,* Vol. 25, pp. 1088 - 1097, 2010.

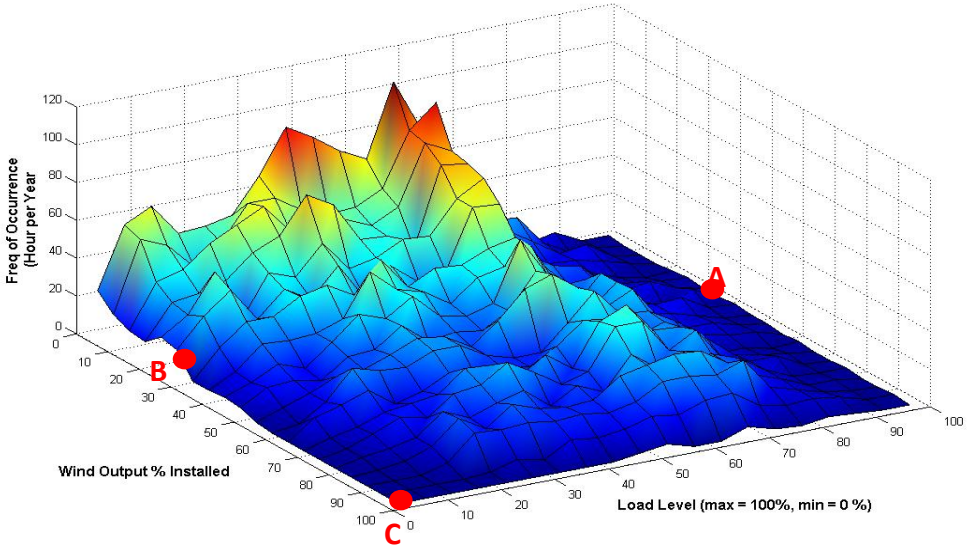
Creep fatigue interaction





Transmission

Transmission



Burke, D.J., and O'Malley M.J. "A Study of Optimal Non-Firm Wind Capacity Connection to Congested Transmission Systems", *IEEE Transactions on Sustainable Energy*, in press, 2011.

Burke, D., and O'Malley, M.J., "Maximum firm wind power connection to security constrained transmission networks", *IEEE Transactions on Power Systems*, Vol. 25, pp. 749 – 759, 2010.

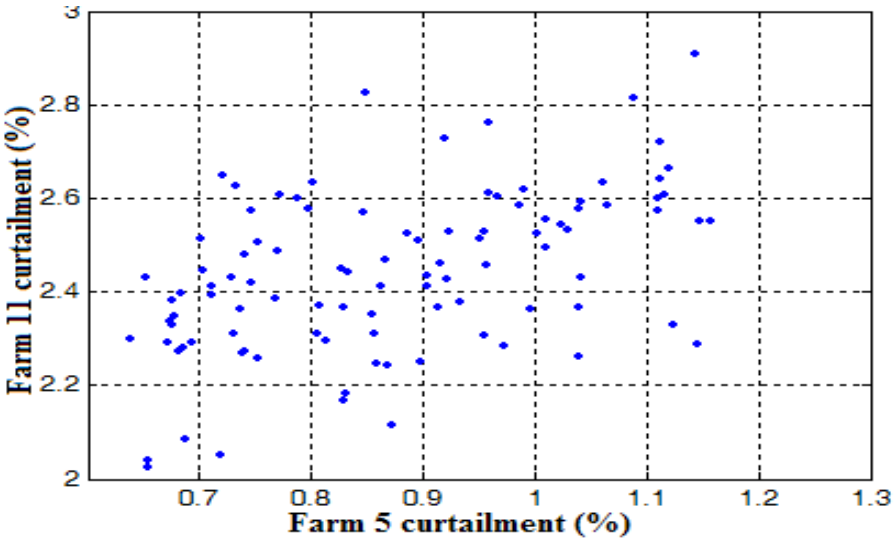
Burke, D J, and O'Malley M.J. "Factors Influencing Wind Energy Curtailment", *IEEE Transactions on Sustainable Energy*, in press, 2011.

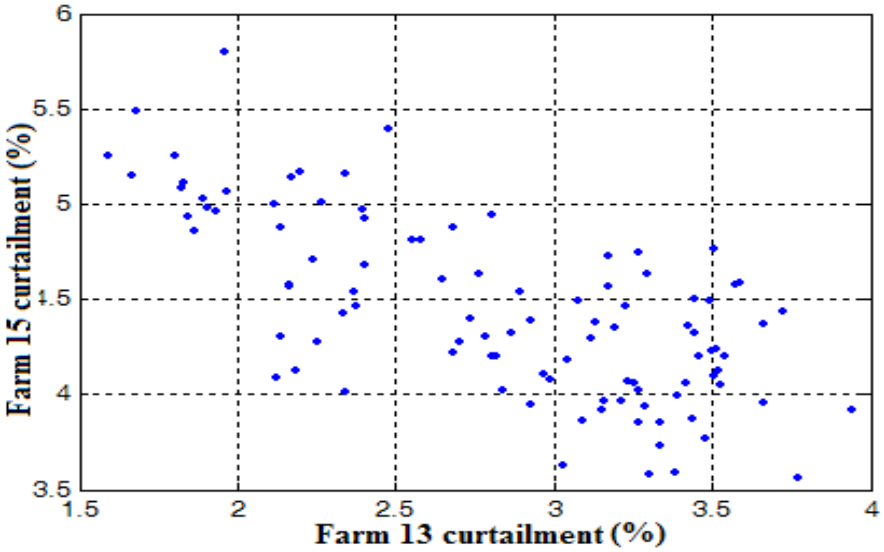
Firm Access

Energy % Penetration	Wind Farm Bus Number						
	12	14	15	25	27	29	30
5	0	0	**93.1**	0	81.4	0	0
6	0	0	**101.3**	0	90.2	0	0
7	0	0	**88.1**	9.5	147.0	0	0
8	33.4	38.9	**45.0**	35.5	138.9	0	0
9	73.6	51.6	**44.6**	30.9	128.3	0	0
9.5	68.7	54.6	**51.5**	40.2	132.7	0	0
10	*infeasible*						

Burke, D. and O'Malley, M.J., "Maximising firm wind power connection to security constrained transmission networks" *IEEE Transactions on Power Systems,* Vol. 25, pp. 749 – 759, 2010.

Curtailment and risk diversification





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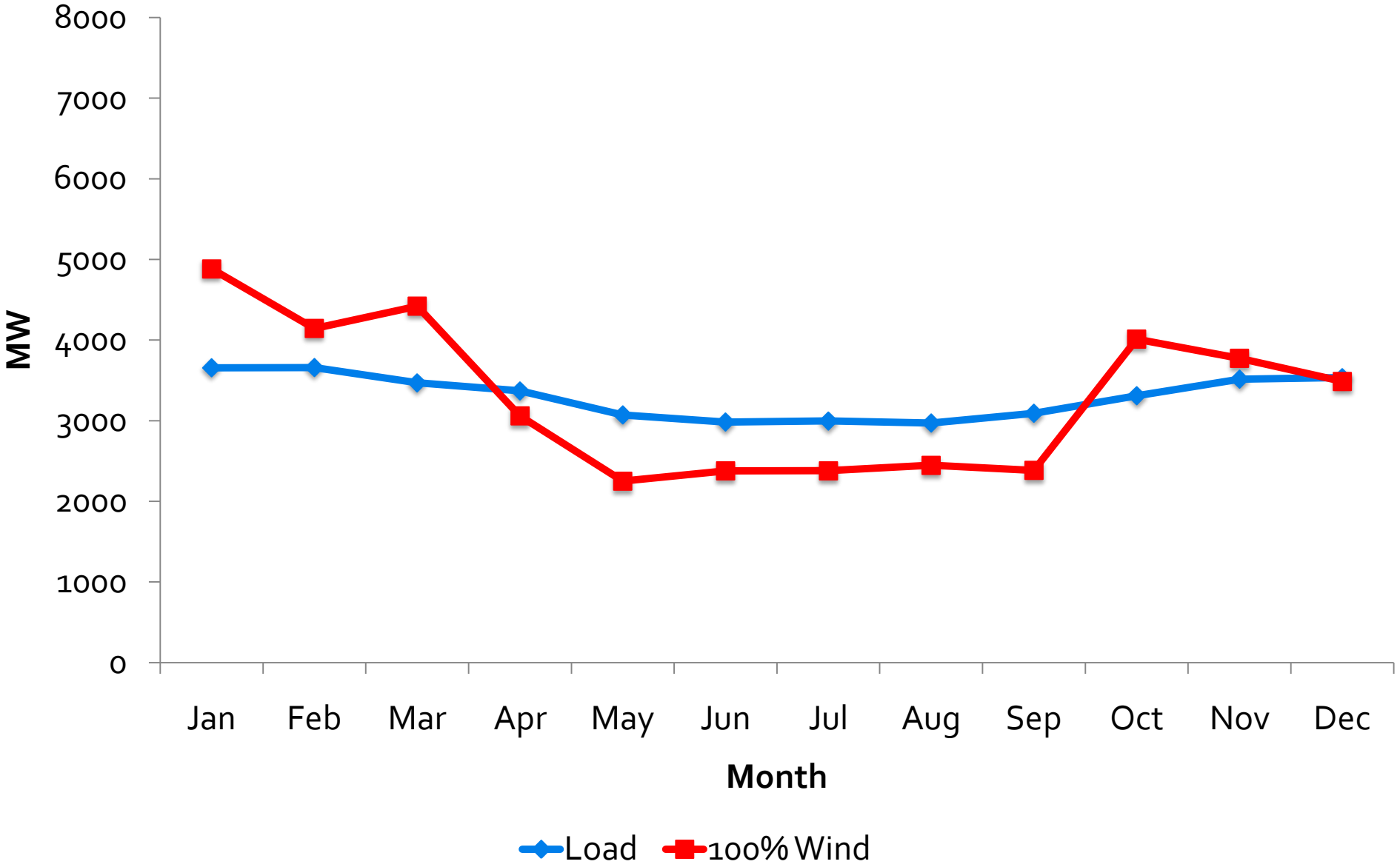
Conclusions & societal issues

Yearly load & 100 % Wind



Demand side management

Disruptive ?

Public acceptance of transmission

Recent Journal Publications

- Burke, D.J., and O'Malley M.J. "A Study of Multivariate Component Analysis Applied to Statistical Distributed Wind Power", *IEEE Transactions on Power Systems*, in press, 2011.
- Meibom, P., Barth, R., Hasche, B., Brand, H., Weber, C. and O´Malley, M.J., "Stochastic optimisation model to study the operational impacts of high wind penetrations in Ireland", *IEEE Transactions on Power Systems*, in press, 2011.
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- Keane, A., Milligan, M., D'Annuzio, C., Dent, C., Dragoon, K., Hasche, B., Holttinen, Samaan, N., Soder, L. and O'Malley, M.J., "Capacity Value of Wind Power, *IEEE Transactions on Power Systems*, Vol. 26, pp. 564 - 572, 2011.
- 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.
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- Holttinen, H, Meibom, P., Orths, A., Lange, B., O'Malley, M.J., Tande, J, Estanqueiro, A., Gomez, E., Söder, L., Strbac, G., Smith, J.C. and van Hulle, F., "Impacts of large amounts of wind power on design and operation of power systems, results of IEA collaboration", *Wind Energy*, Vol. 14, pp. 179-192, 2011.
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- Nyamdash, B., Denny, E., and O'Malley, M.J. "The viability of balancing wind power with large scale energy storage", *Energy Policy*, Vol. 38, pp. 7200-7208, 2010.
- Troy, N., Denny, E. and O'Malley, M.J. "Base load cycling on a system with significant wind penetration", *IEEE Transactions on Power Systems*, Vol. 25, pp. 1088 - 1097, 2010.
- Burke, D., and O'Malley, M.J., "Maximizing firm wind connection to security constrained transmission networks", *IEEE Transactions on Power Systems*, Vol. 25, pp. 749 – 759, 2010.
- Vittal, E., O'Malley, M.J. and Keane, A., "A steady state voltage stability analysis of power systems with high penetrations of wind", *IEEE Transactions on Power Systems*, Vol. 25, pp. 433 – 442, 2010. Also presented at IEEE PES Meeting Minneapolis, July 2010.
- Doherty, R, Mullane, A., Lalor, G., Burke, D., Bryson, A. and O'Malley, M.J. "An Assessment of the Impact of Wind Generation on System Frequency", *IEEE Transactions on Power Systems*, Vol. 25, pp. 452 – 460, 2010.

Recent relevant reports

- Eto, J., J. Undrill, P. Mackin, R. Daschmans, B. Williams, B. Haney, R. Hunt, J. Ellis, H. Illian, C. Martinez, M. O'Malley, K. Coughlin, and K.H. LaCommare,""Use of Frequency Response Metrics to Assess the Planning and Operating Requirements for Reliable Integration of Variable Renewable Generation", Lawrence Berkley National Laboratory, Berkeley, 2010. http://www.ferc.gov/industries/electric/indus-act/reliability/frequencyresponsemetrics-report.pdf

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- Holttinen, H.. Meibom, P., Orths, A., van Hulle, F., Lange, B., O'Malley, M., Pierik, J., Ummels, B., Tande, J, Estanqueiro, A., Matos, M., Gomez, E., Soder, L., Strbac, G., Shakoor, A., Ricardo, J., Smith, C., Milligan, M., Ela, E. Design and operation of power systems with large amounts of wind power. IEA Task 25 Final report, Phase one 2006-08, 2009. http://www.ieawind.org/AnnexXXV/PDF/Final%20Report%20Task%2025%202008/T2493.pdf

- EirGrid and SONI, "All Island TSO facilitation of Renewables Studies", June 2010. http://www.eirgrid.com/media/Renewable%20Studies%20V3.pdf

- International Panel on Climate Change (IPCC) Special Report on Renewable Energy Sources and Climate Change Mitigation, Final draft report to be approved at IPCC Plenary Session, Abu Dhabi, UAEE 5-8 May 2011.

  http://www.ipcc-wg3.de/publications/special-reports/srren

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- Current research Team: Dr. Damian Flynn, Dr. Eleanor Denny, Dr. Andrew Keane, Dr. Ciara O'Connor, Dr. Andrej Gubina, Mr. Paul Smith, Mr. Michael Power, Mr. Ronan Doherty, Mr. Daniel Burke, Mr. Ronan Fitzmaurice, Mr. Batsaikhan Nyamdash, Mr. Eknath Vittal, Mr. Peter Richardson, Ms. Niamh Troy, Mr. Aonghus Short, Ms. Amy O'Mahoney, Ms. Paul Cuffe, Mr. Eamonn Lannoye, Mr. David Kavanagh, Mr. Colm Lowery, Mr. Stefano Verde, Ms. Lisa Ruttledge, Ms. Muireann Lynch, Mr. Eamon Keane, Mr. David Fletcher, Mr. Lasantha Meegahapola, Mr. Erik Ela, Mr. Benish Paily, Mr. Mario Džamarija, Mr. Gaspar Artac, Ms. Rachael O' Hegarty, Ms. Magda Szczepanska
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- Collaborators: Peter Meibom, Brian Parsons, Michael Milligan, Erik Ela, Prof. Janusz Bialek, Dr. Brendan Fox, Prof. John FitzGerald Dr. Chris Dent

Harvesting Renewable Energy
The Grid Integration Challenge

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