Integrating Wind in Ireland: Experience and Studies

Mark O'Malley

Director, Electricity Research Centre

University College Dublin

mark.omalley@ucd.ie

www.ucd.ie/erc

electricity research centre

Integration Workshop, MIT Wind Week

January 21th 2011

UCD DUBLIN

Electricity Research Centre (ERC), Industry Members

Other stakeholders on ERC board:

seai | ESRI | Department of Communications Energy & Natural Resources

Major Funding sources:

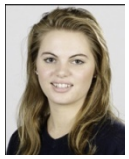
erc electricity research centre | SFI | IRCSET | HEA Higher Education Authority An tÚdarás um Ard-Oideachas

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





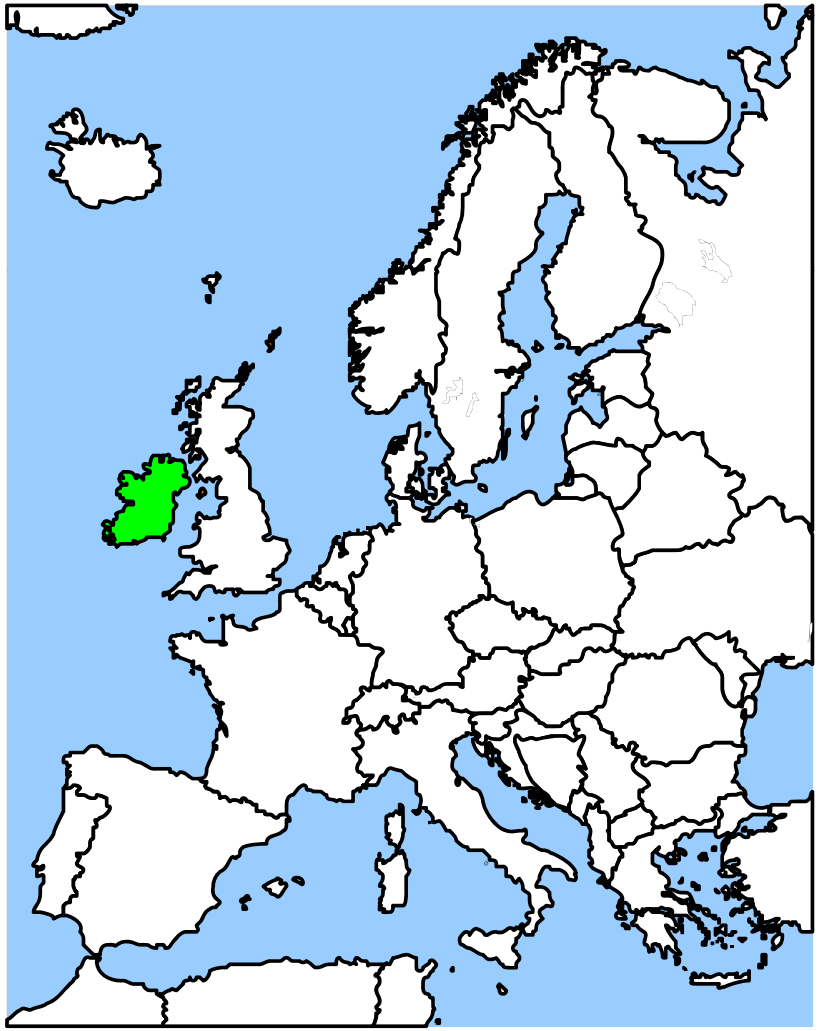




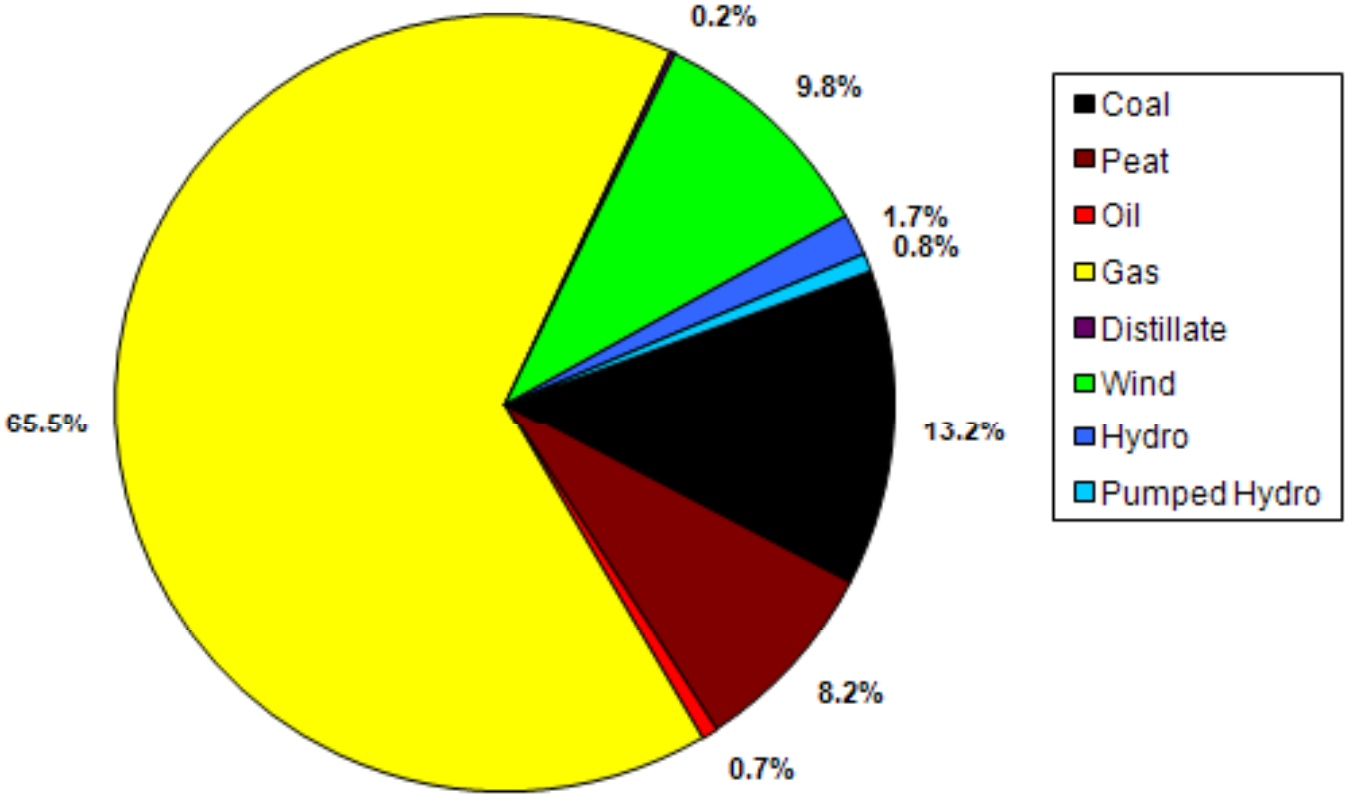
Ireland has a unique renewable resource & technical environment

Ireland: All Island Grid

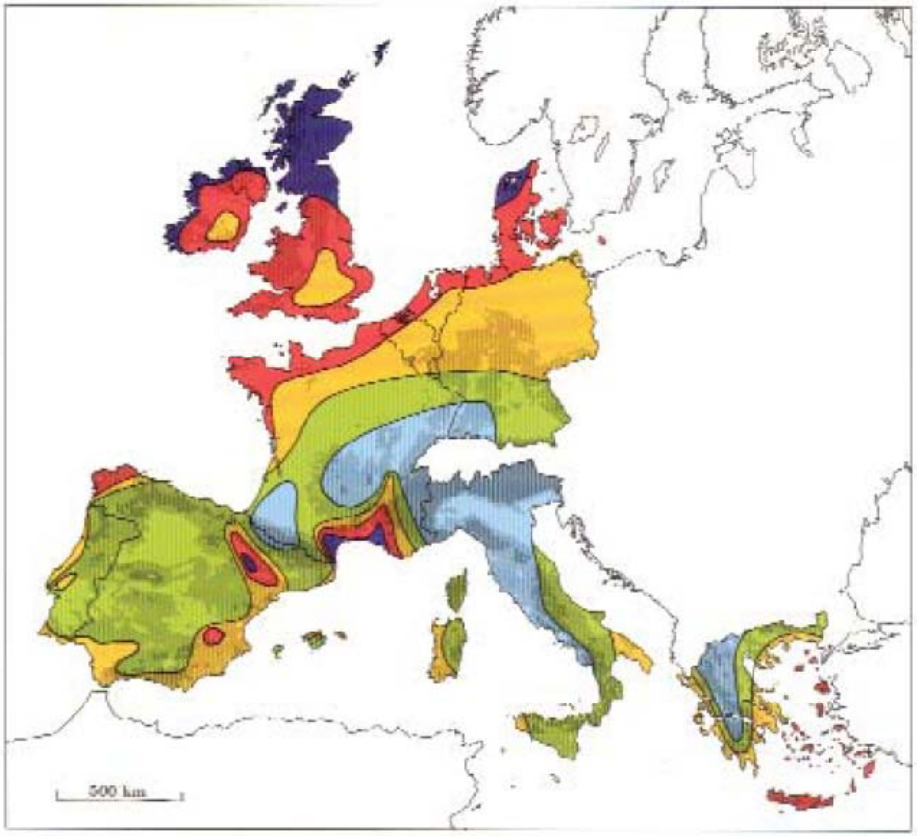
- Republic of Ireland (RoI) & Northern Ireland
- 9.7 GW Installed
- 1.8 GW Wind (> 10 % energy)
- 450 HVDC to GB
- Max load: 6.5 GW
- Min load: 2.4 GW



Reliance on imported fossil fuel (RoI)

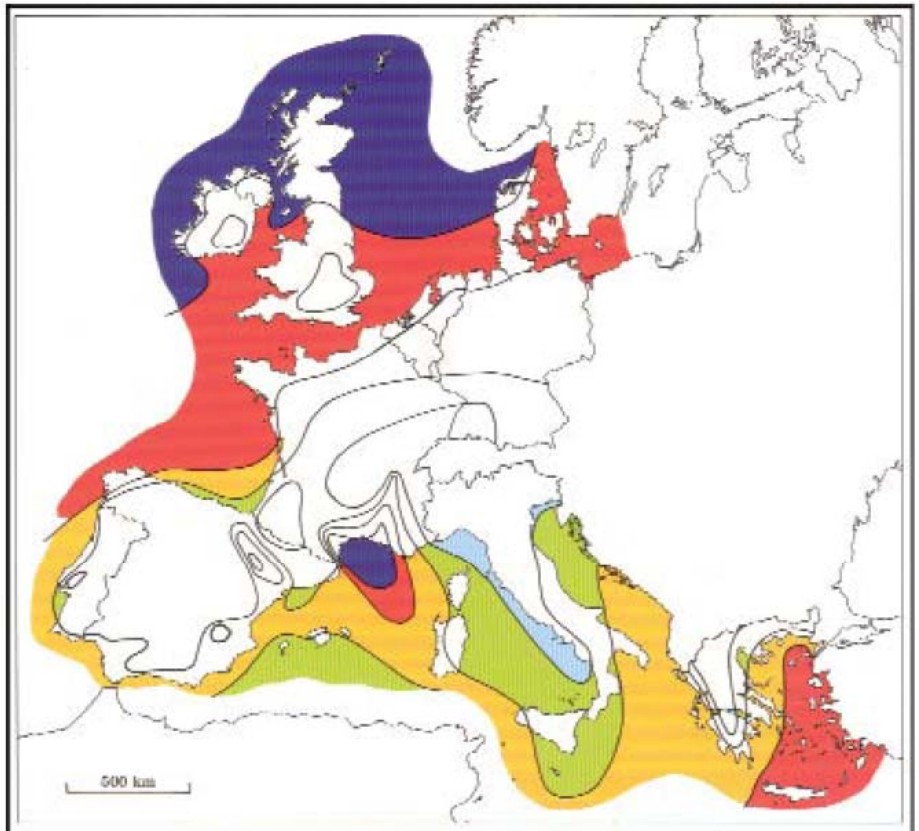


European Wind Resources



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]	
	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	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

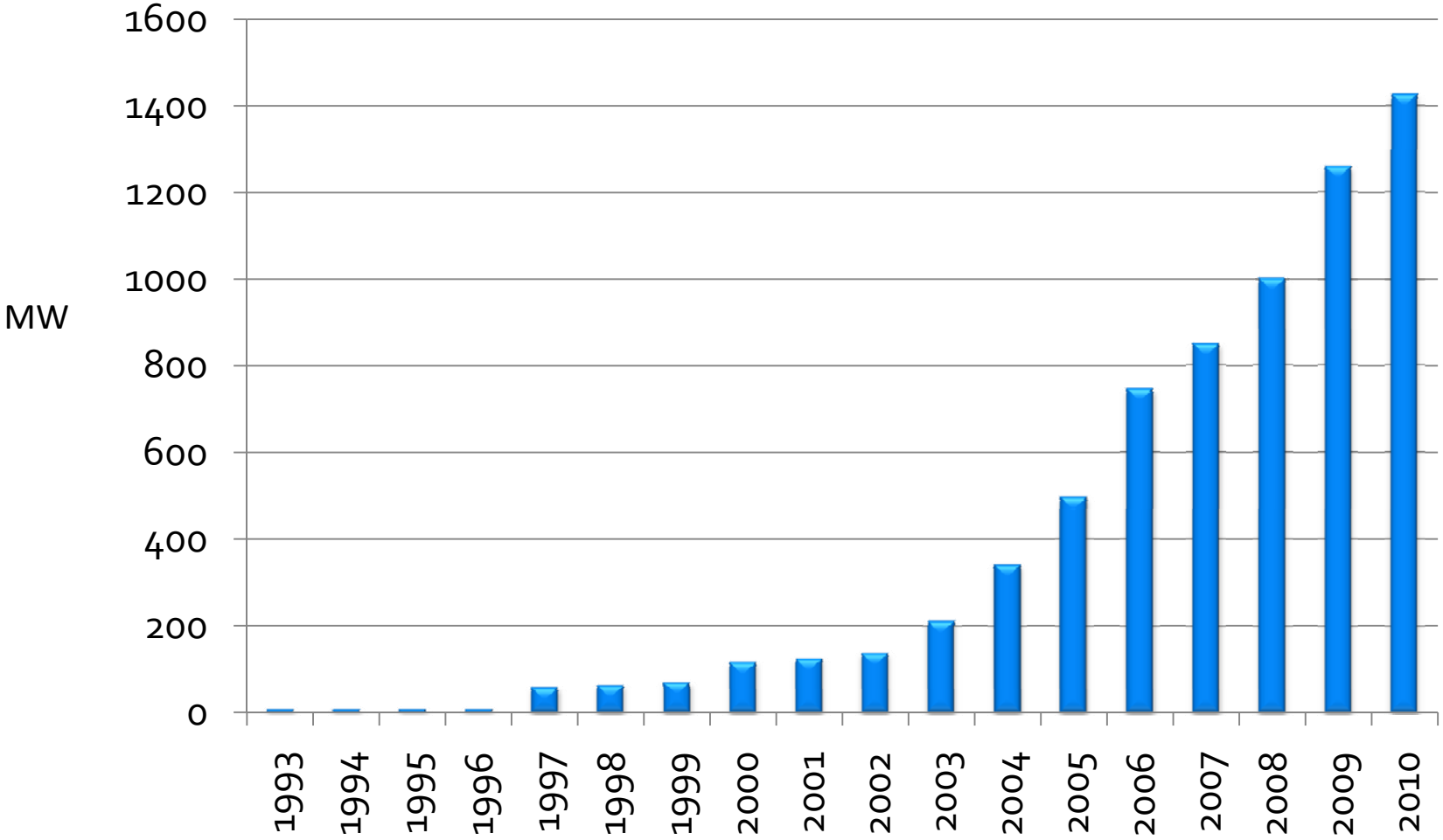
	10 m		25 m		50 m		100 m		200 m	
	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}	ms^{-1}	Wm^{-2}
	> 8.0	> 600	> 8.5	> 700	> 9.0	> 800	> 10.0	> 1100	> 11.0	> 1500
	7.0-8.0	350-600	7.5-8.5	450-700	8.0-9.0	600-800	8.5-10.0	650-1100	9.5-11.0	900-1500
	6.0-7.0	250-500	6.5-7.5	300-450	7.0-8.0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

Offshore

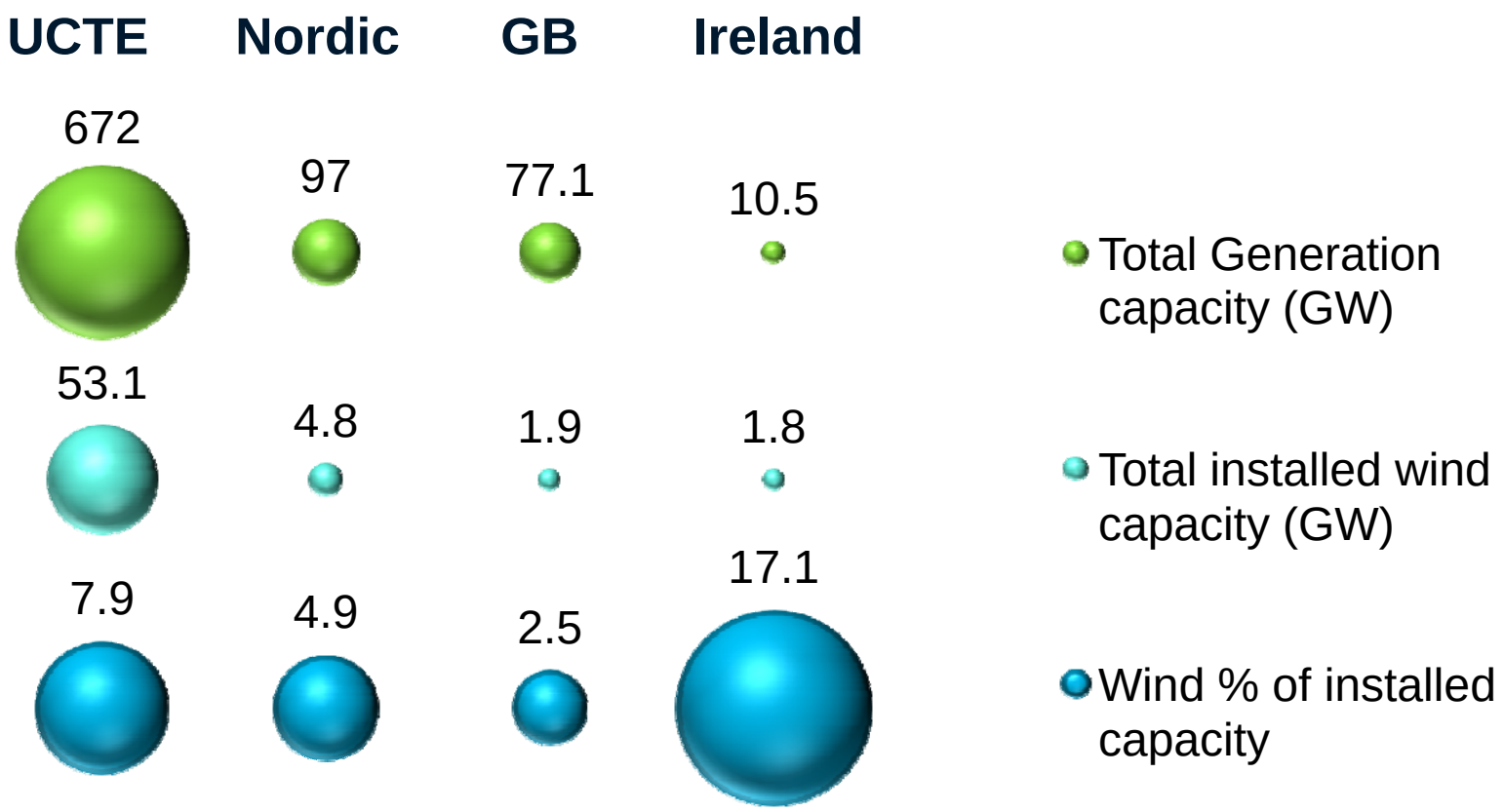
Sustainable development commission, Wind Power in the UK, 2005

Wind Installed in Republic of Ireland



Source: EirGrid

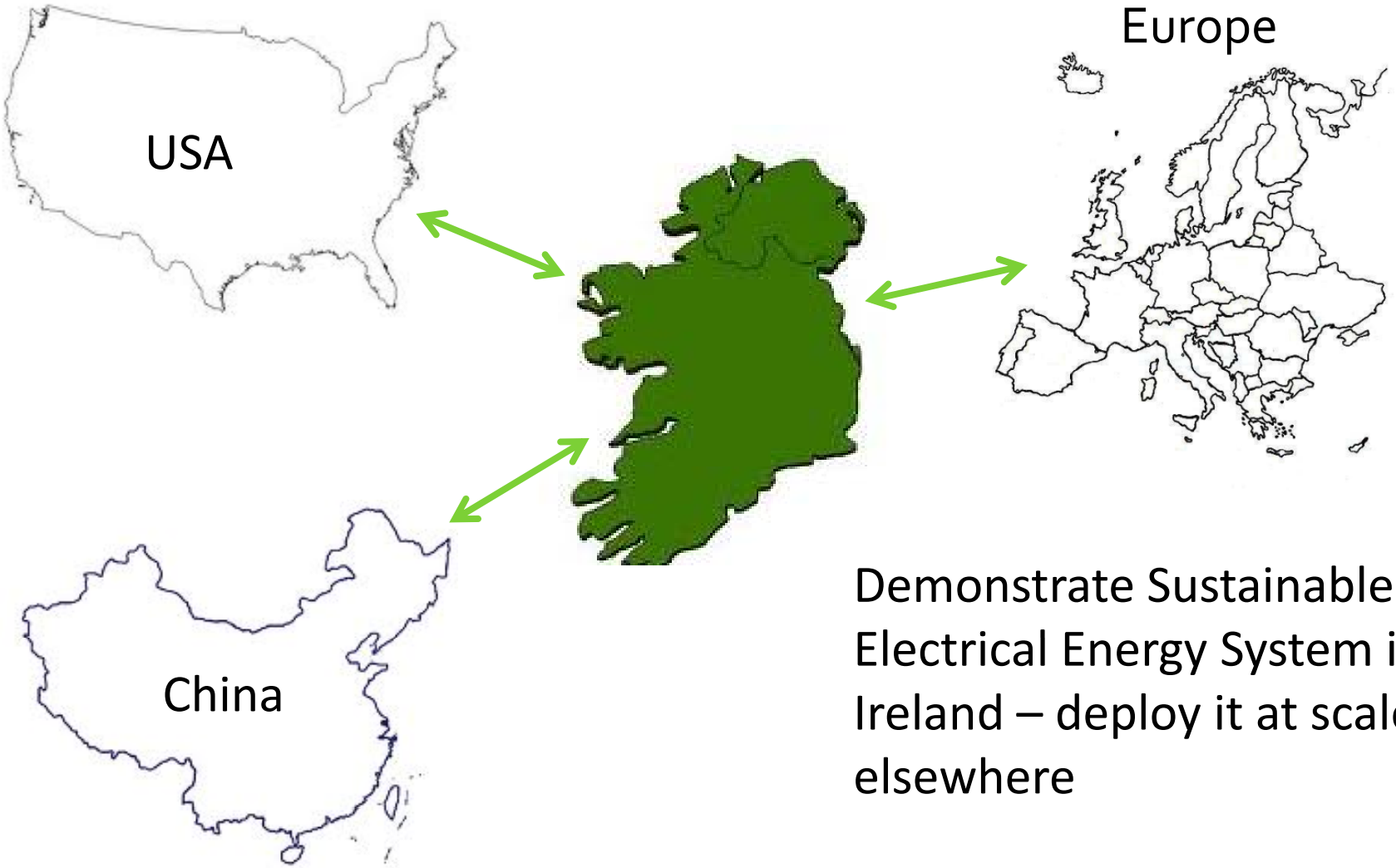
Ireland: Very High Wind Penetration



Figures for end 2008

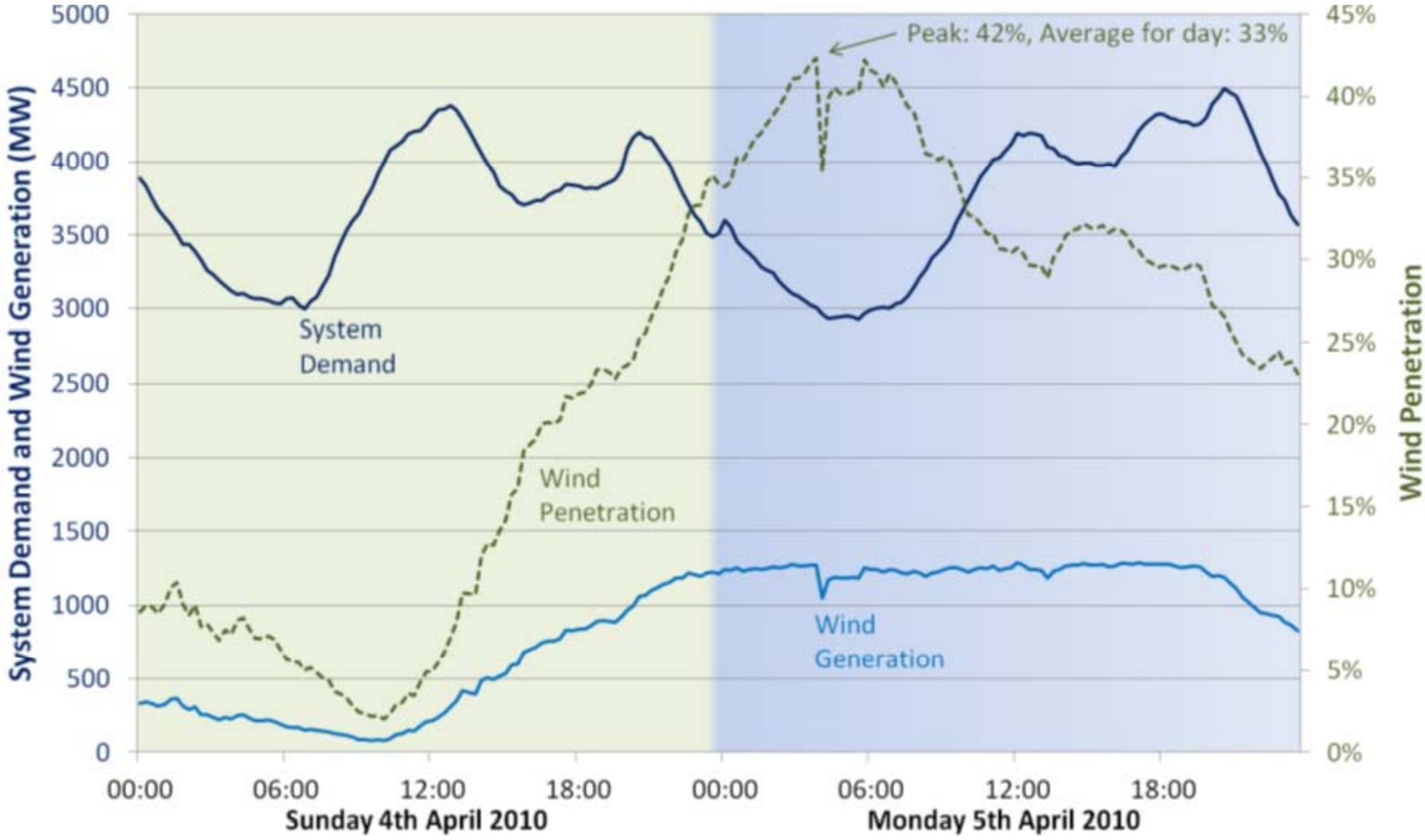
Source: Global wind energy outlook 2008, EirGrid, UK National Grid, NORDEL, Eurelectric

Ireland, an exemplar for the world



Demonstrate Sustainable Electrical Energy System in Ireland – deploy it at scale elsewhere

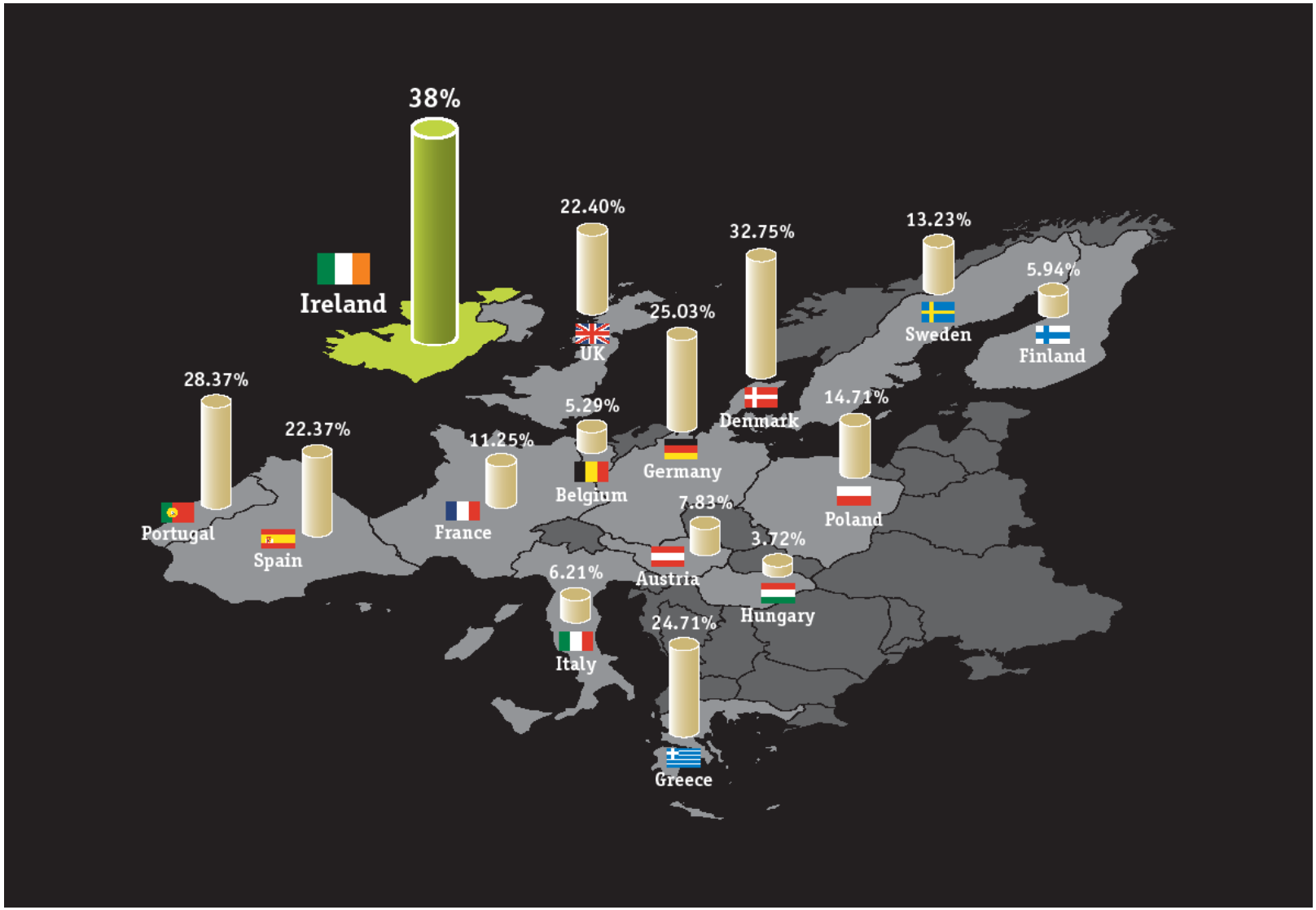
Wind in Republic of Ireland, April 2010



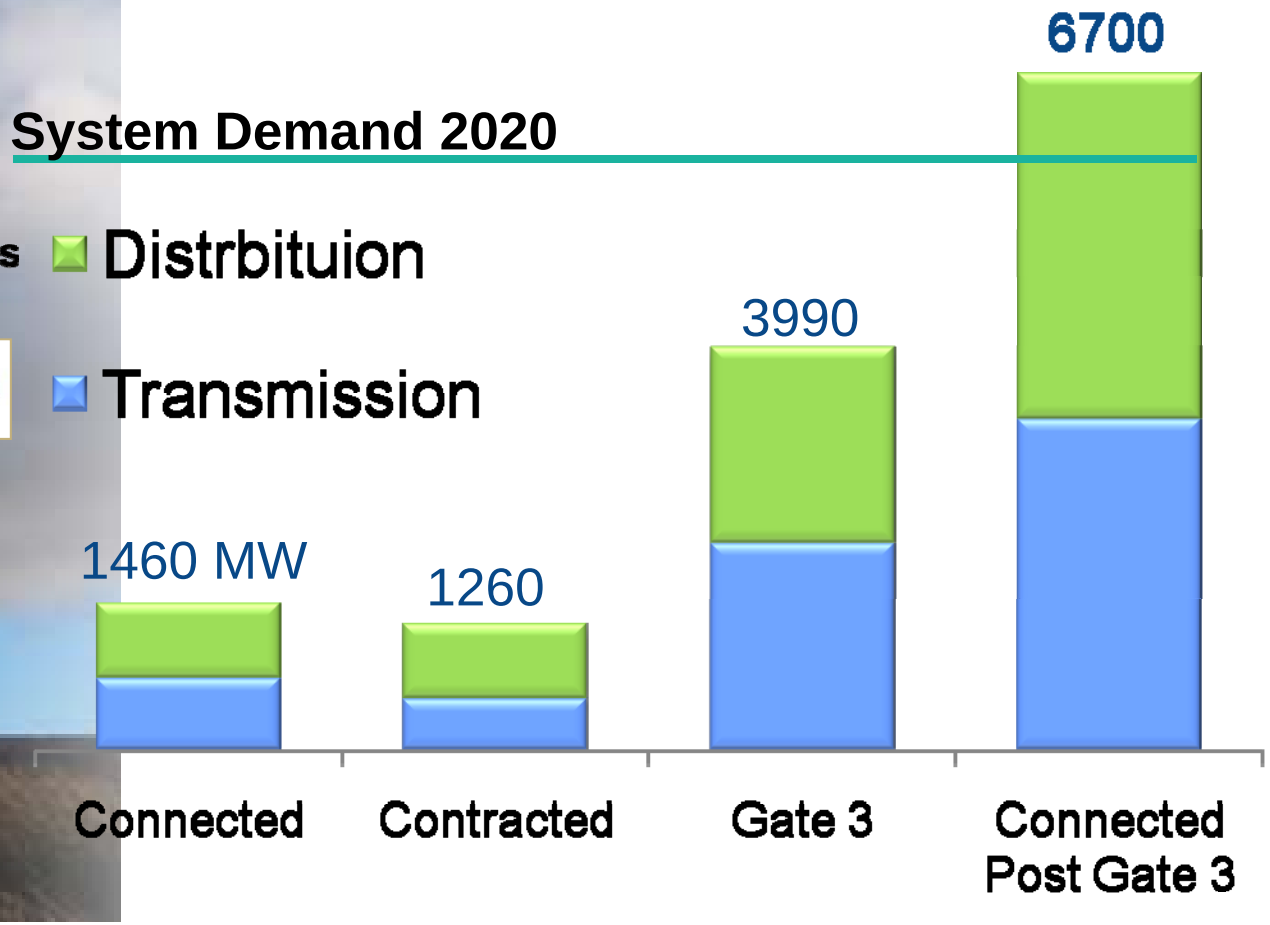
~1 .2 GW wind power change in 18 hours
(2 % to 42 % penetration)

All island data from EirGrid & SONI

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

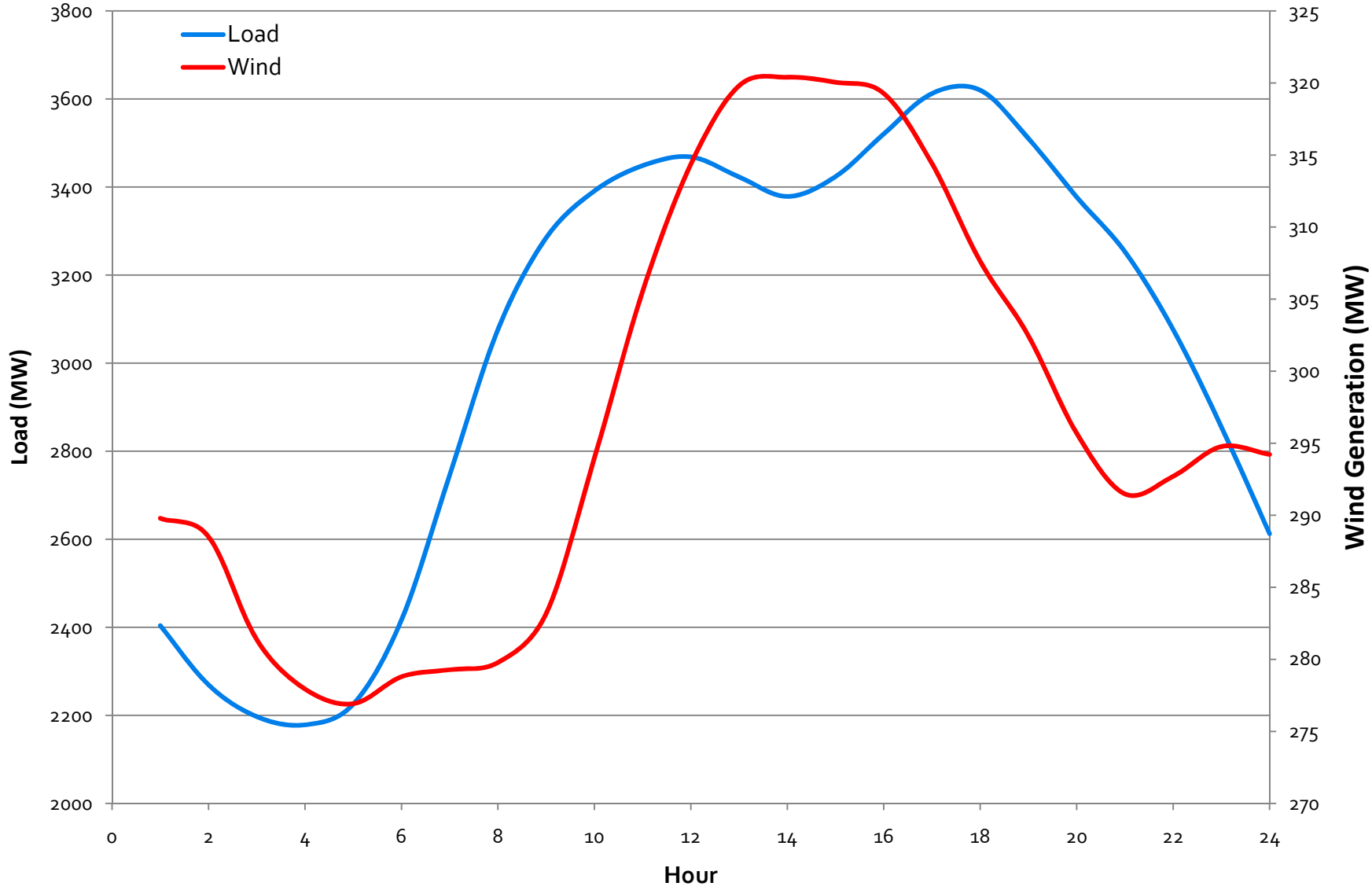


Wind Connections MW

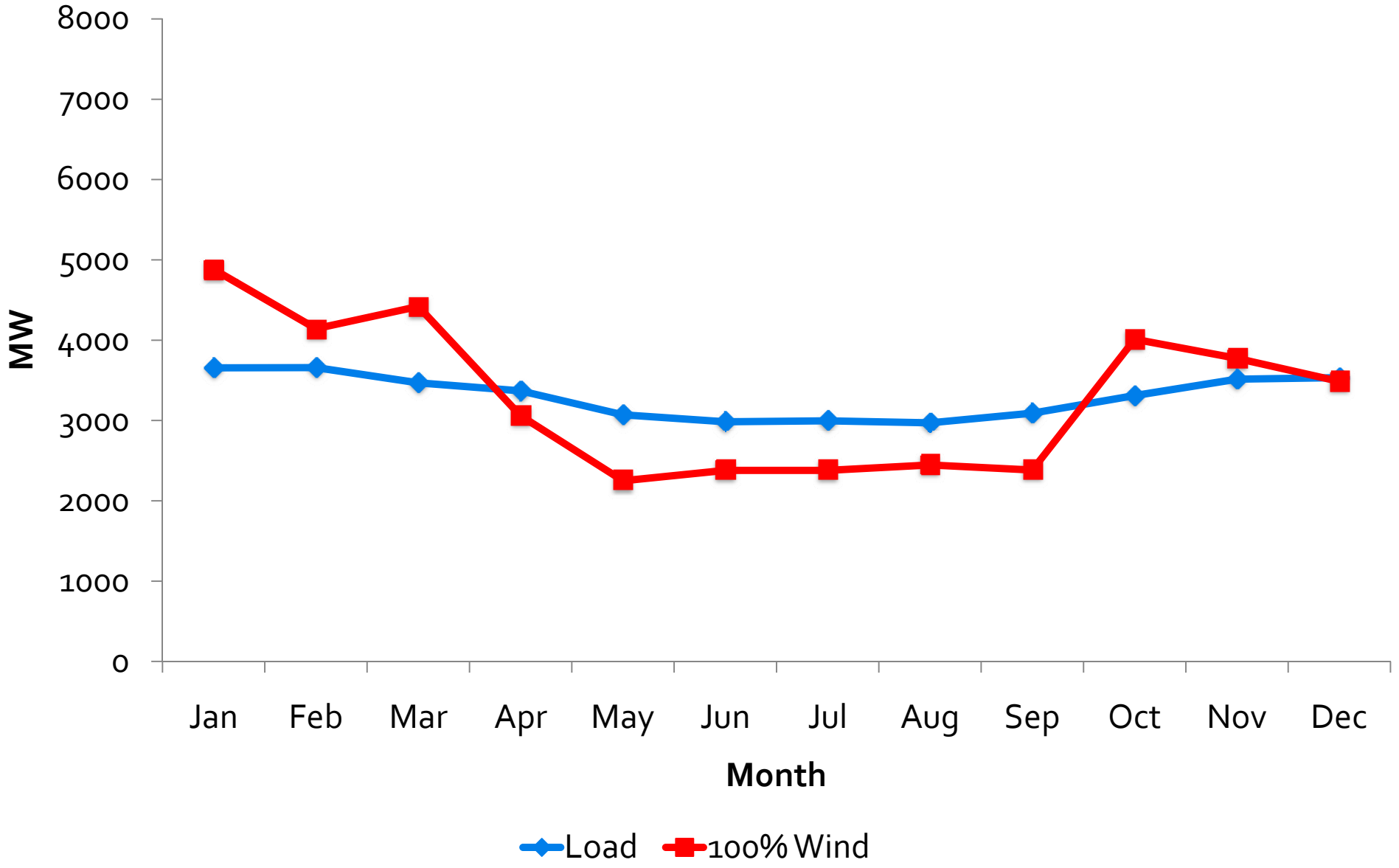


Wind Resource

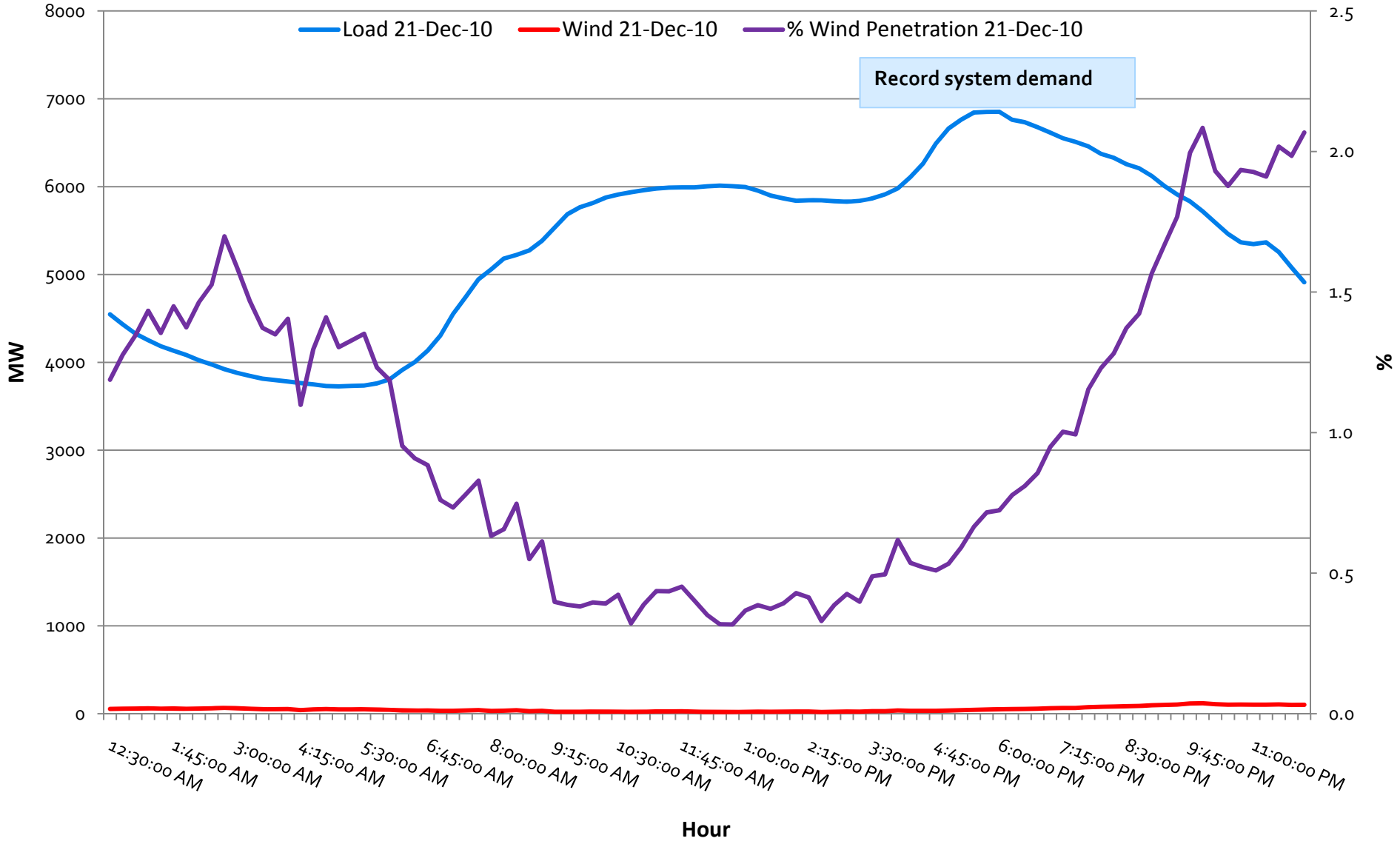
Load and Wind Averaged by Hour (2010)



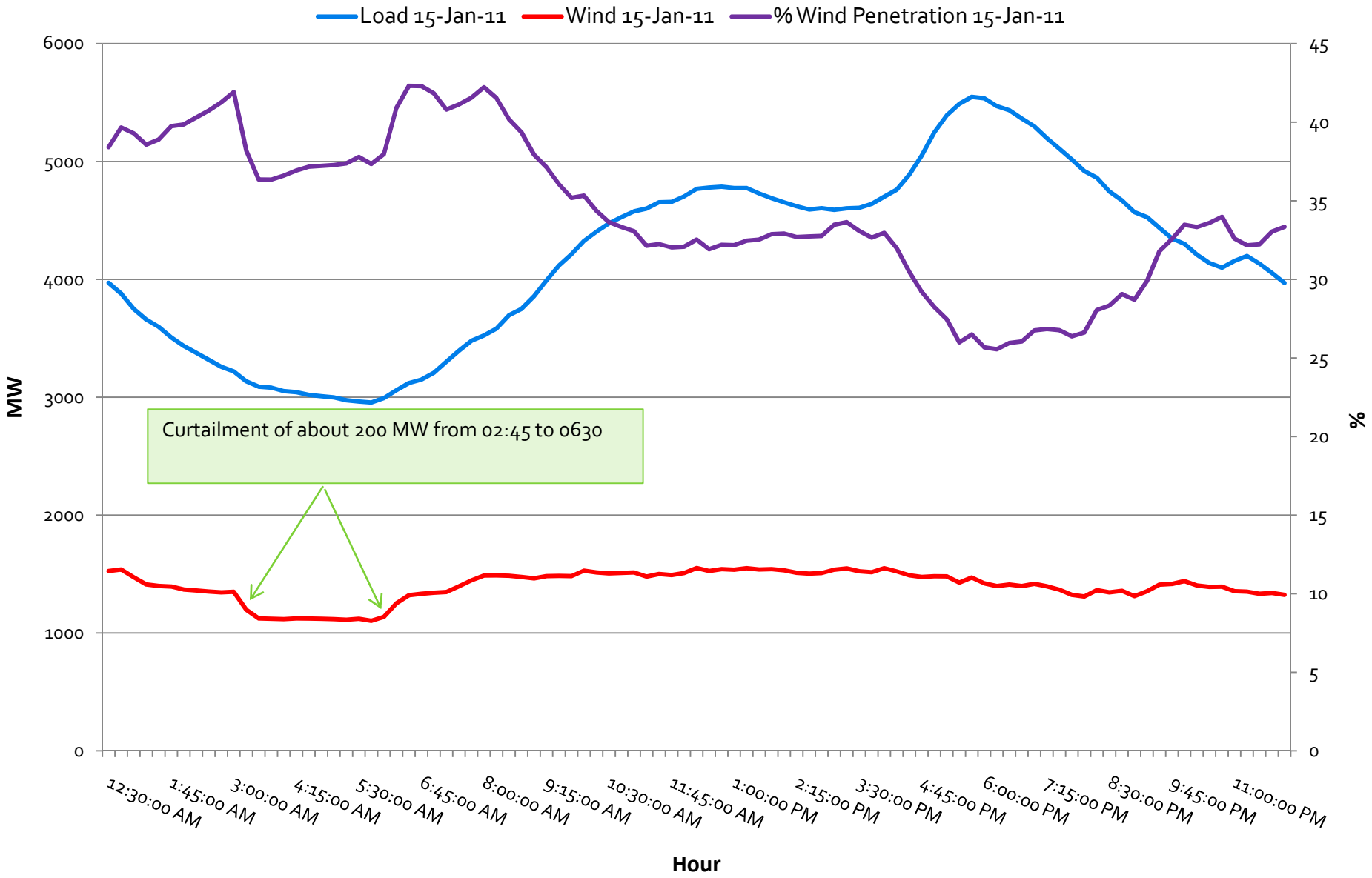
Seasonal (100 % Wind)



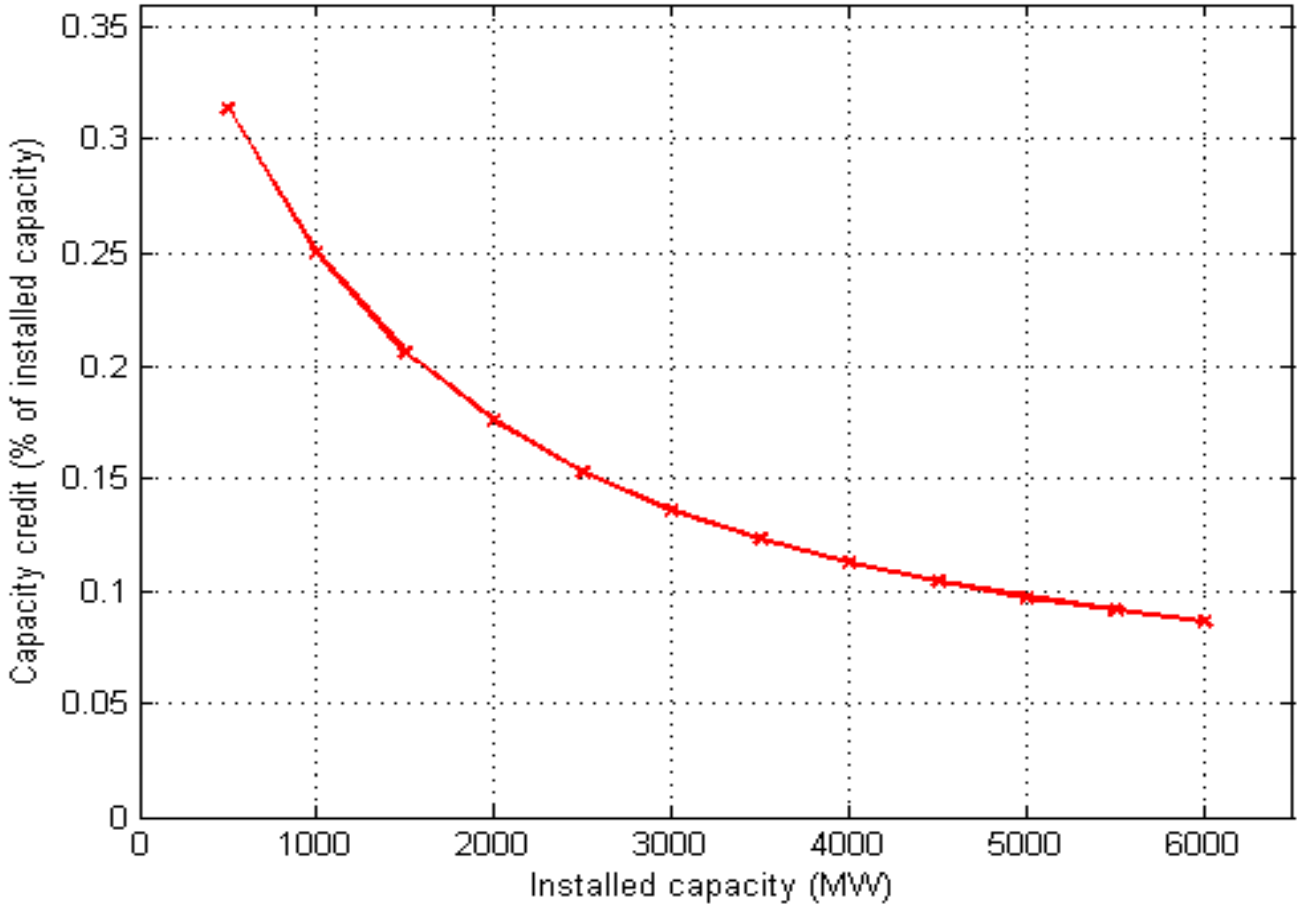
Ireland Wind & Load (21 Dec 2010)



Ireland, Wind & Load – 15 Jan 2011

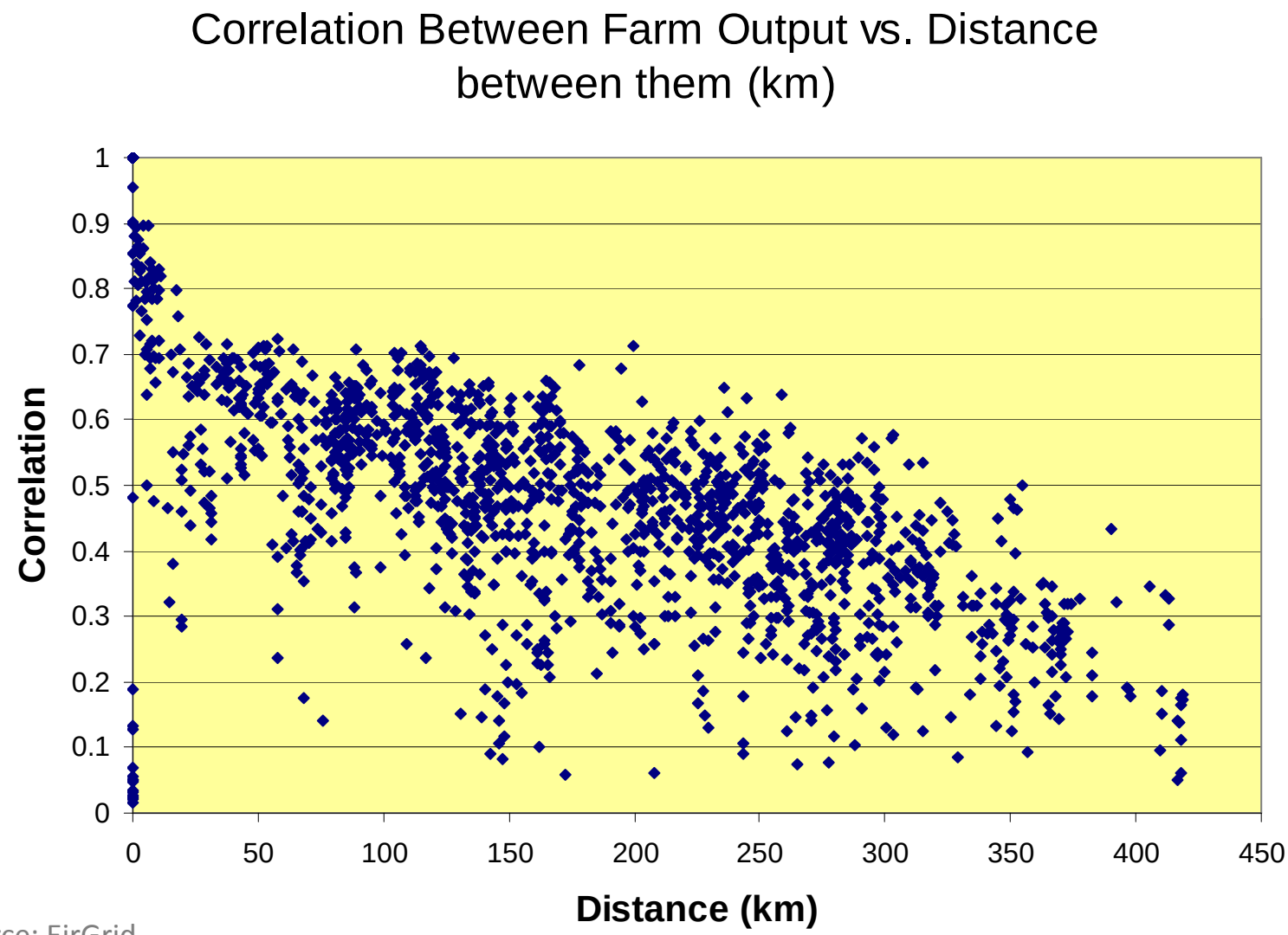


Capacity Credit (Value) Ireland



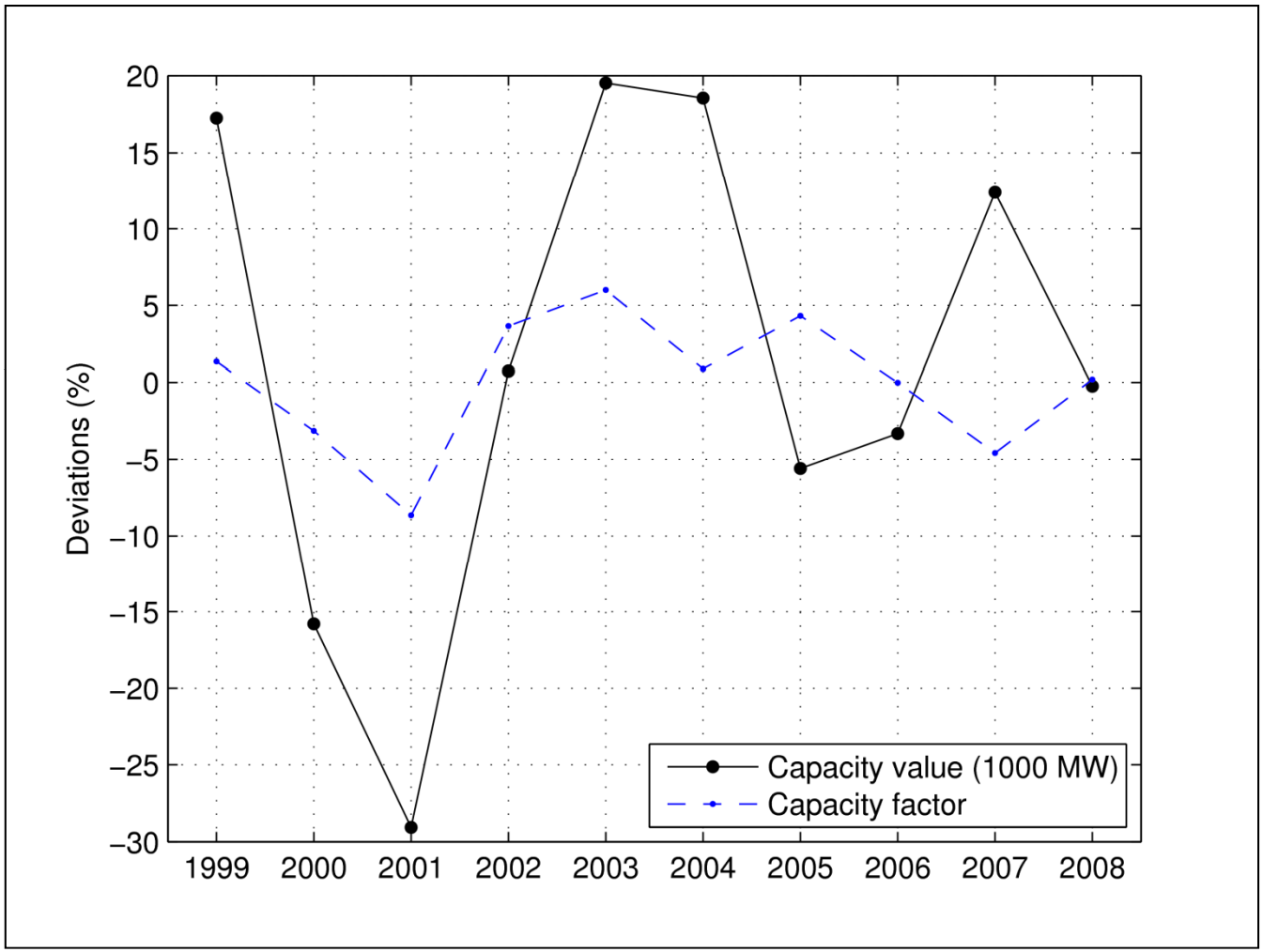
Keane, A., Milligan, M., D'Annuzio, C., Dent, C., Dragoon, K., Hasche, B., Holttinen, Samaan, N., Soder, L. and O'Malley, M.J., "Capacity Credit of Wind Power, *IEEE Trans. Power Syst.,*in press, 2010.

Correlation Between Wind Farms



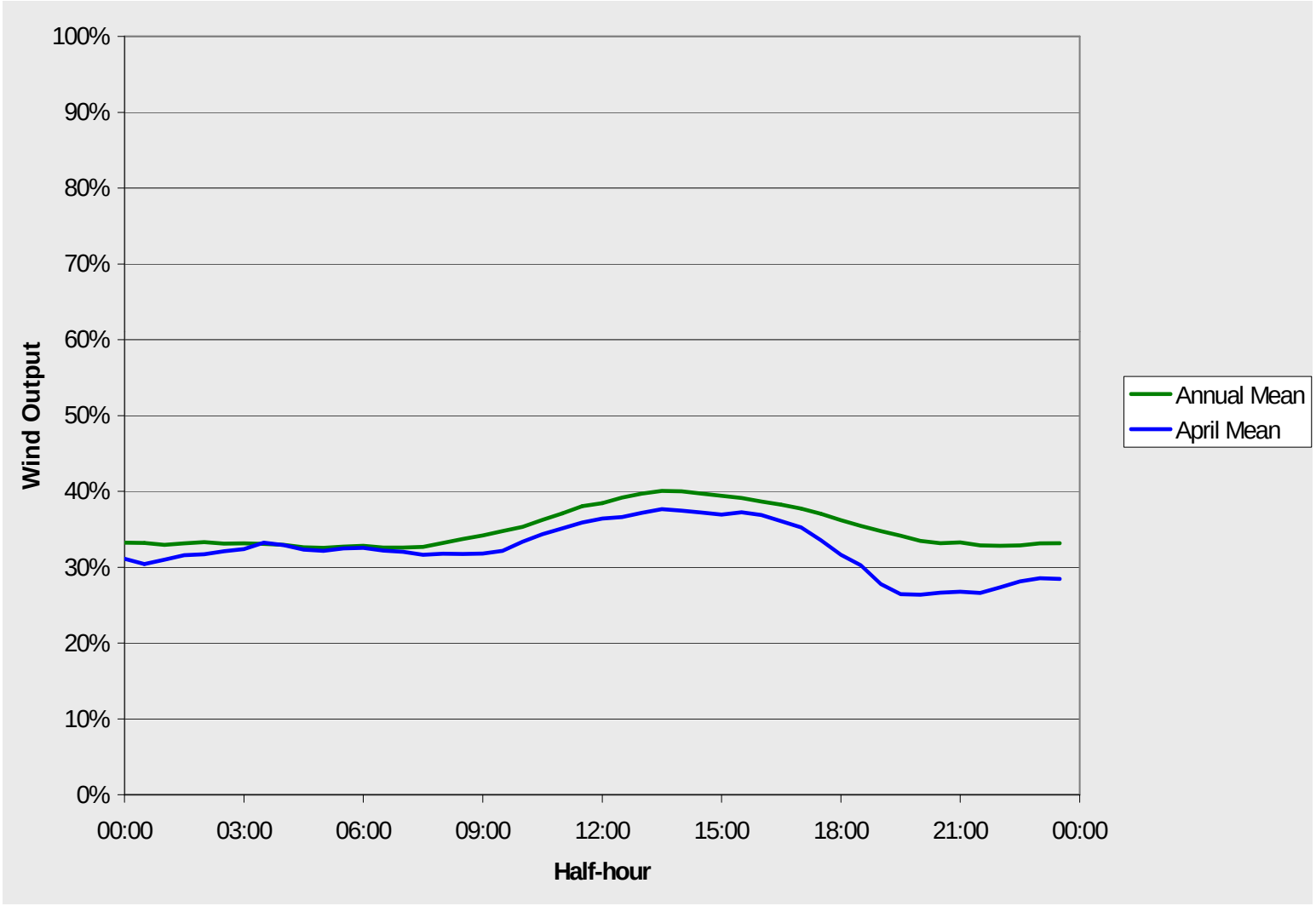
Source: EirGrid

Yearly variations



Hasche, B., Keane, A. and O'Malley, M.J. "Capacity credit of wind power: calculation and data requirements", *IEEE Trans. Power Syst.,* in press, 2011.

Annual and April Mean Wind Output



Source: EirGrid

Capacity factor (Republic of Ireland)

	Capacity Factor
Average (1999 – 2009)	31 %
Max (1999 – 2009)	34 %
Min (1999 – 2009)	29 %
Capacity factor 2010	23 %

**** Note: Preliminary date not for quoting

Grid Studies

Wind energy integration studies/reports


GARRAD HASSAN

ESB INTERNATIONAL

THE IMPACTS OF INCREASED LEVELS OF WIND PENETRATION ON THE ELECTRICITY SYSTEMS OF THE REPUBLIC OF IRELAND AND NORTHERN IRELAND: FINAL REPORT

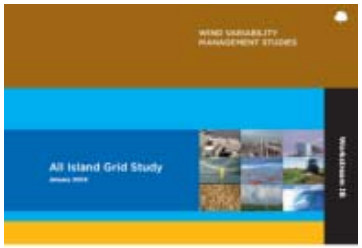
Client	Commission for Energy Regulation/OFREG NI
Contact	Ms Sheenagh Rooney
Document No	3096/GR/04
Issue	E
Status	FINAL
Classification	Client's Discretion
Date	11 February 03

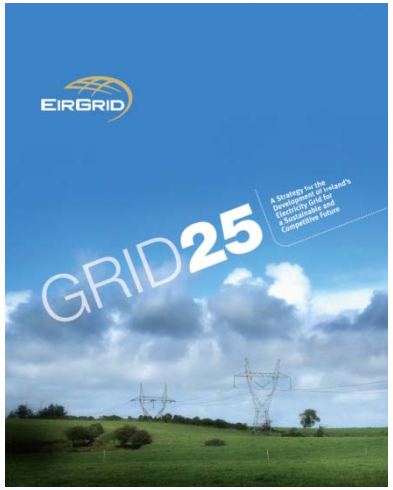
Author: P Gardiner, H Snodin, A Higgins, S McGoldrick

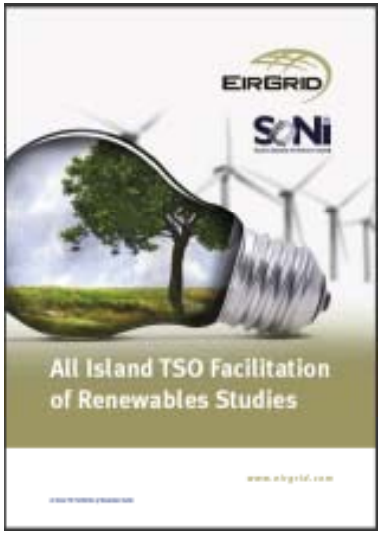
Checked by: P Gardiner, B O Gallachoir

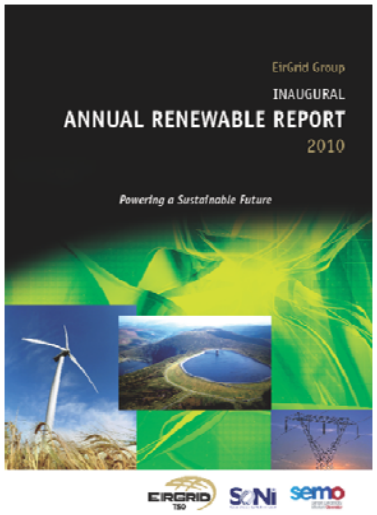
Approved by: A D Garrad

Garrad Hassan and Partners Limited
2004 Maryhill Road, Glasgow G20 0AB, Scotland Tel +44(0)141 945 4774 Fax +44(0)141 945 3076
Registered in England 1878456

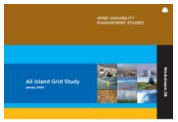




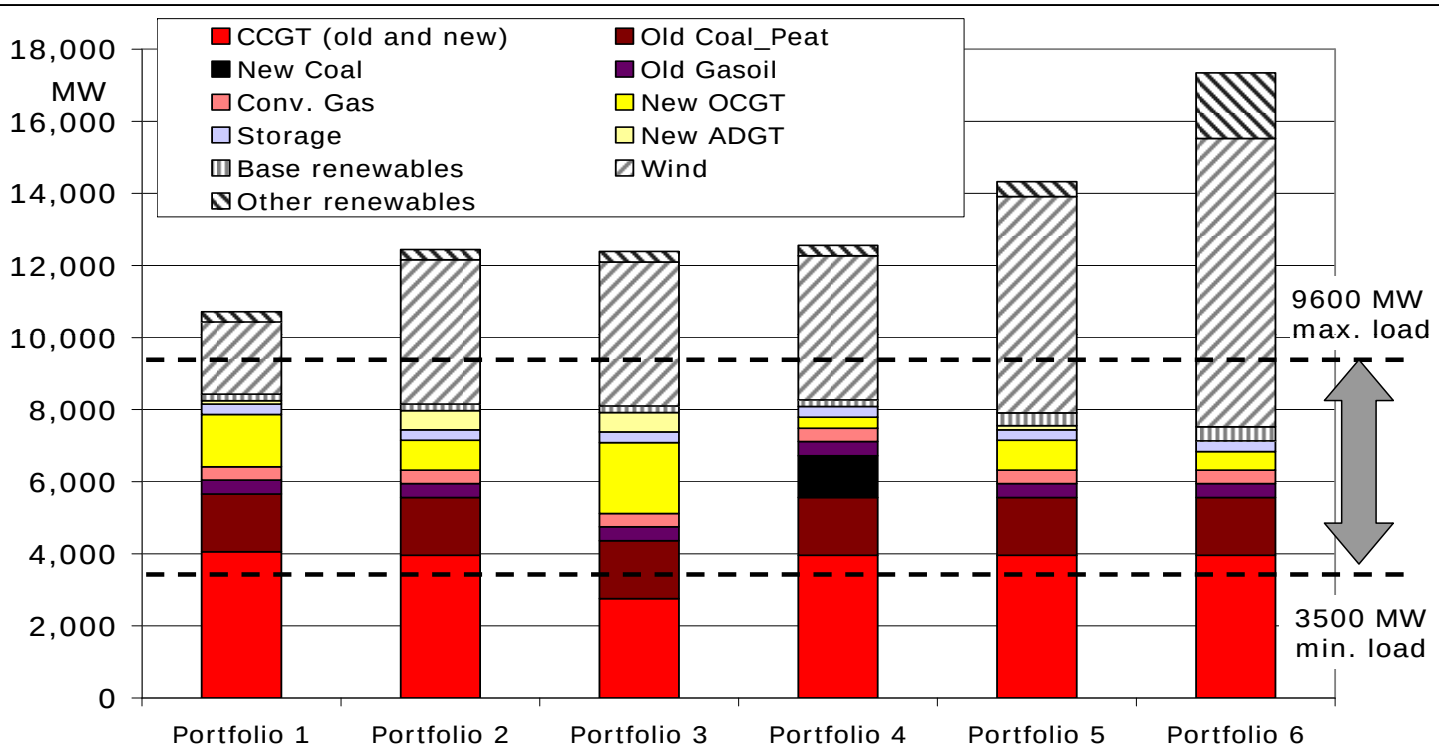




All Island Grid Study (AIGS)



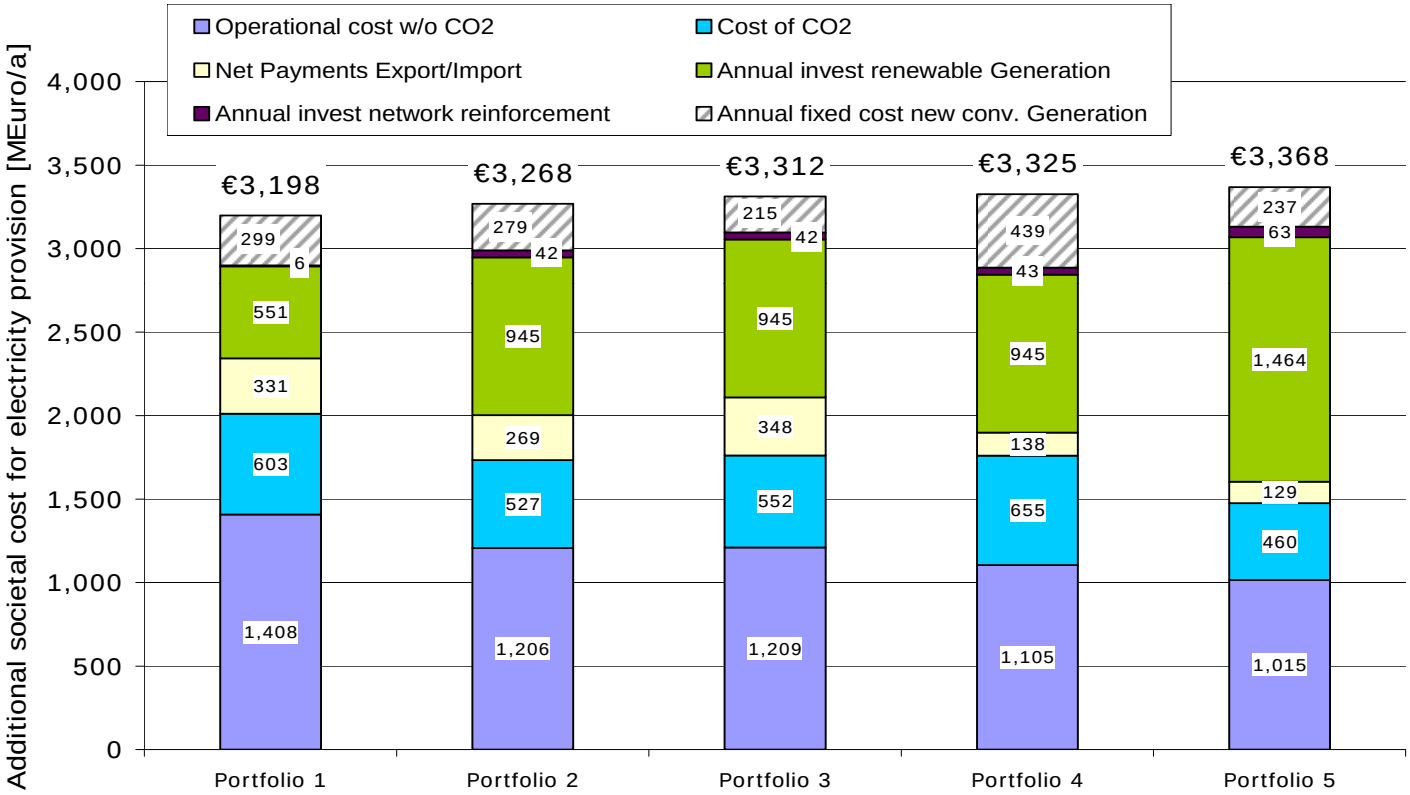
AIGS: Portfolios



Share of Renewables

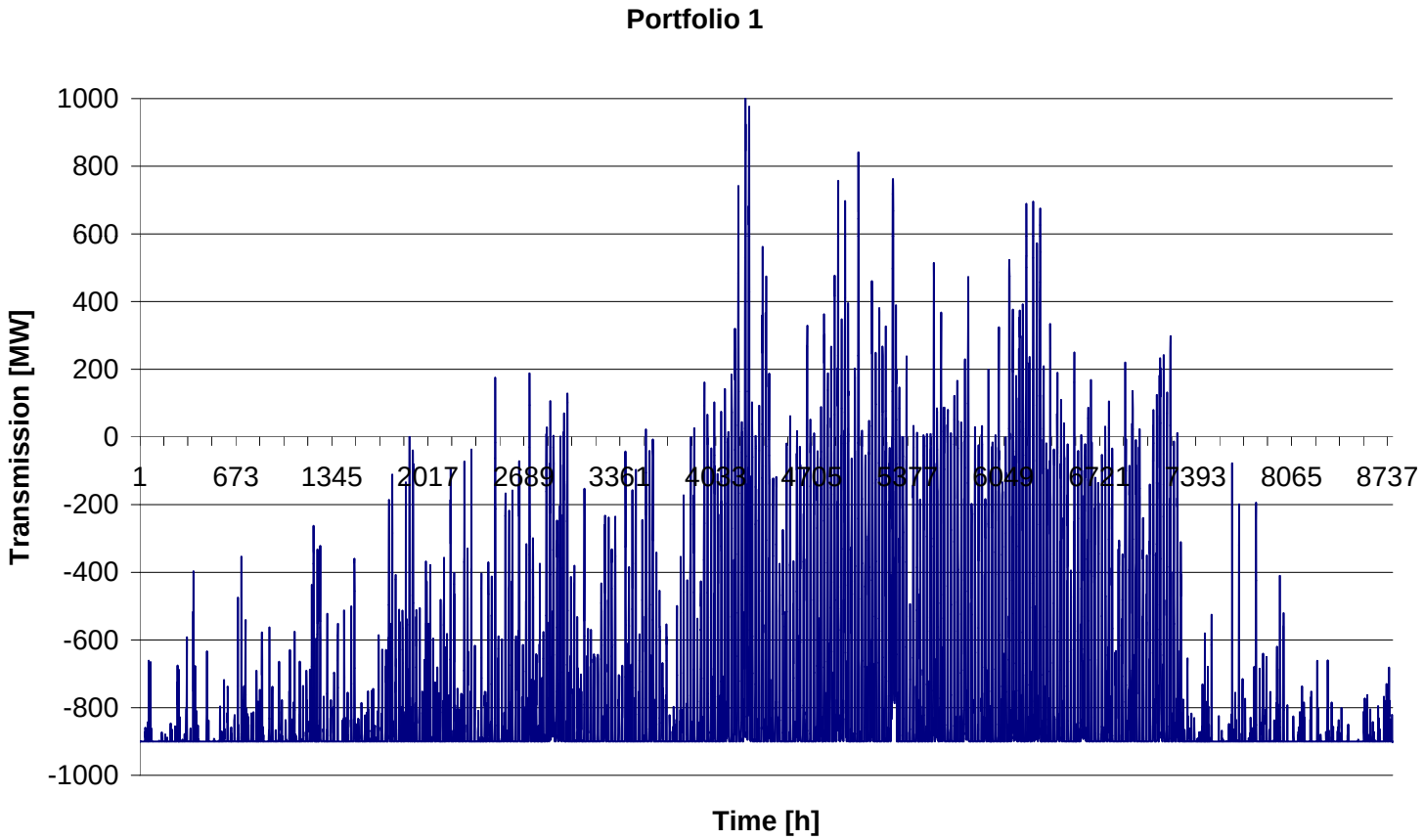
	Portfolio 1	Portfolio 2	Portfolio 3	Portfolio 4	Portfolio 5	Portfolio 6
Capacity	23 %	36 %	36 %	36 %	47 %	59 %
Energy	16 %	27 %	27 %	27 %	42 %	59 %

AIGS: Societal Costs of Adopting Portfolios

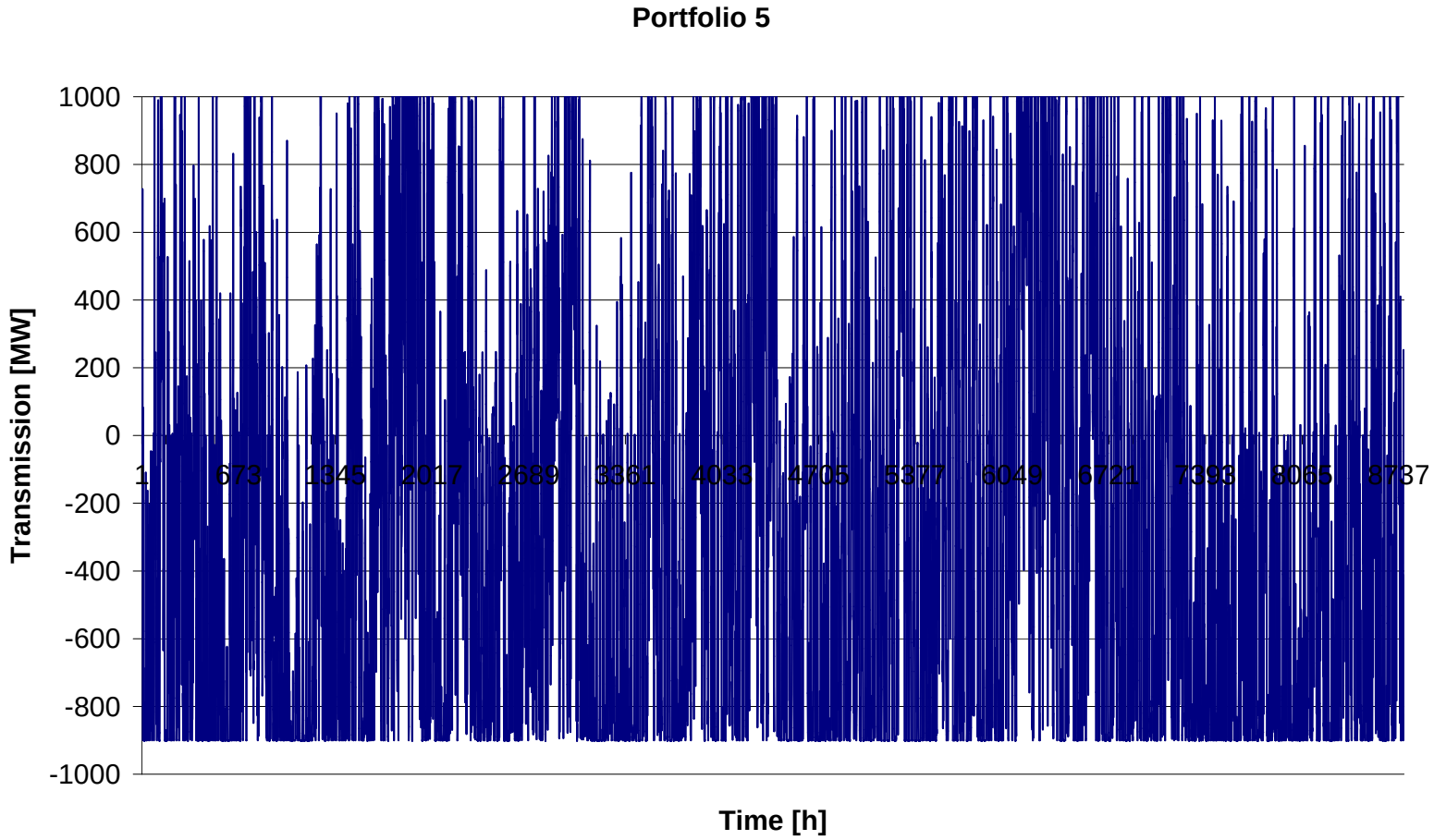


RE share of demand	16%	27%	27%	27%	42%
CO_2 emissions [Mt/a]	20	18	18	22	15

AIGS: Import/export GB (portfolio 1)

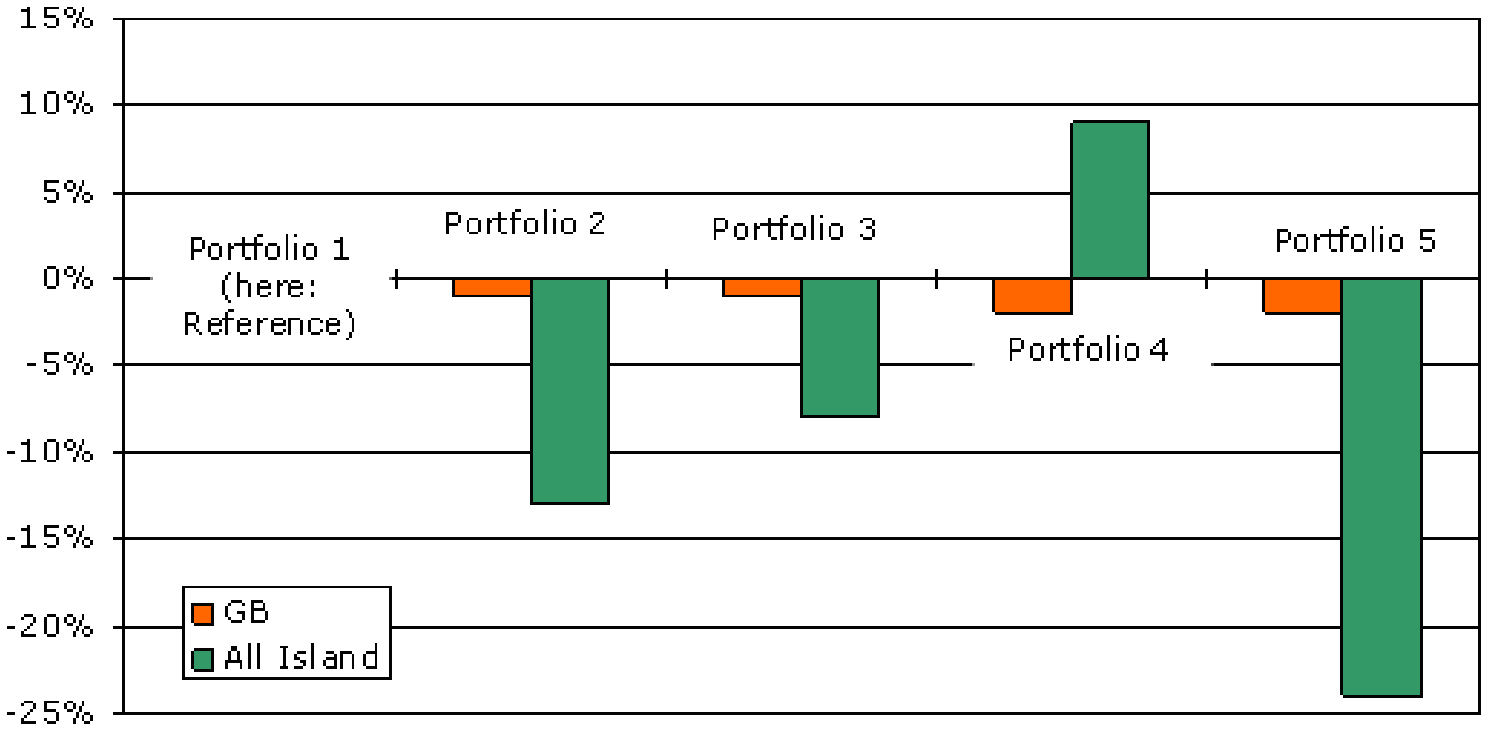


AIGS: Import/export GB (portfolio 5)



Denny, E., Tuohy, A., Meibom, P., Keane, A., Flynn, D. Mullane, A. and O'Malley, M.J., "The Impact of Interconnection on Electricity Systems with Large Penetrations of Wind Generation", *Energy Policy*, in press, 2011.

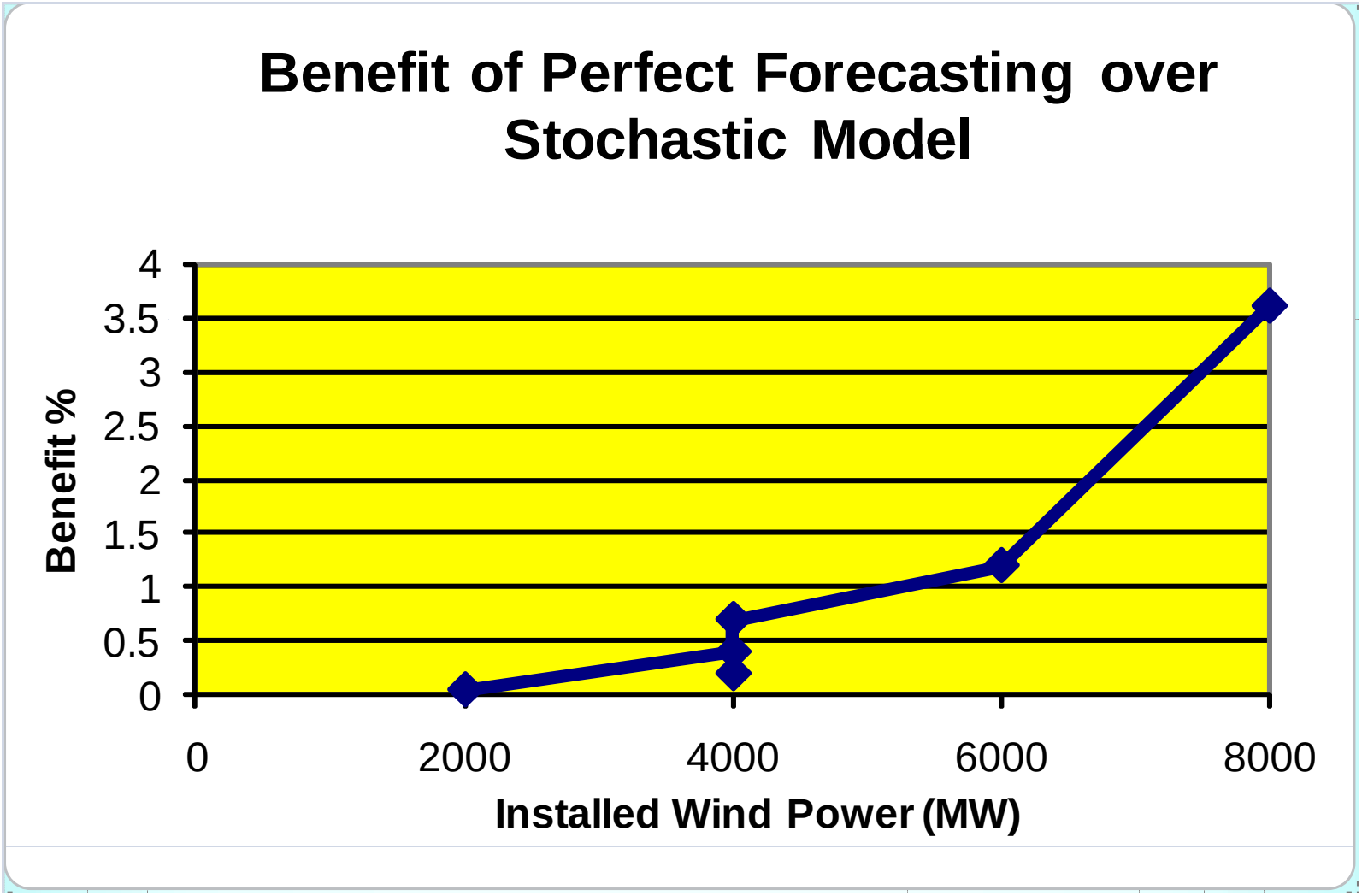
AIGS: Relative CO_2 Emissions Impact



AIGS: Benefits of Improved Forecasting

	P1	P2	P3	P4	P5	P6
Absolute cost reductions due to perfect forecast [MEuro]	1.2	8.0	4.8	13.6	18.5	65.0
Relative cost reductions due to perfect forecast [%]	0.05	0.4	0.2	0.7	1.2	3.6

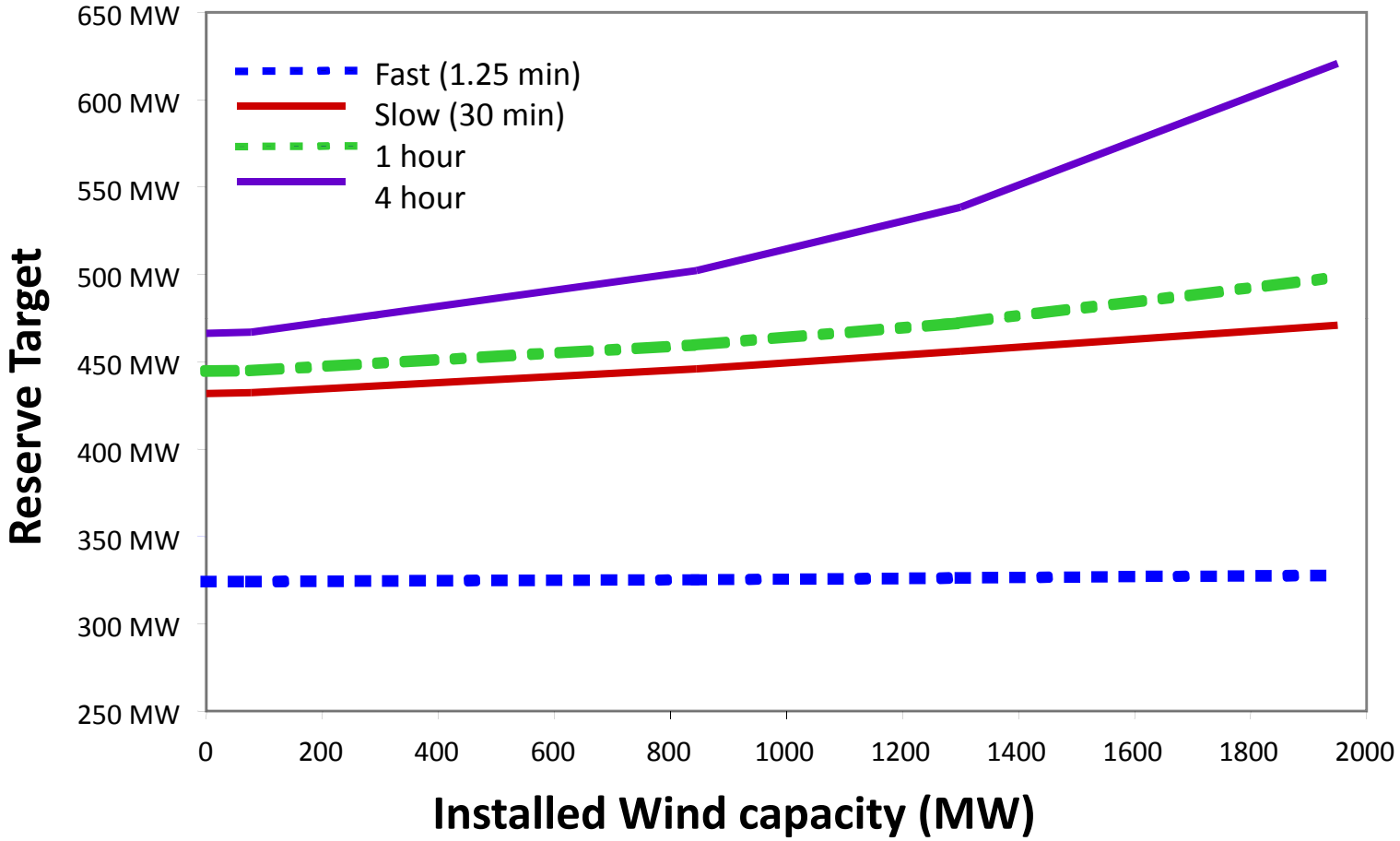
AIGS: Benefits of Improved Forecasting



AIGS: Wind curtailment

	P1	P2	P3	P4	P5	P6
Provision of spinning reserves [TWh]	0	0	0.01	0	0.07	0.10
Other reasons than provison of spinning reserve [TWh]	0	0	0	0	0.02	0.48
Total curtailment as percentage of wind power production	0	0	0	0	0.5	2.3

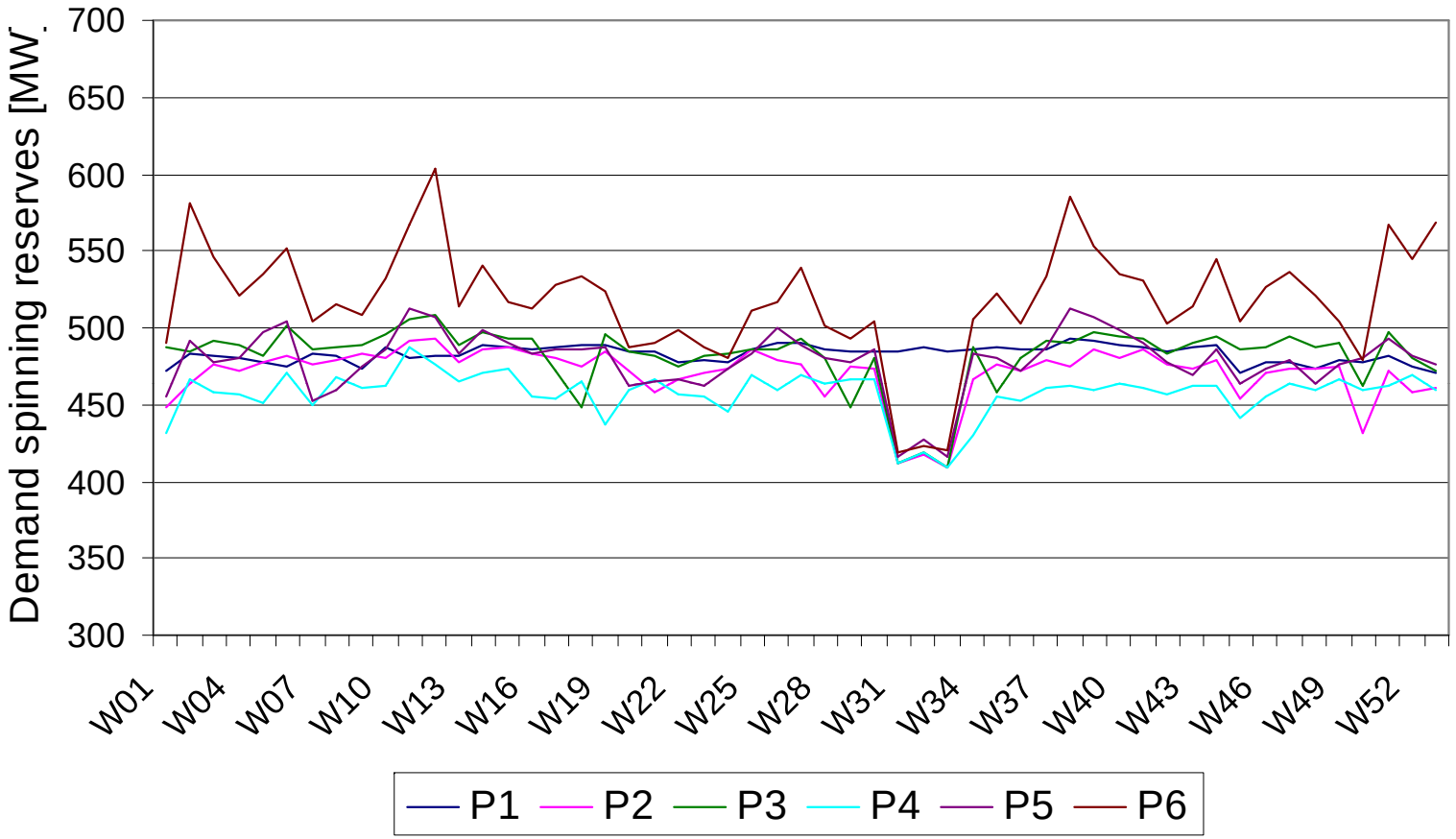
Reserve targets



ILEX Energy, UCD, QUB and UMIST, "Operating reserve requirements as wind power penetration

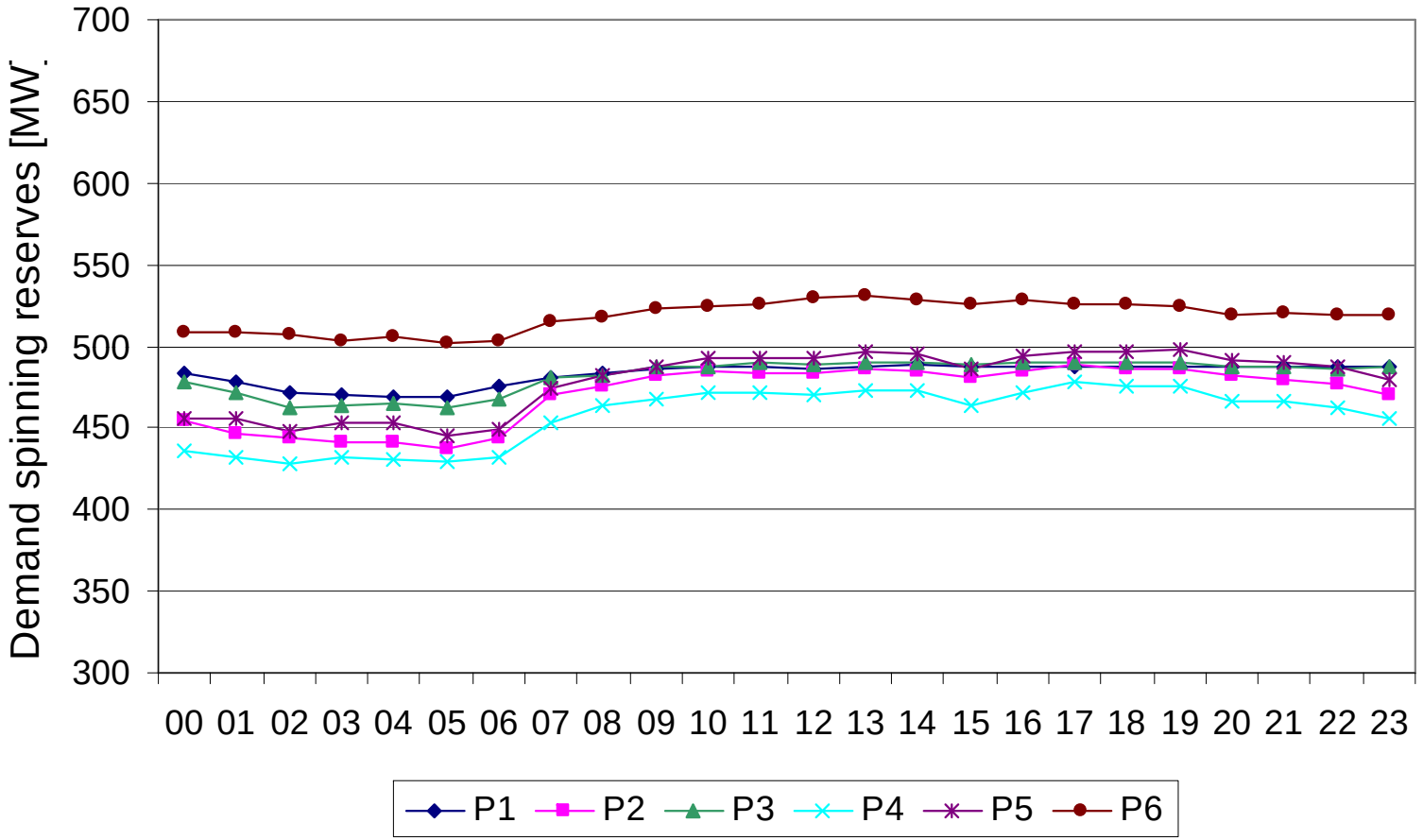
**Non-Grid study information

AIGS: Demand for spinning reserve



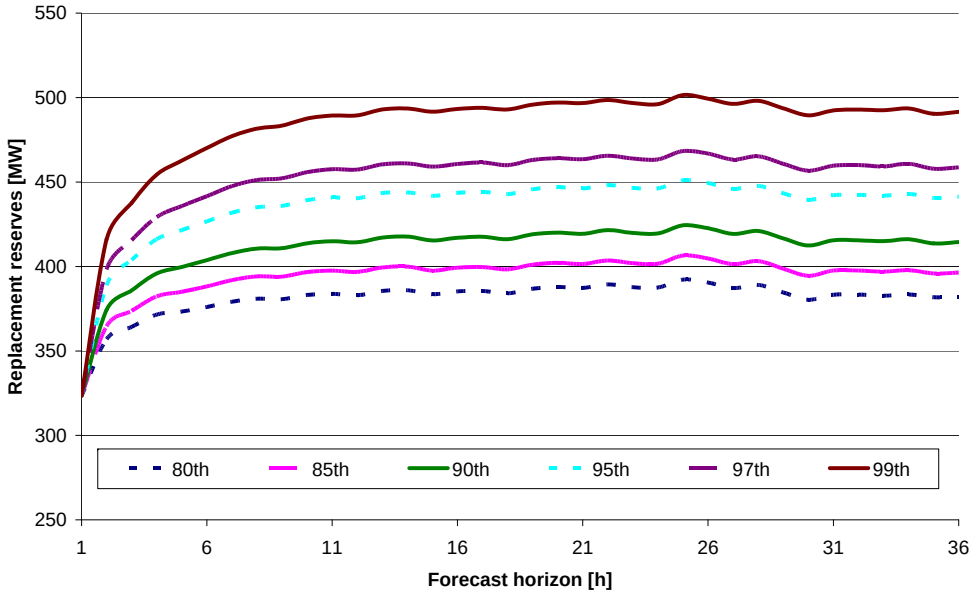
Demand for spinning reserve during the year distributed on weeks in MW

AIGS: Demand for spinning reserve



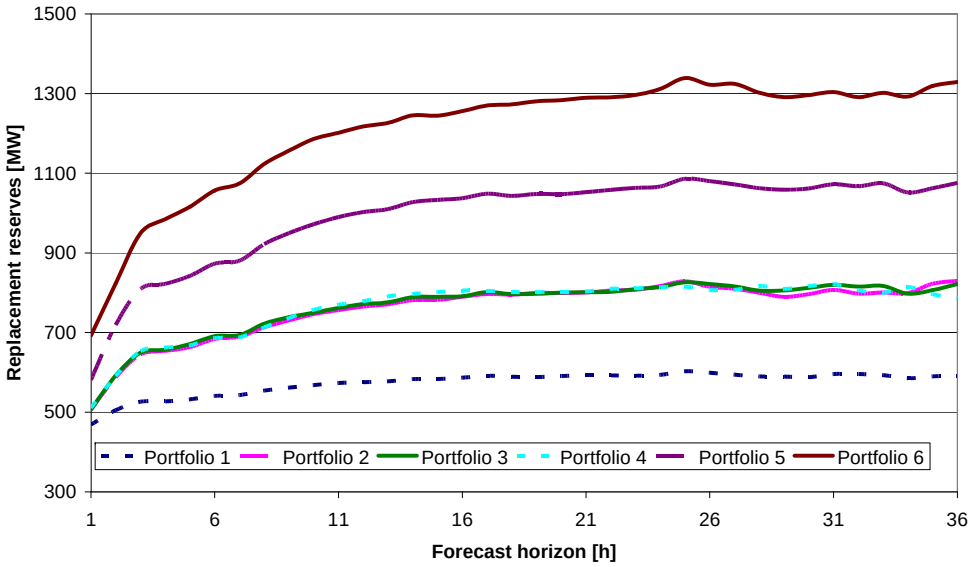
Average demand for spinning reserve during the year distributed on hours during the day in MW

AIGS: Demand for replacement reserve



Average demand for replacement reserves due to load forecast errors and forced outages dependant on the forecast horizon for different percentiles given in MW [*Present power system*]

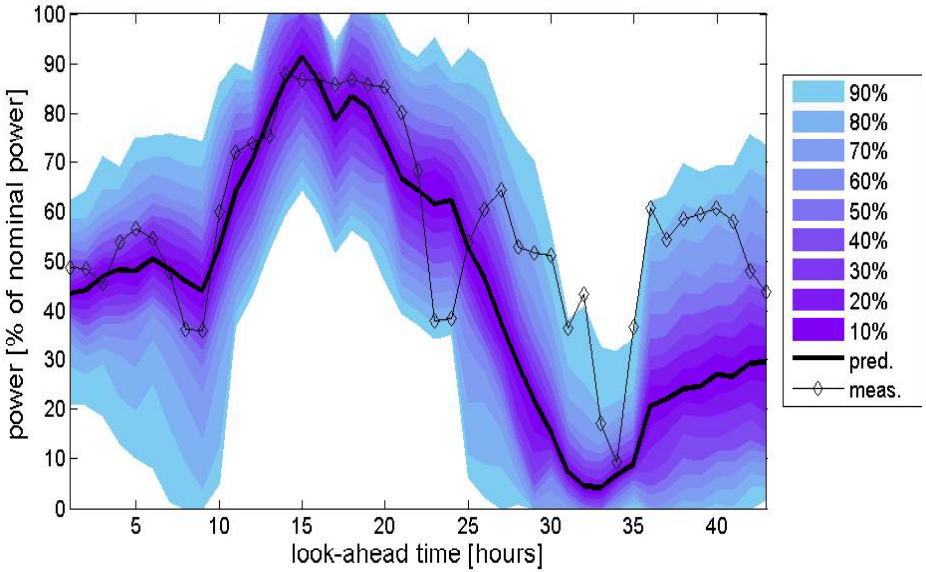
Average demand for replacement reserves dependant on the forecast horizon for portfolios P1 – P6 given in MW [*90th percentile*]

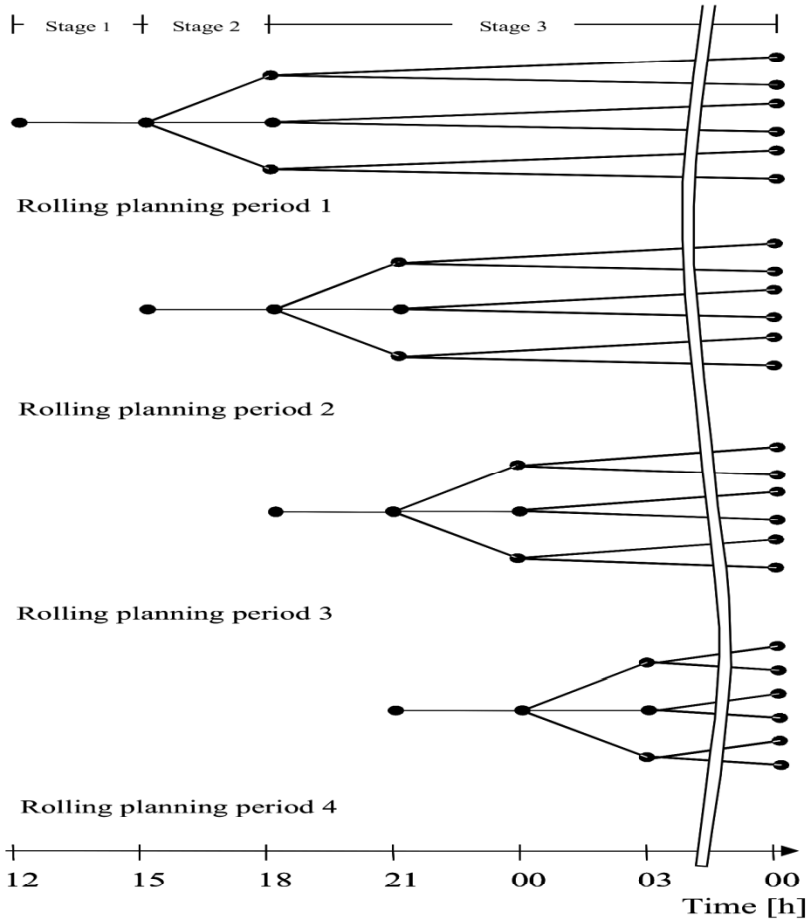


Risø DTU

Stochastic Unit Commitment

Wilmar: Stochastic Unit Commitment

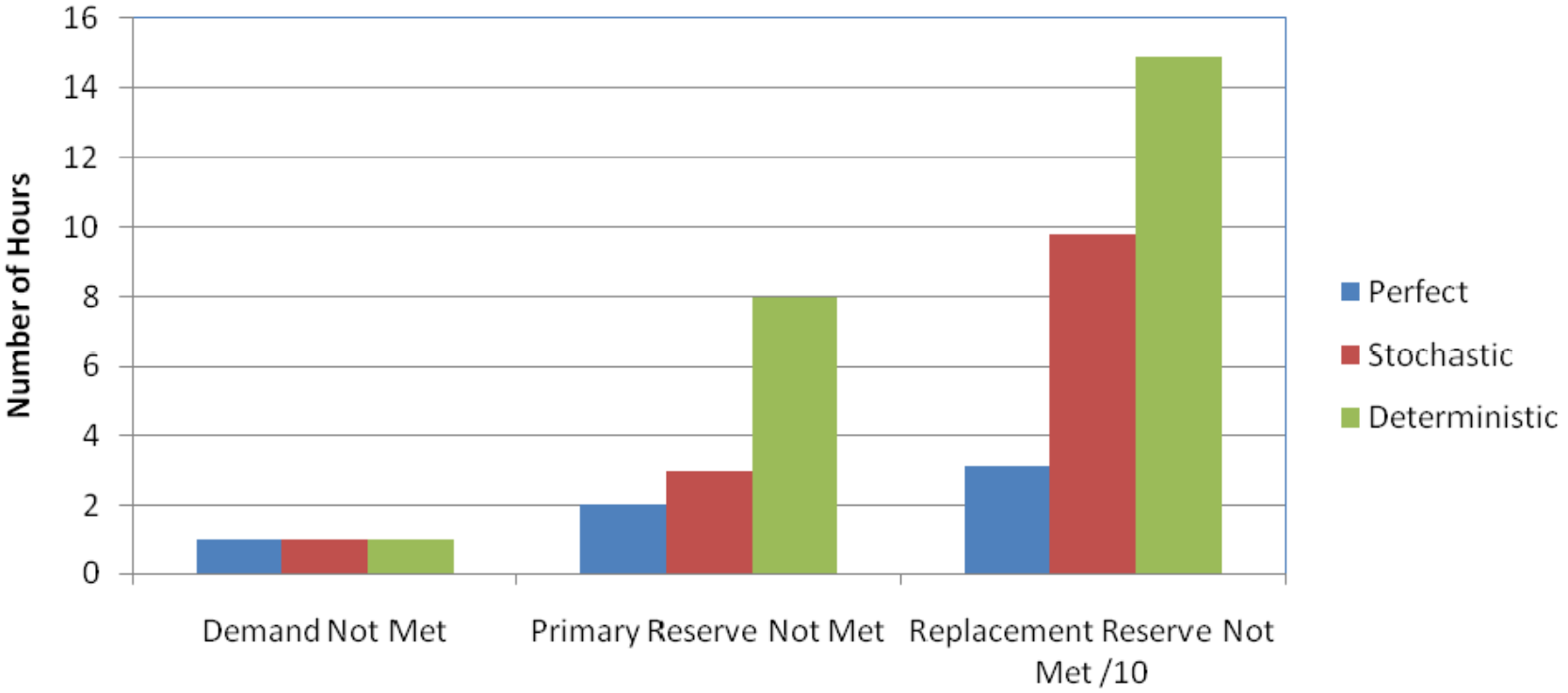




Meibom, P., Barth, R., Hasche, B., Brand, H., Weber, C. and O´Malley, M.J., "Stochastic optimisation model to study the operational impacts of high wind penetrations in Ireland", *IEEE Transactions Power Systems,* in press, 2011.

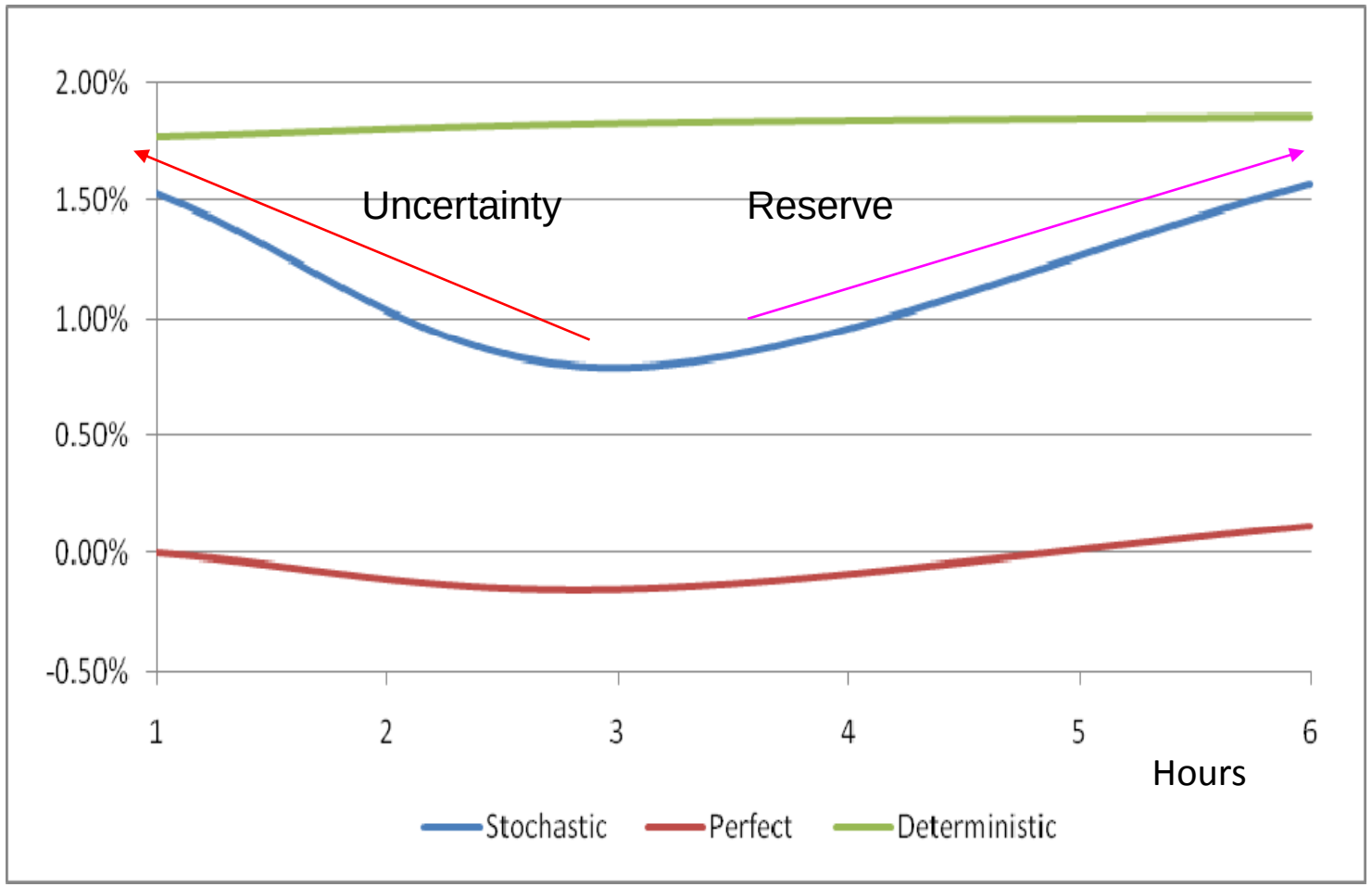
Performance of Schedules

- 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.

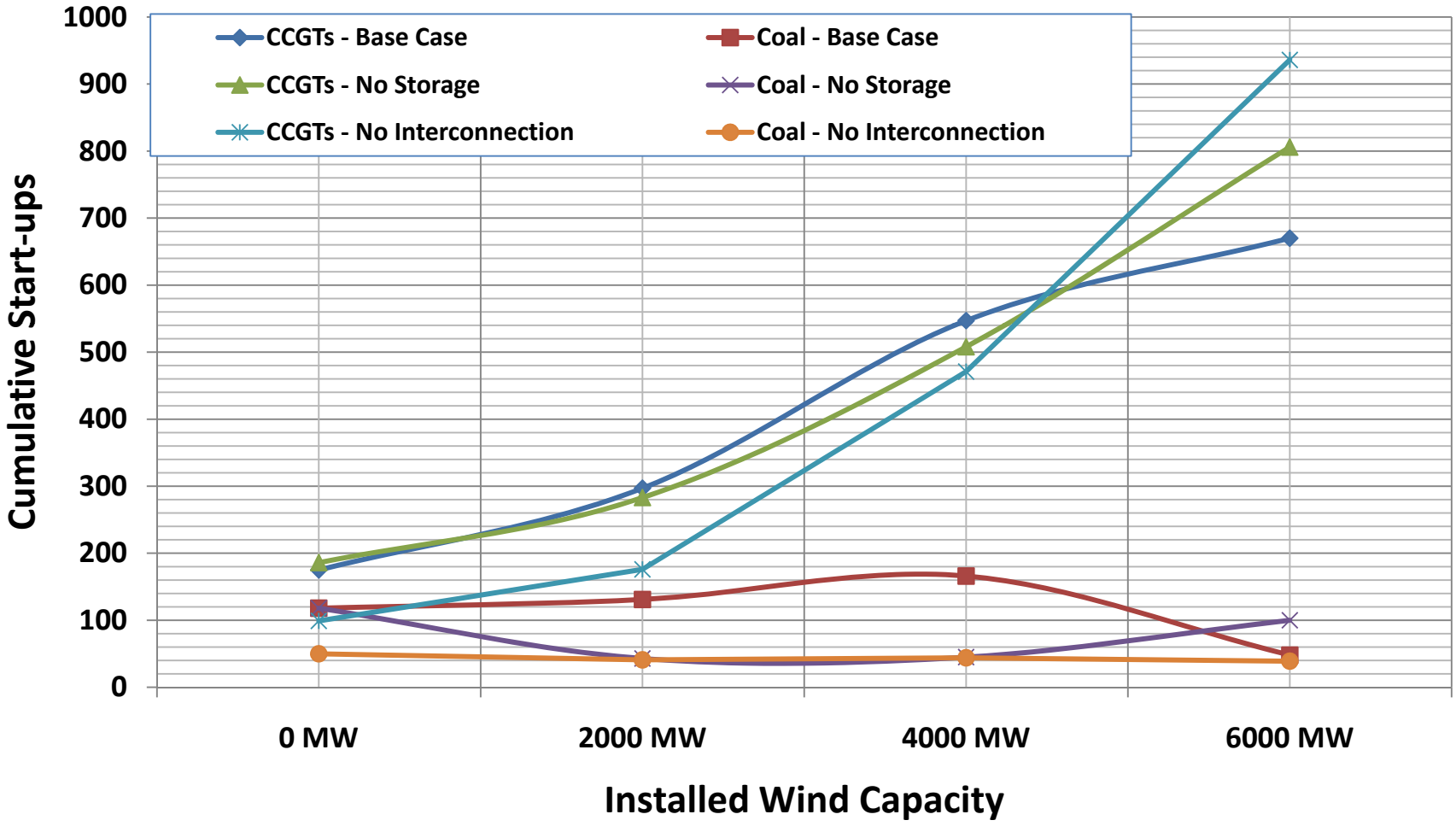
System Costs - Effect of Rolling UC



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

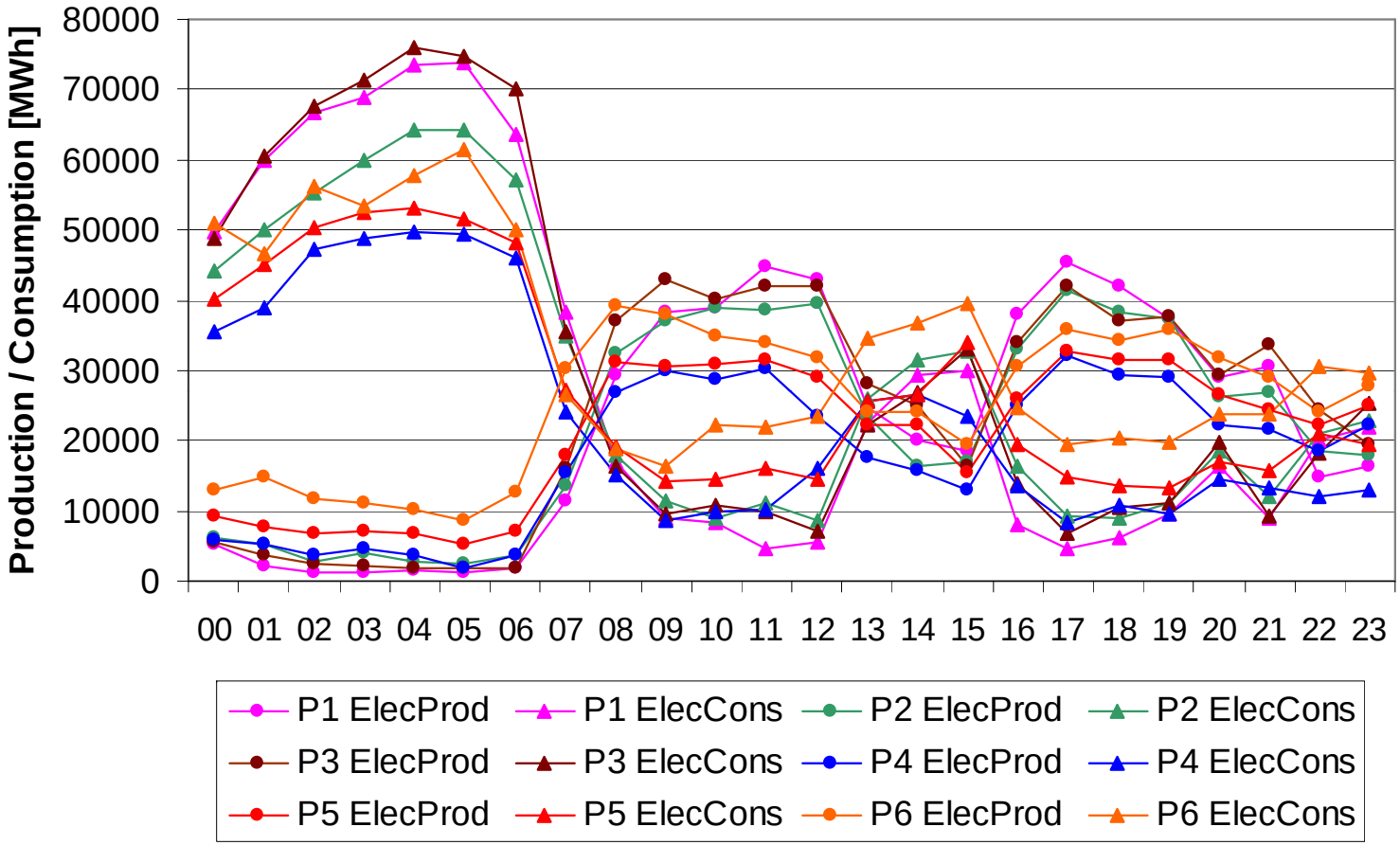
Impact of Wind on Base-load Start-ups



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.

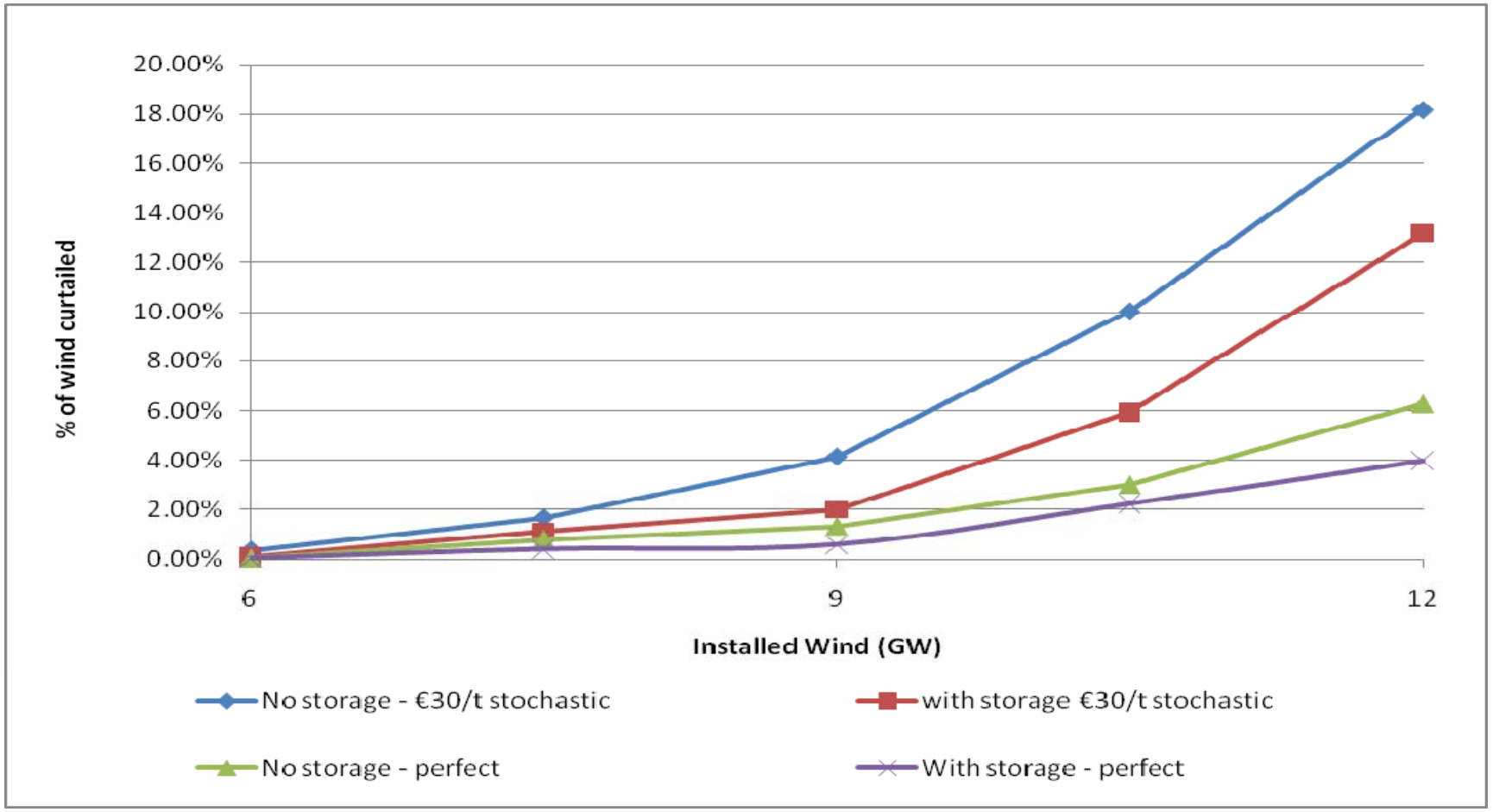
Storage

AIGS: Pump storage utilisation



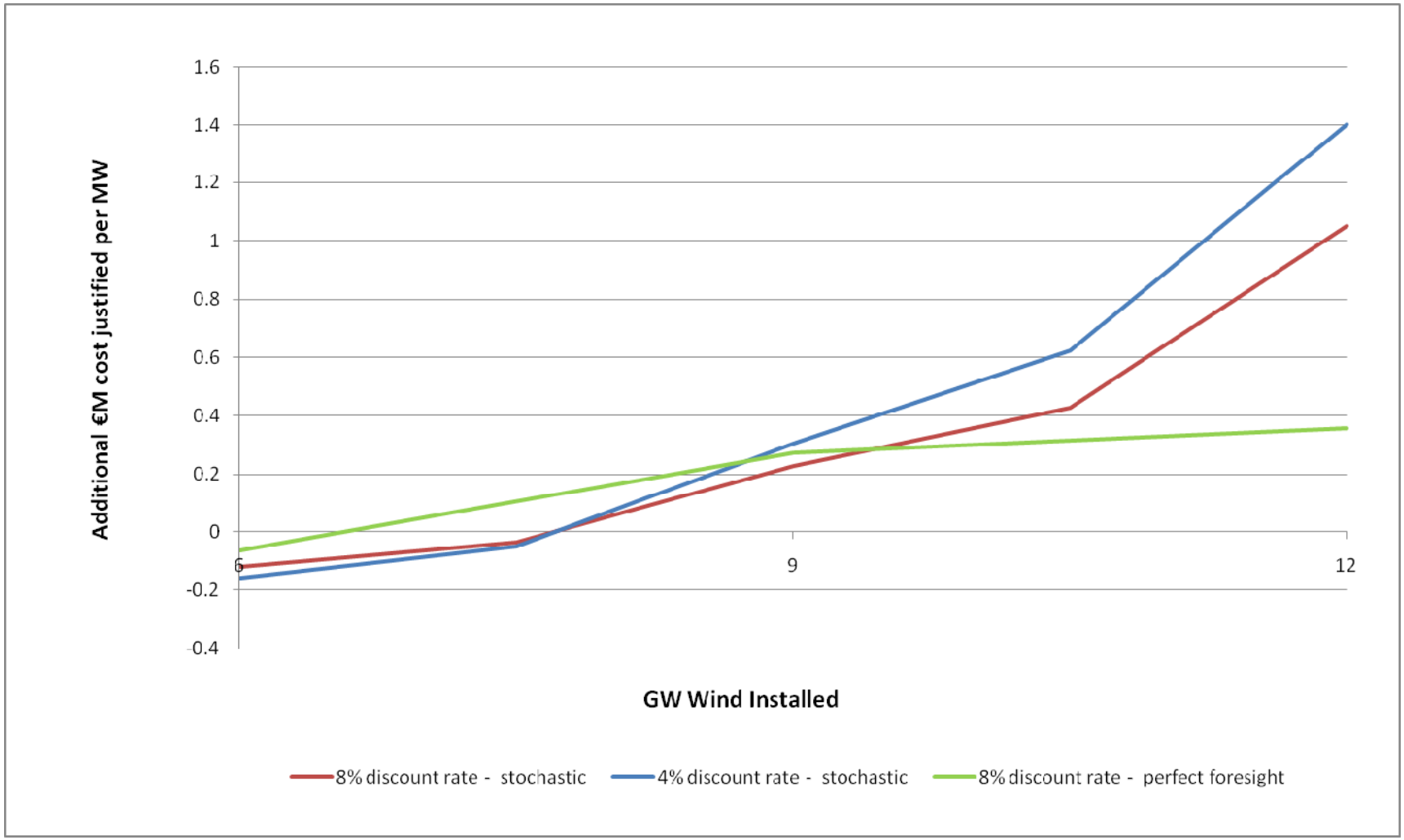
The yearly electricity production and electricity consumption of Turlough Hill distributed on the hours during a day in MWh

Curtailment



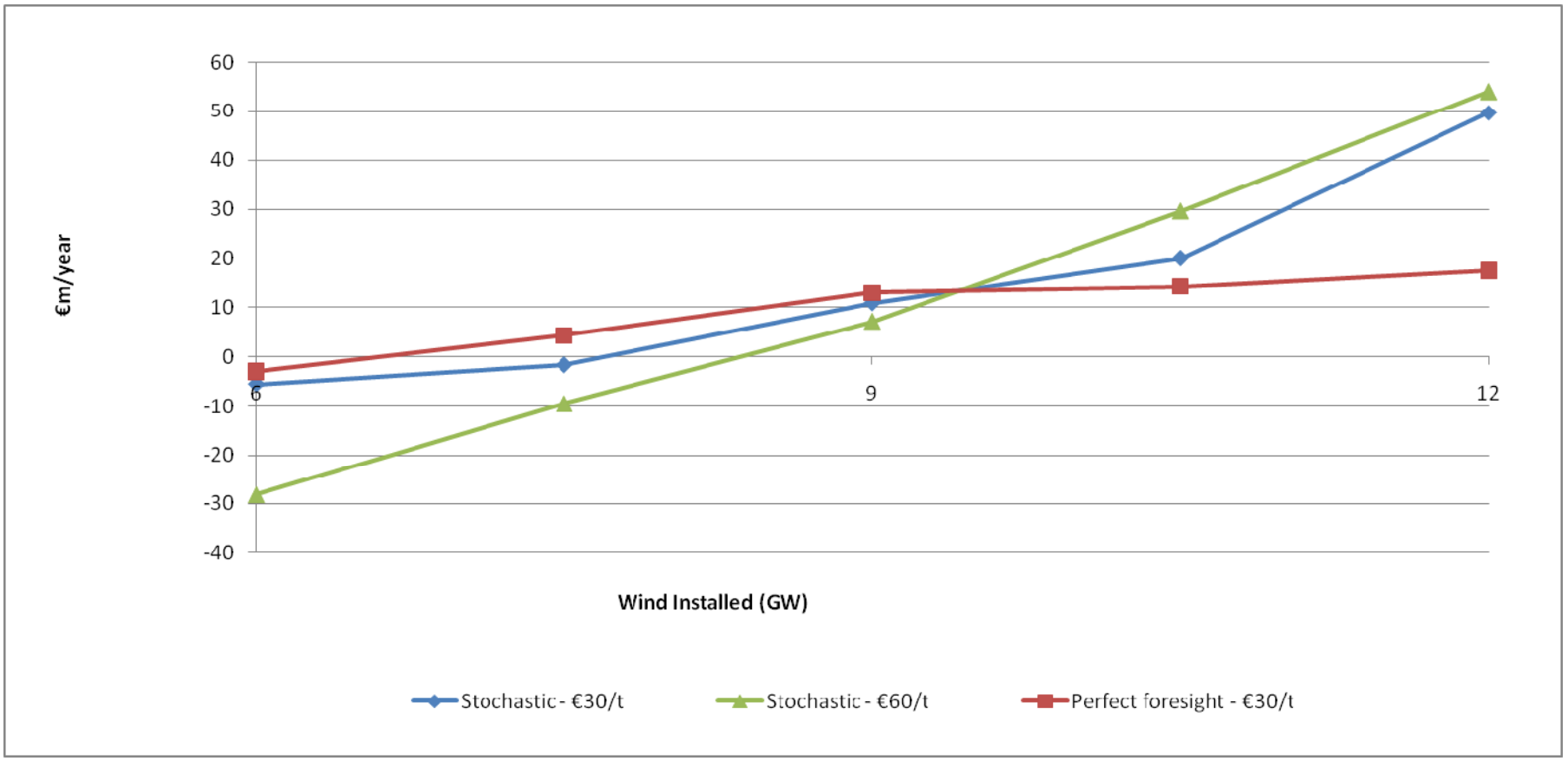
Tuohy, A. And O'Malley, M.J., "Pumped Storage in Systems with Very High Wind Penetration", *Energy Policy*, in press, 2011.

Additional Capital Expenditure justified



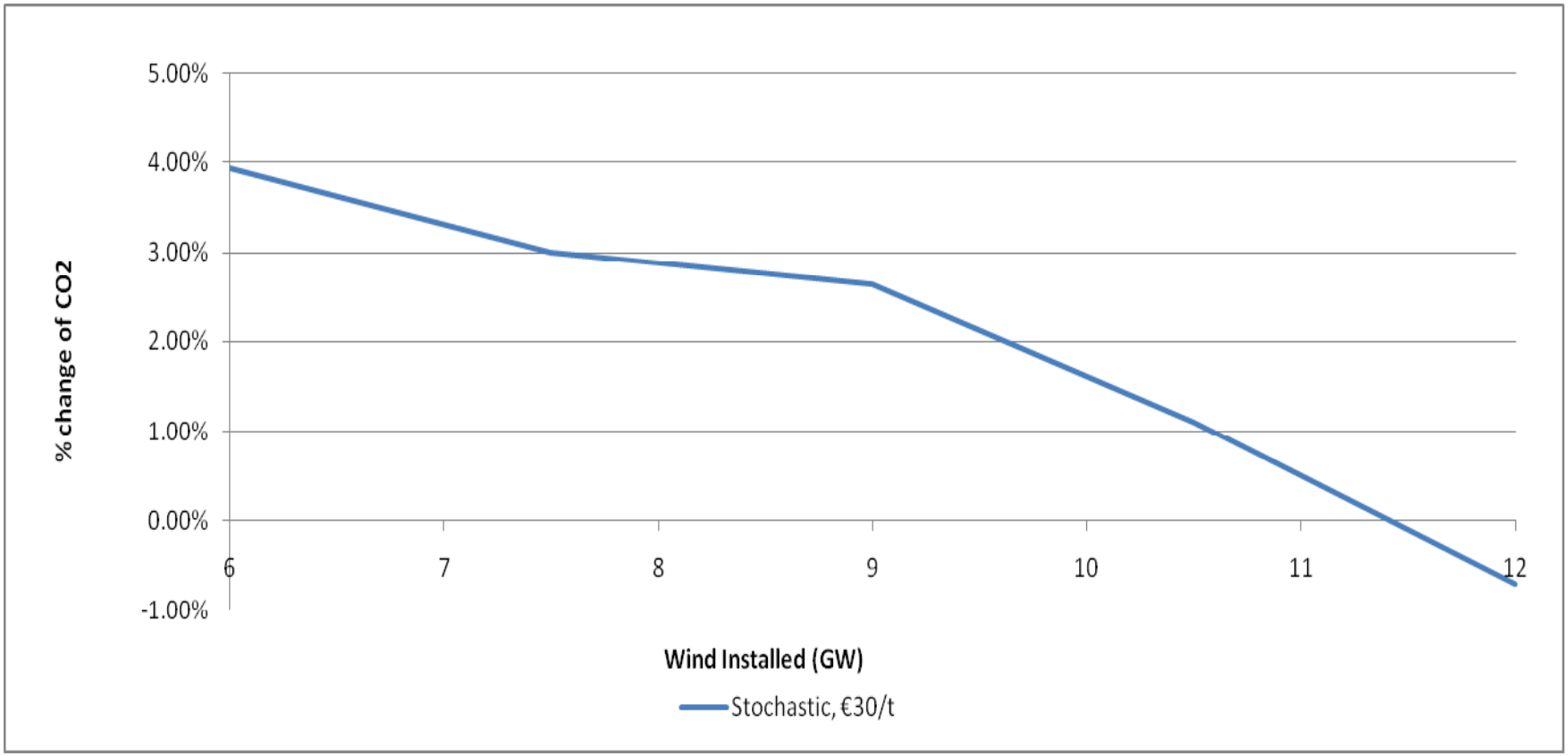
Tuohy, A. And O'Malley, M.J., "Pumped Storage in Systems with Very High Wind Penetration", *Energy Policy*, in press, 2011.

Operational Costs



Relative to base case (+ saving) (- loss)

Emissions



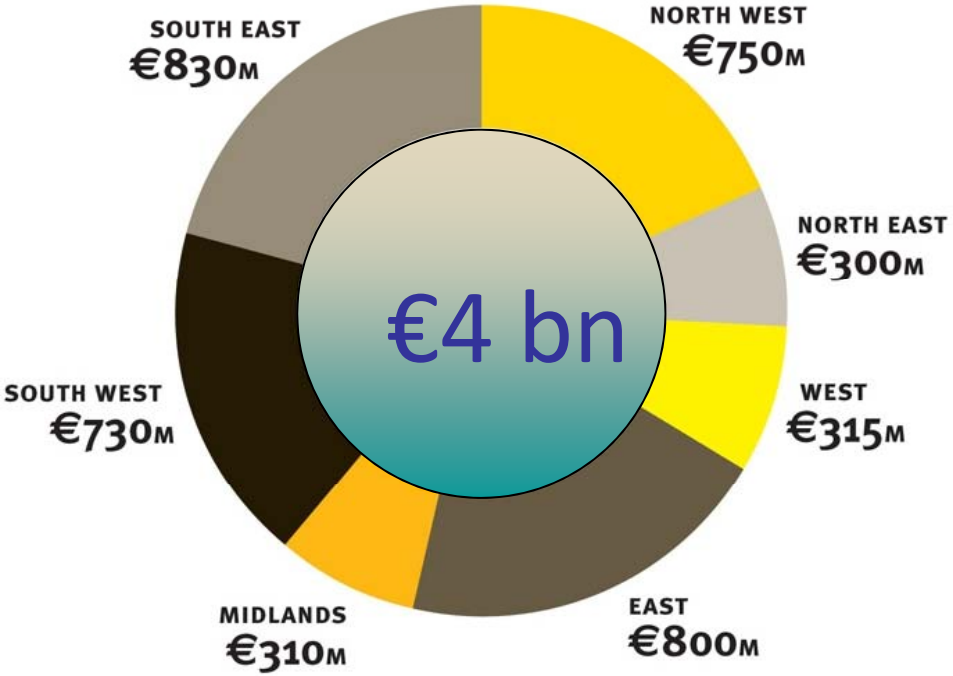
Tuohy, A. and O'Malley, M.J., "Pumped Storage in Systems with Very High Wind Penetration", *Energy Policy*, in press, 2011.


tappytoast

Developing the Grid - Grid25

MOM1

- 2,200 km Upgrades
- 1,150 km new build
- €4 billion



EIRGRID

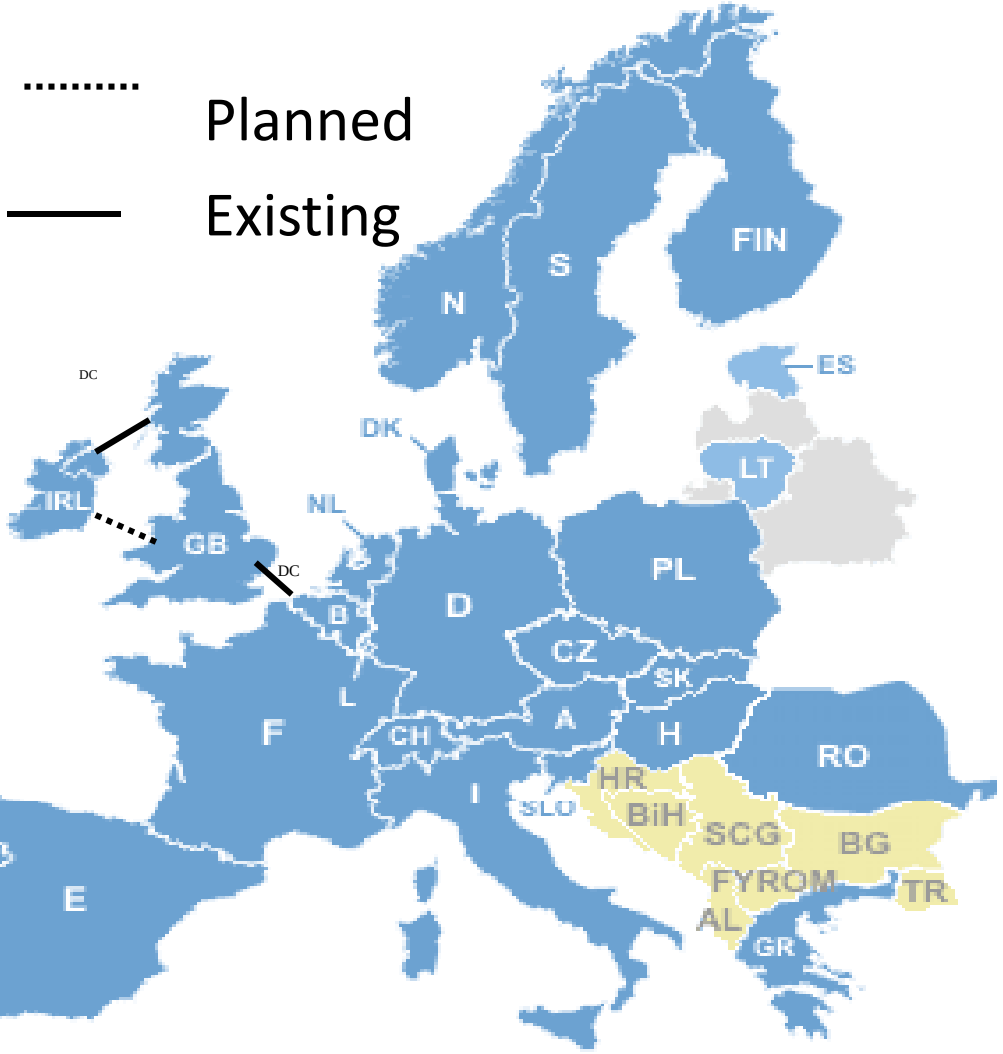
Slide 52

MOM1 This is a slide Dermot used for our first years no logo on it but I put one in

Mark O'Malley, 12/6/2010

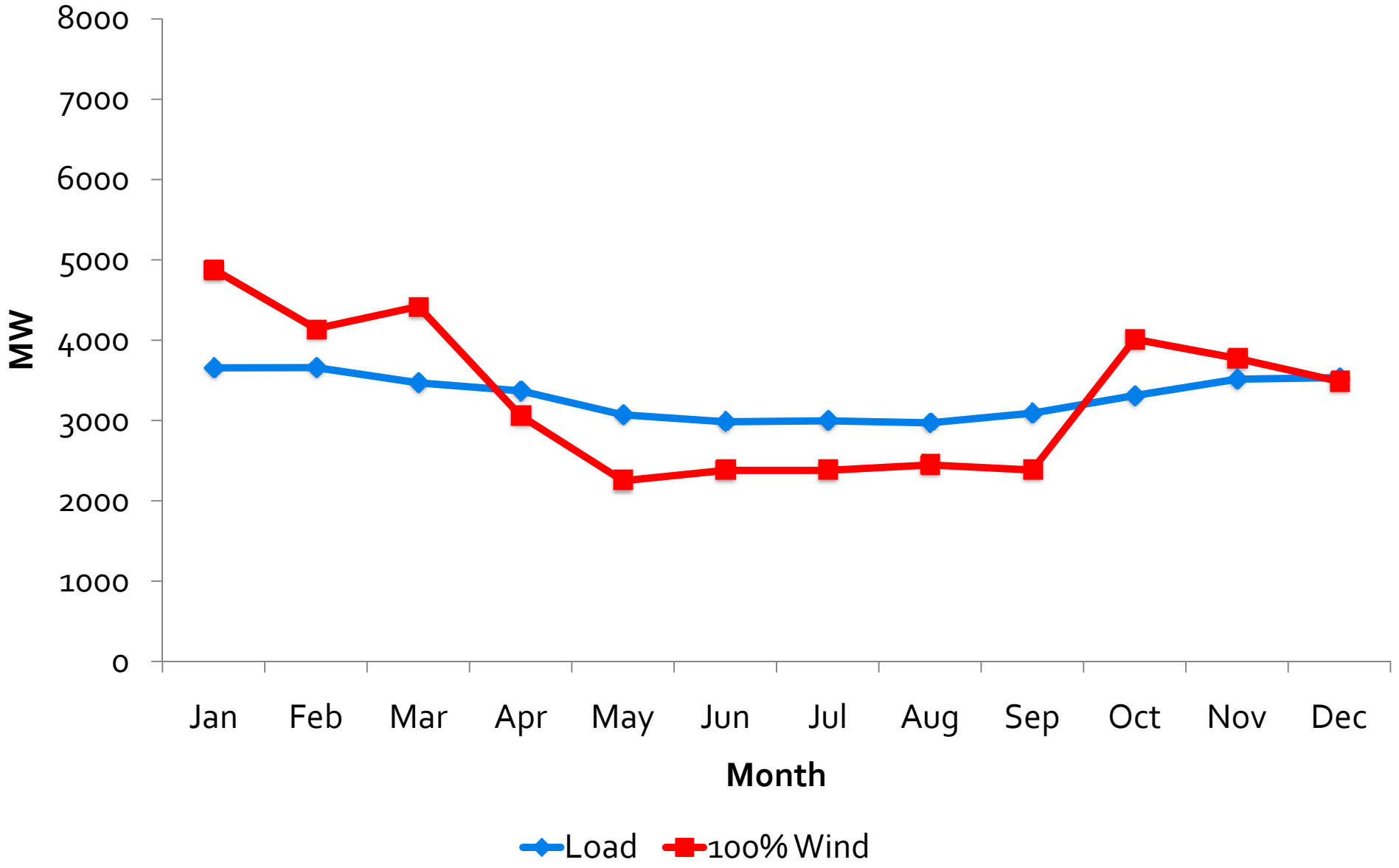
Public acceptance of transmission

Interconnection



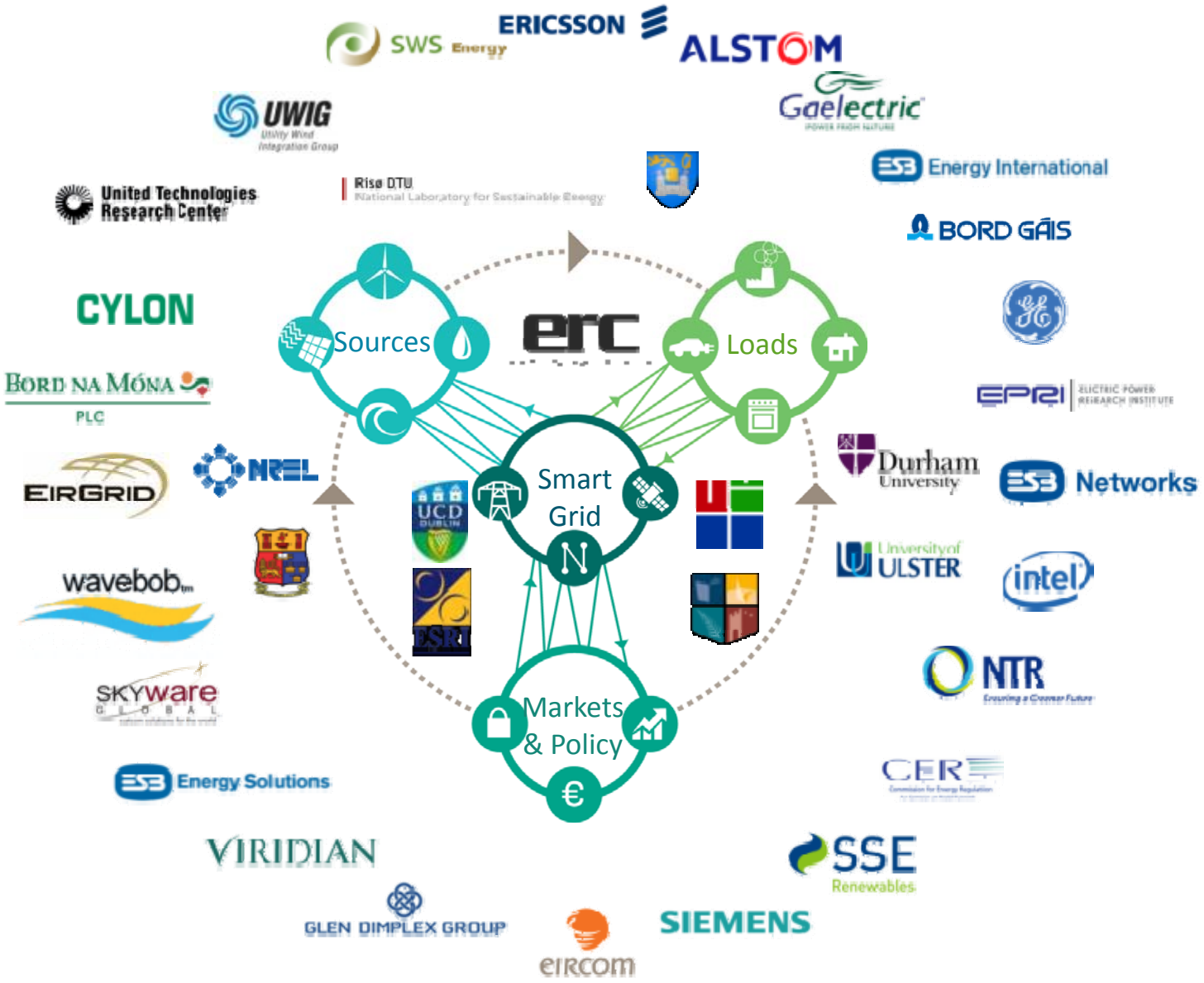
Denny, E., Tuohy, A., Meibom, P., Keane, A., Flynn, D. Mullane, A. and O'Malley, M.J., "The Impact of Interconnection on Electricity Systems with Large Penetrations of Wind Generation", *Energy Policy*, in press, 2010.

Seasonal (100 % Wind)



Research & Demonstration

Sustainable Electrical Energy Systems (2011–2015)

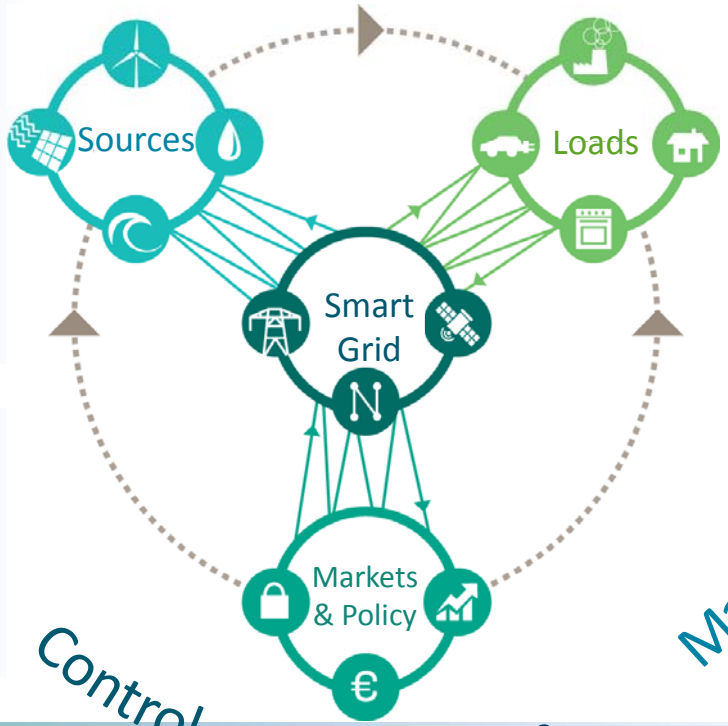


Research & demonstration programme

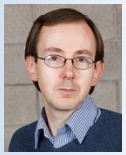
DEVELOP STRUCTURE TO DELIVER A FLEXIBLE & INTEGRATED GRID

DEFINE MARKET POLICY & FRAMEWORK

IMPLEMENT ICT & DEMONSTRATIONS

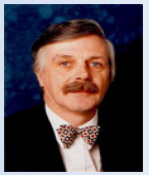




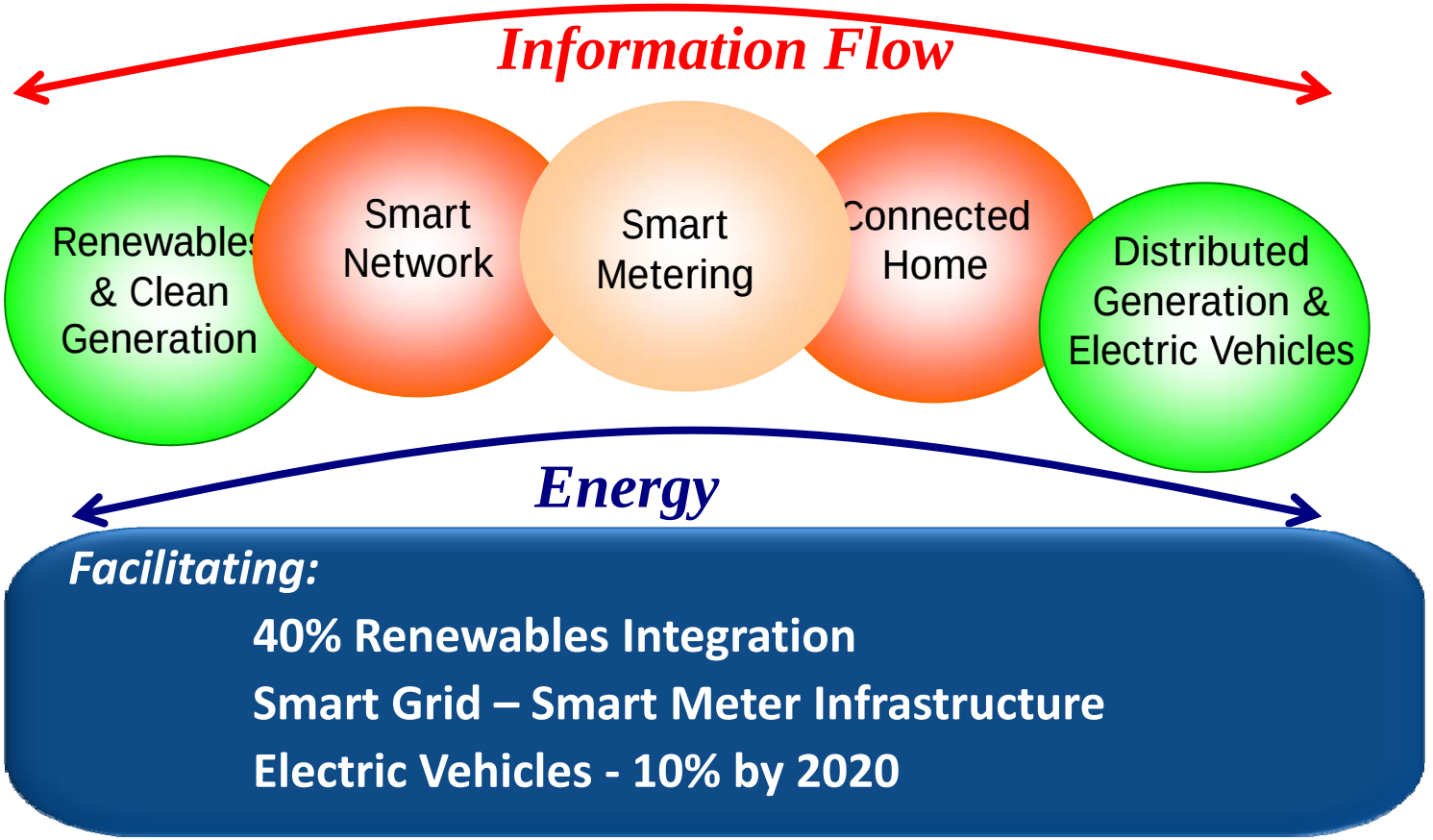






ESB Integrated Smart Networks Model



Conclusions

Conclusions

- Good wind resource – very high targets
- Transmission is a problem
- Interconnection is a good option
- Large scale storage is challenging
- Dynamics are an issue
- Flexibility is the key
- Large research programme
- Combination of solutions will emerge
- Societal issues are very important

Recent Journal Publications

- Tuohy, A. and O'Malley, M.J., "Pumped Storage in Systems with Very High Wind Penetration", *Energy Policy*, in press, 2011.
- Burke, D.J., and O'Malley M.J. "Factors influencing wind energy curtailment", *IEEE Transactions on Sustainable Energy*, in press, 2011.
- 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.
- 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.
- Keane, A., Milligan, M., D'Annuzio, C., Dent, C., Dragoon, K., Hasche, B., Holttinen, Samaan, N., Soder, L. and O'Malley, M.J., "Capacity Credit of Wind Power, *IEEE Transactions on Power Systems*, in press, 2011.
- 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*, in press, 2011.
- Hasche, B., Keane, A. and O'Malley, M.J. "Capacity credit of wind power: calculation and data requirements", *IEEE Transactions on Power Systems*, in press, 2011.
- Fitzmaurice, R., Keane, A., and O'Malley, M.J., "Effect of Short Term Risk Aversive Dispatch on a Complex System Model for Power Systems", *IEEE Transactions on Power Systems*, in press, 2011.
- Denny, E., Tuohy, A., Meibom, P., Keane, A., Flynn, D. Mullane, A. and O'Malley, M.J., "The Impact of Interconnection on Electricity Systems with Large Penetrations of Wind Generation", *Energy Policy*, Vol. 38, pp. 6946-6954, 2010.
- 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., "Maximum firm wind power 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 Time-Series Power Flow Methodology Applied to Power Systems With High Penetrations of Wind", *IEEE Transactions on Power Systems*, Vol. 25, pp. 433 – 442, 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.

Acknowledgements

- Prof. Bob Thomas, Cornell & Ms. Rachael O' Hegarty
- Industry: ABB, Bord Gais, Bord Na Mona, Commission for Energy Regulation, Cylon Controls, EirGrid, EPRI, ESB Energy International, ESB Networks, ESB Energy Solutions, Gaelectric, Intel, Siemens, SSE Renwables, United Technologies Research Centre (UTRC), Viridian
- Funding Agencies: Department of Communications Energy and Natural Resources, The Economic and Social Research Institute (ESRI), Electrici.ty Research Centre (ERC), Enterprise Ireland, EU, Irish Research Council for Science, Engineering & Technology, Science Foundation Ireland, Sustainable Energy Ireland, Teagasc, IRCHSS, PRTLI
- 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
- Graduated PhDs: Dr. Daniel Burke, Dr. Aidan Tuohy, Dr. Garth Bryans, Dr. Eleanor Denny, Dr. Ronan Doherty, Dr. Meadhbh Flynn, Dr. Andrew Keane, Dr. Gill Lalor, Dr. Jonathan O'Sullivan, Dr. Michael Walsh
- Graduated Masters: Ms. Sonya Twohig, Mr. Jody Dillon, Mr. Shane Rourke, Mr. Paul Sheridan, Mr. Fintan Slye
- Collaborators: Peter Meibom, Brian Parsons, Michael Milligan, Erik Ela, Prof. Janusz Bialek, Dr. Brendan Fox, Prof. John FitzGerald Dr. Chris Dent

Integrating Wind in Ireland: Experience and Studies

Mark O'Malley

Director, Electricity Research Centre

University College Dublin

mark.omalley@ucd.ie

www.ucd.ie/erc

electricity research centre

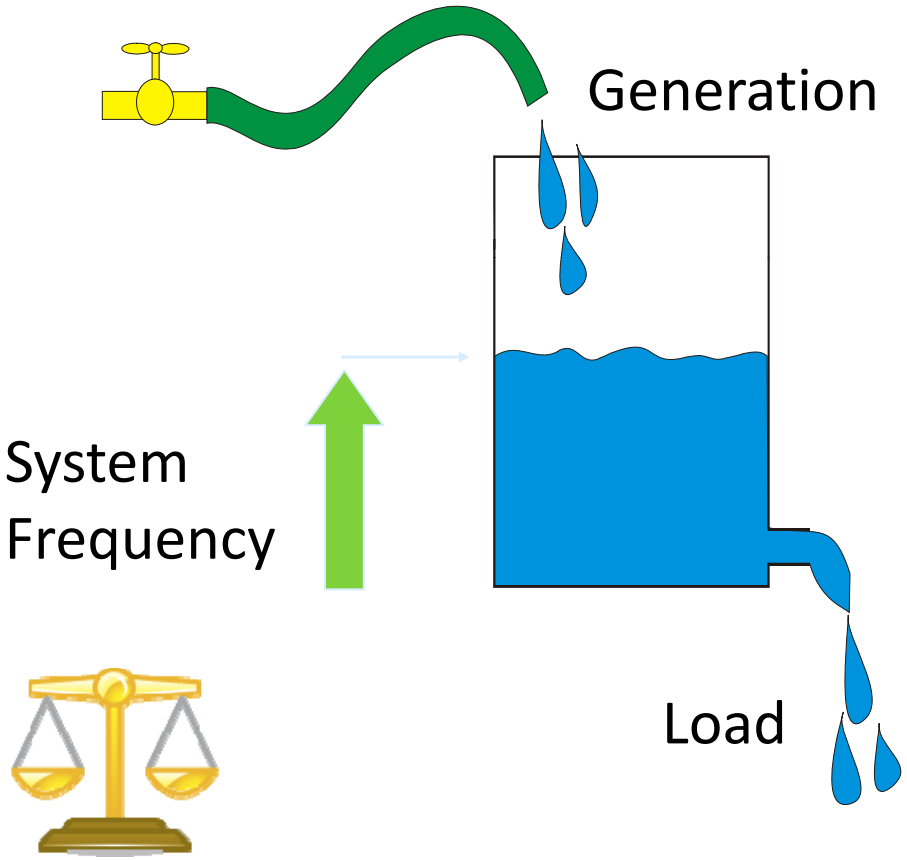
Integration Workshop, MIT Wind Week

January 21th 2011

UCD DUBLIN

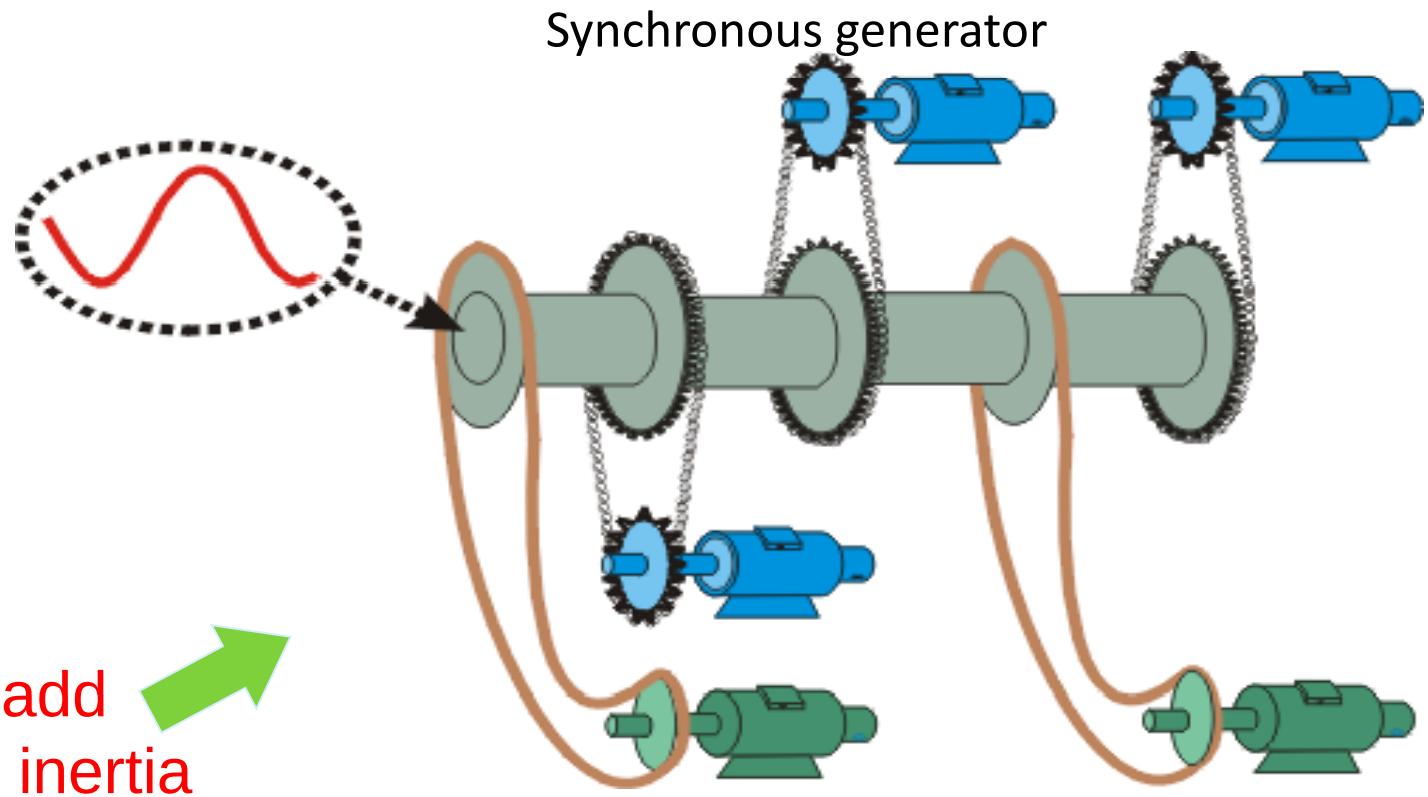
Dynamics: Frequency Stability

System Frequency control

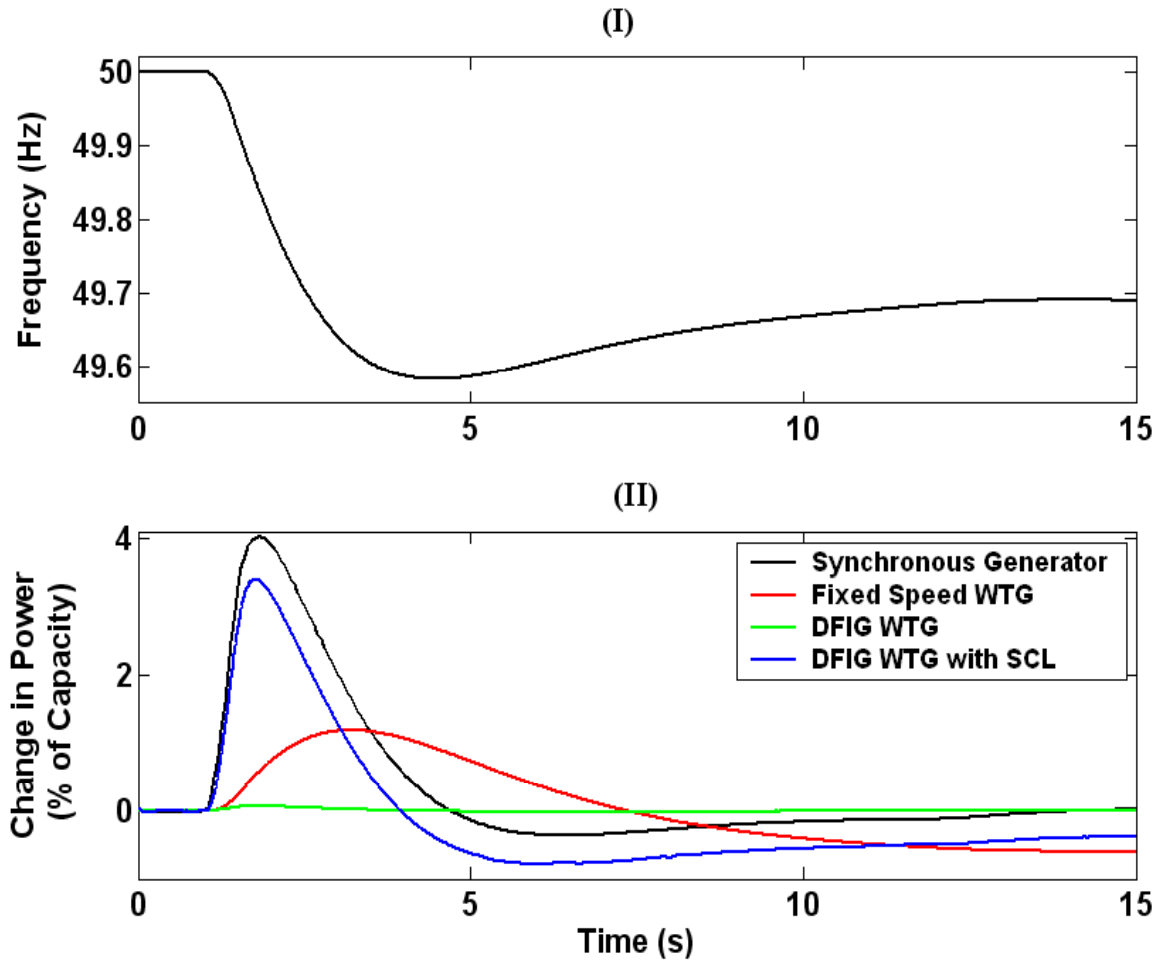


- If generation and load are matched water level (system frequency) will remain constant
- Mismatches will result in a change in water level (system frequency)

Frequency control

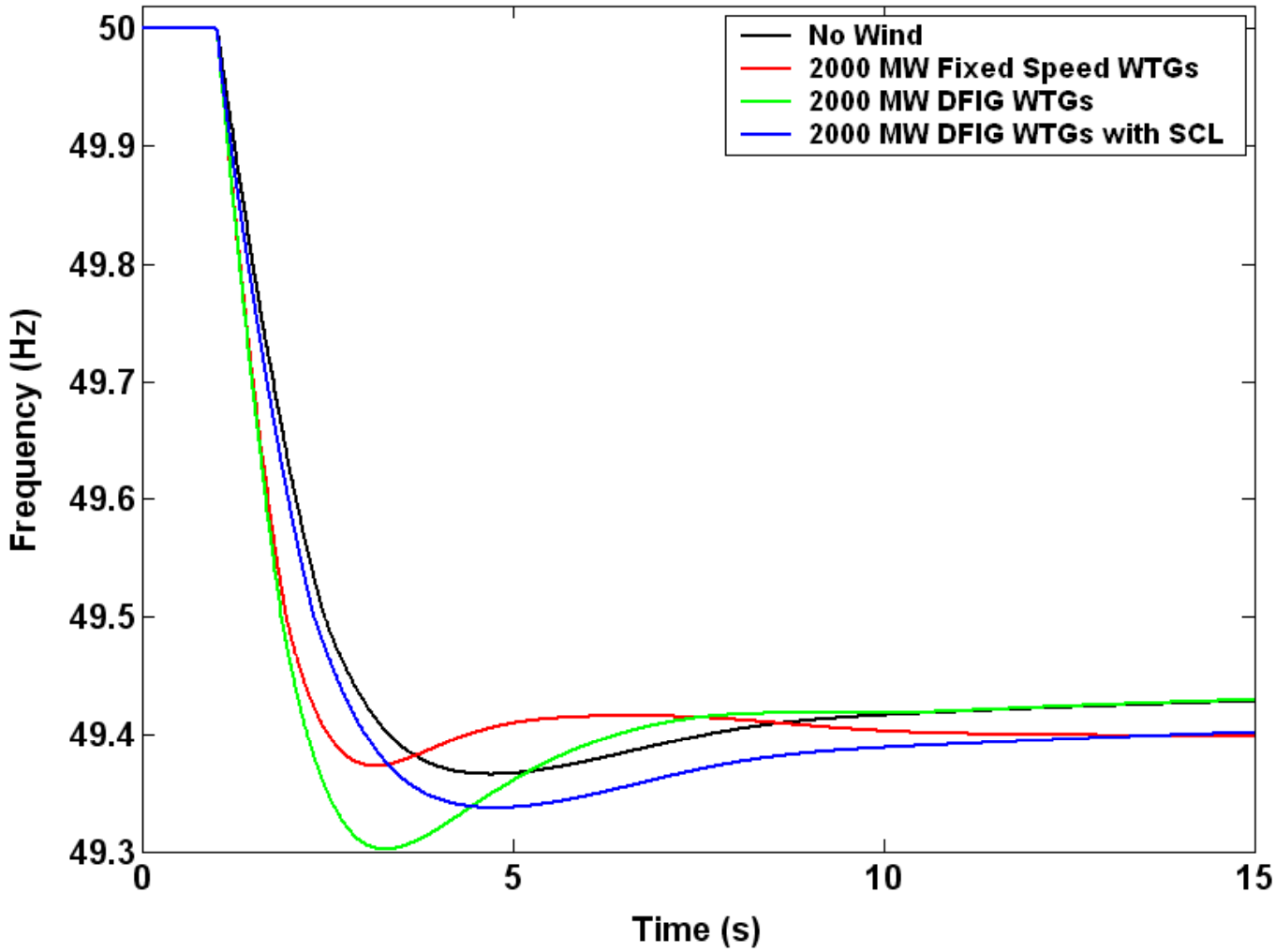


Wind Turbine Inertial Response



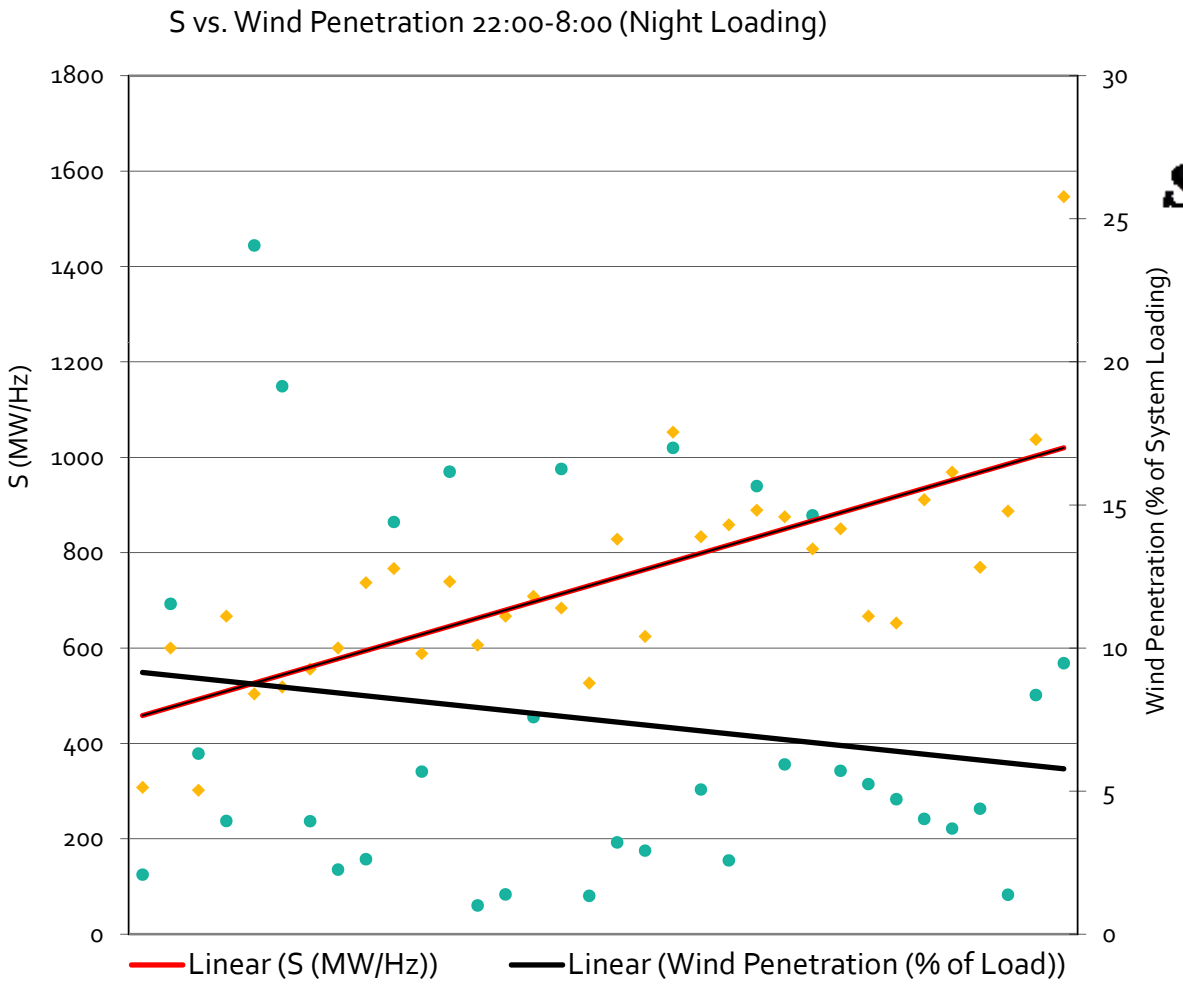
Mullane, A. and O'Malley, M.J., "The inertial-response of induction-machine based wind-turbines", *IEEE Transactions on Power Systems*, Vol. 20, pp. 1496 – 1503, 2005 .

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



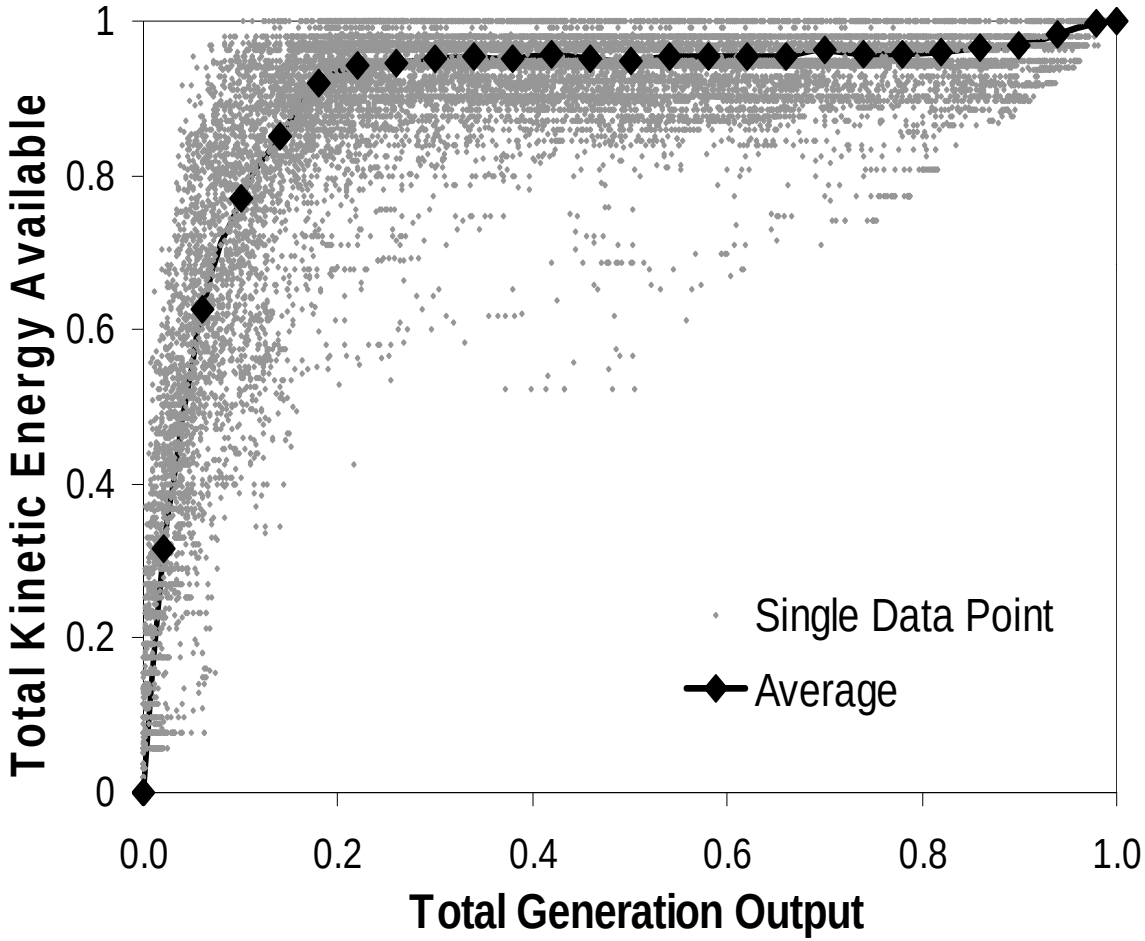
- Frequency response

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

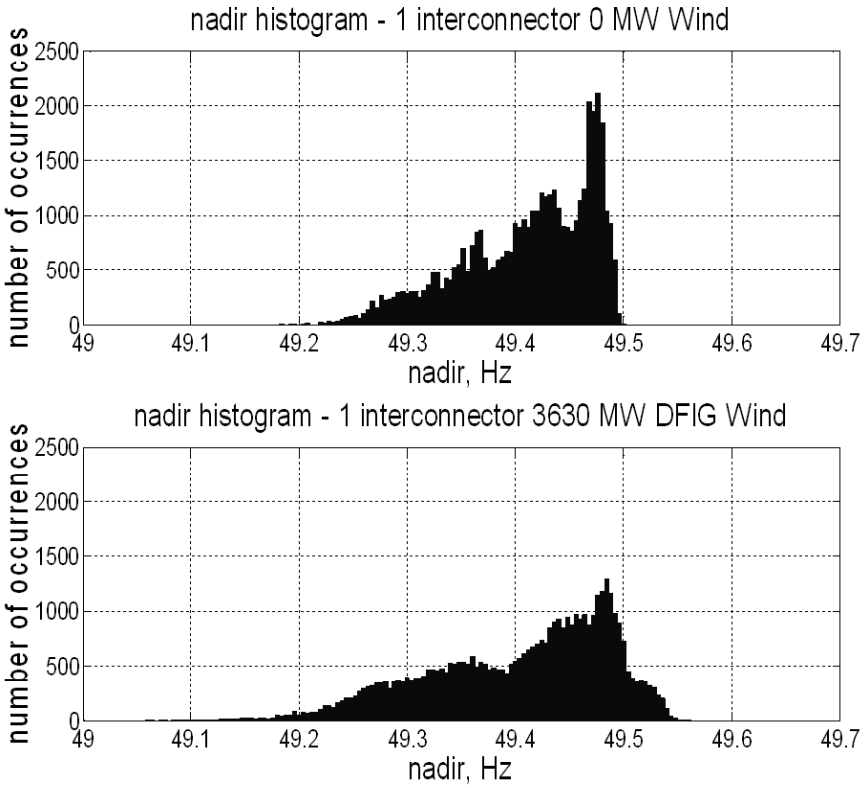
  - Wind penetration increases
  - Stiffness decreases
    - Indicates increased vulnerability to a loss of generation event
- Should there be a market in frequency response ?

Doherty, R., Lalor, G. and O'Malley, M.J., "Frequency Control in Competitive Electricity Market Dispatch", *IEEE Transactions on Power Systems*", Vol. 20, pp. 1588 - 1596, 2005.

Experimental data: Inertia



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.

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

Joseph H. Eto, Principal Investigator
Lawrence Berkeley National Laboratory

John Undrill
John Undrill, LLC

Peter Mackin, Ron Daschmans, Ben Williams, Brian Haney, Randall Hunt, Jeff Ellis
Utility Systems Efficiencies, Inc.

Howard Illian
EnergyMark, Inc.

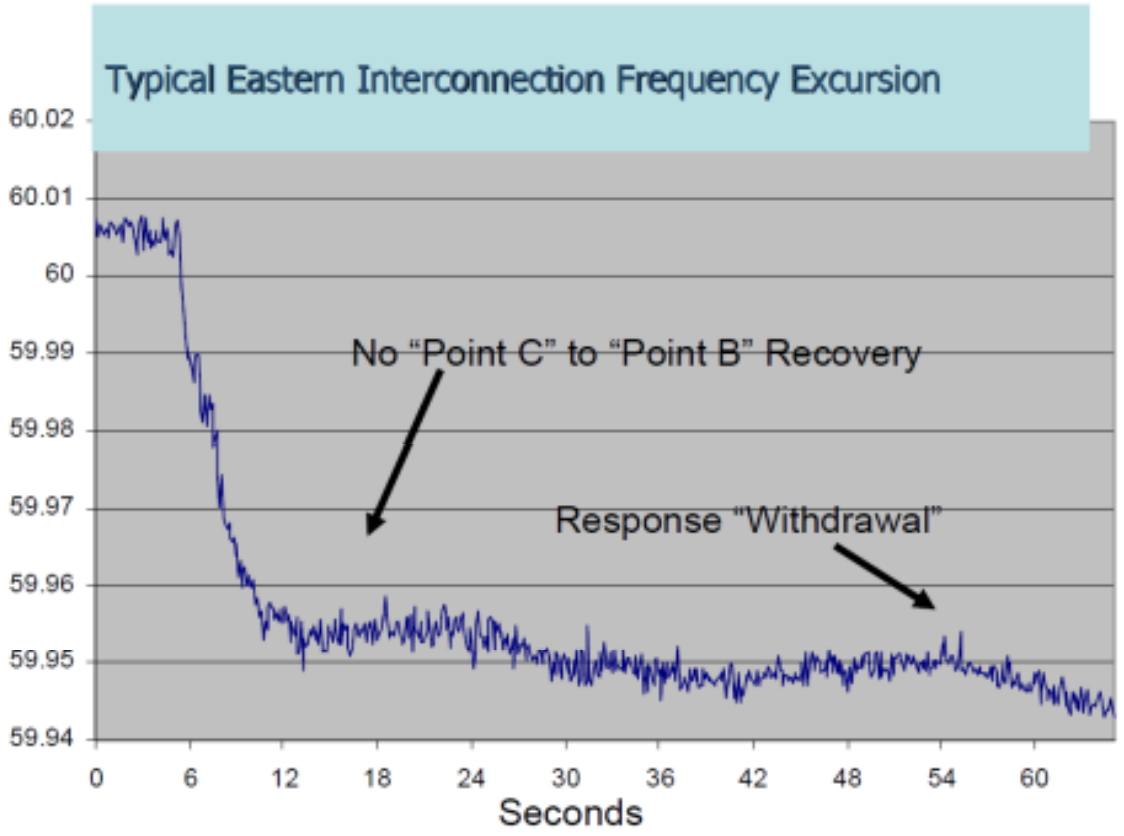
Carlos Martinez
Electric Power Group, LLC

Mark O'Malley
University College Dublin

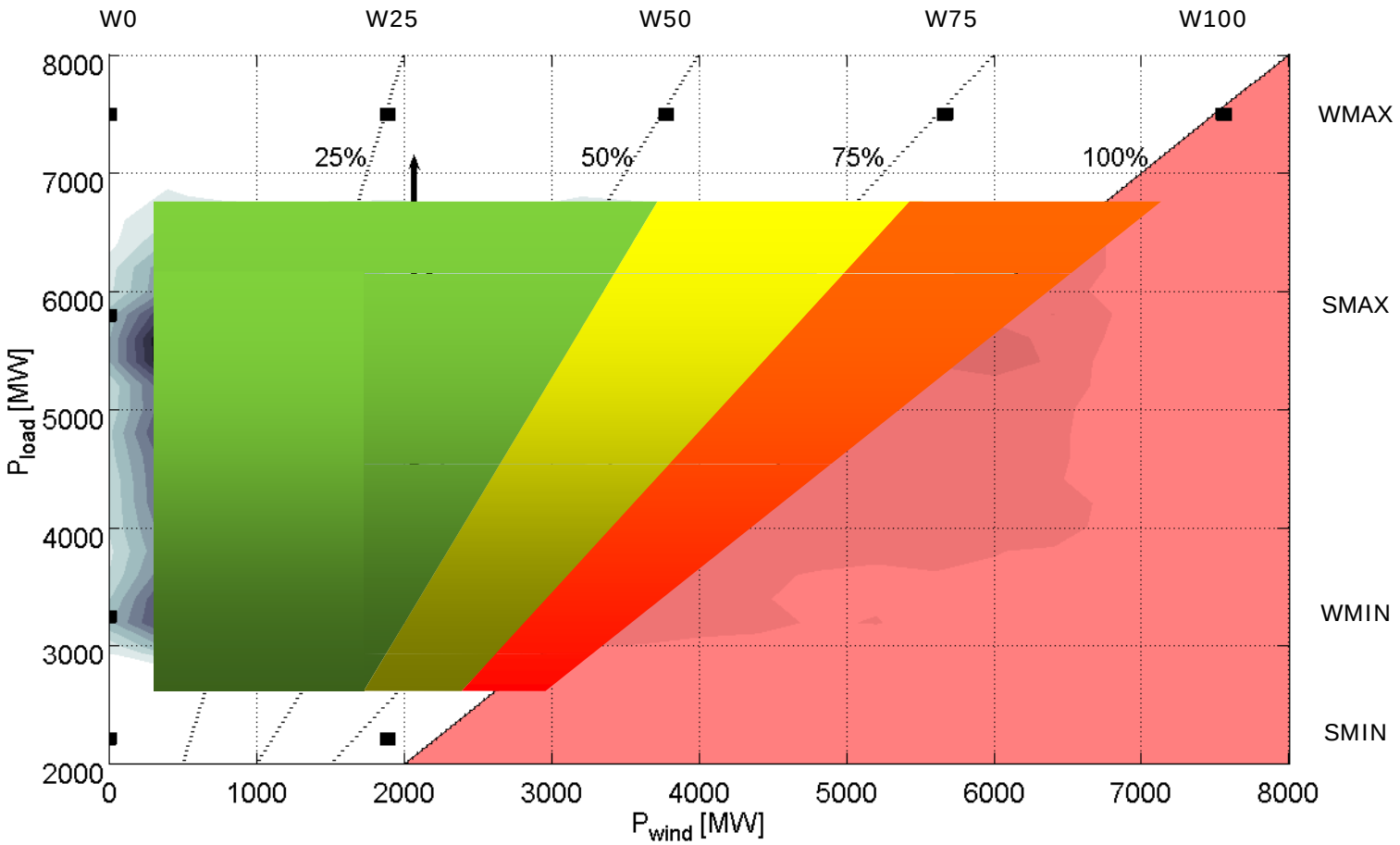
Katie Coughlin, Kristina Hamachi LaCommare
Lawrence Berkeley National Laboratory

December 2010

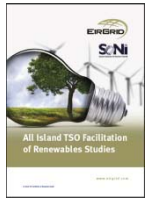
The work described in this report was funded by the Federal Energy Regulatory Commission, Office of Electric Reliability. The Lawrence Berkeley National Laboratory is operated by the University of California for the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

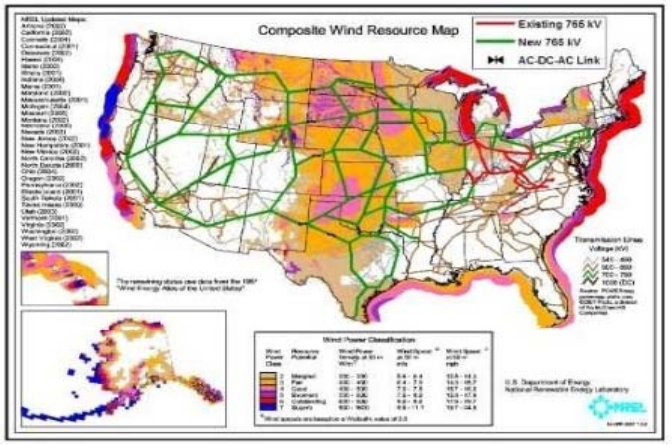


Operational Boundaries



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





Transmission