

# Grid Integration Challenges and Solutions

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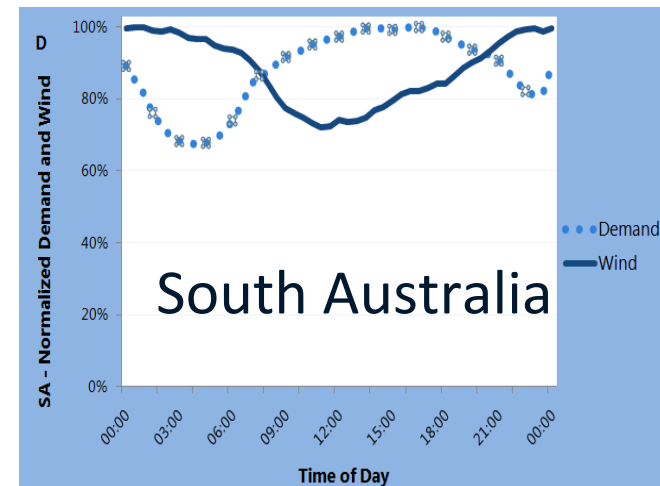
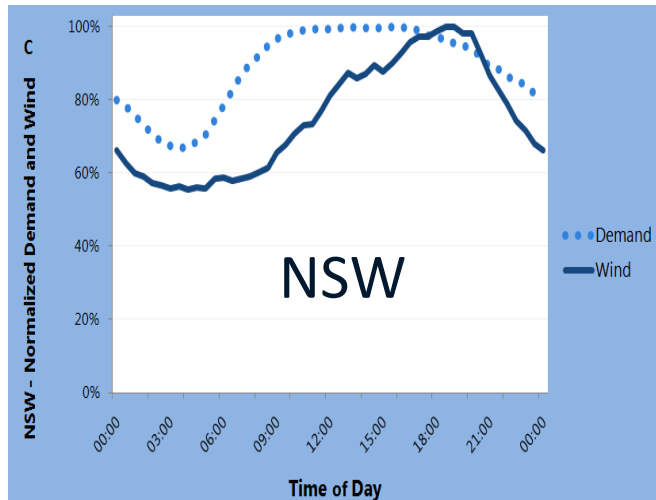
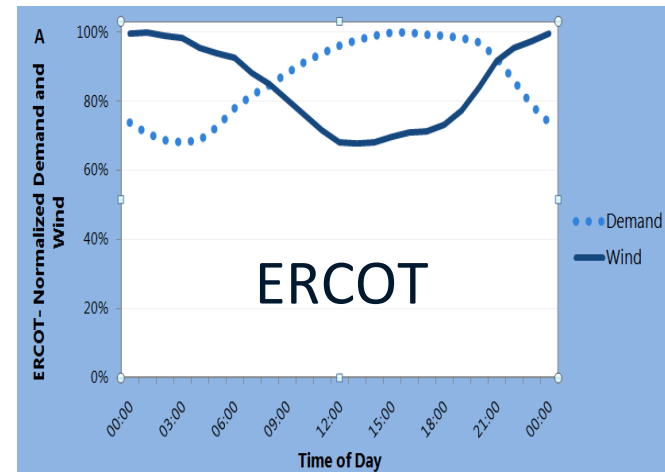
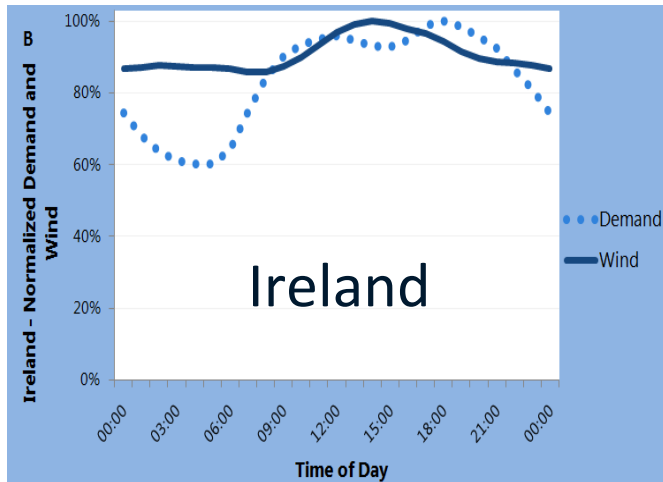


# Penetration Metrics

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

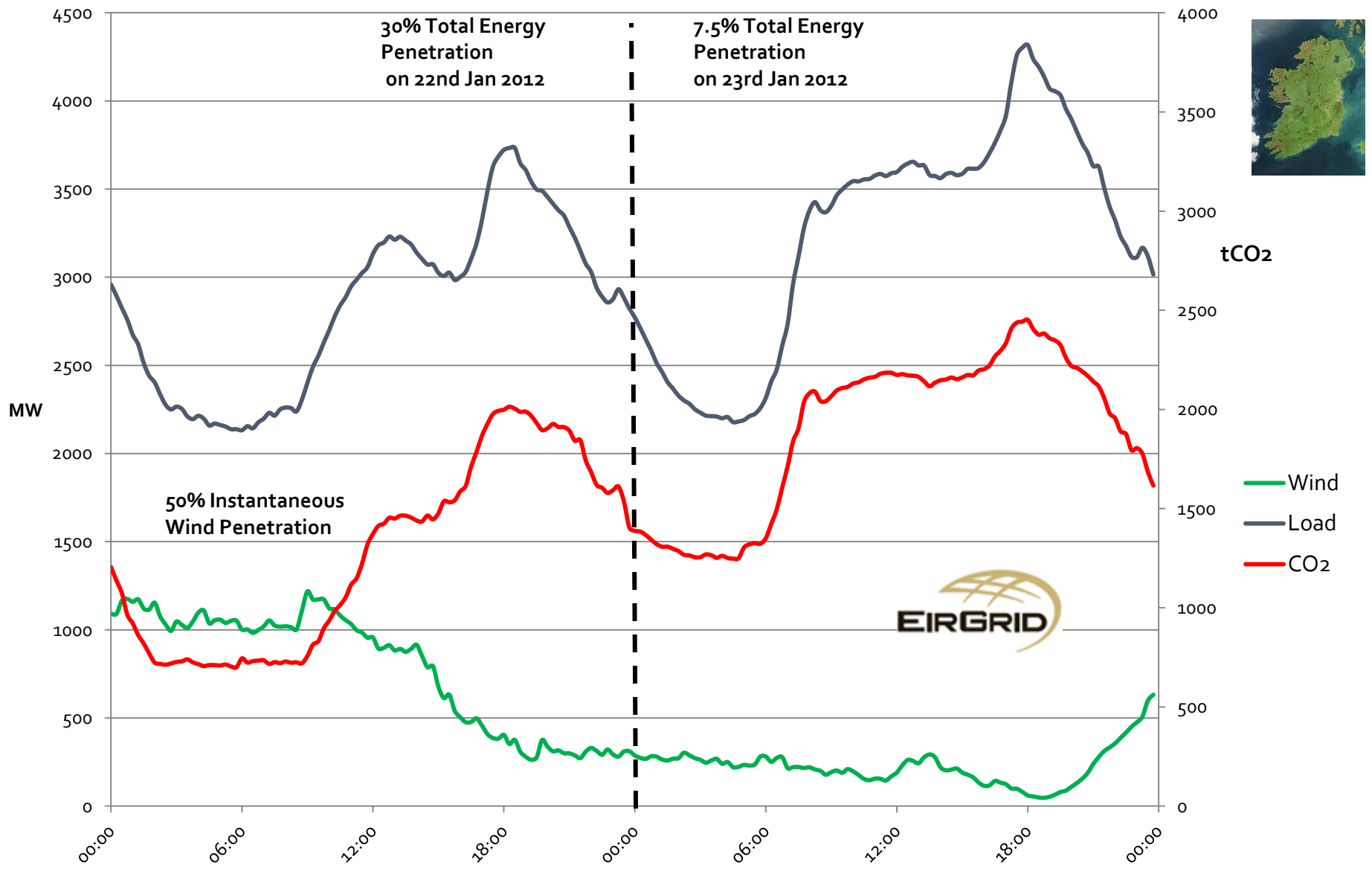
AEMO, Australian Energy Market Operator, "Wind Integration In Electricity Grids: International Practice And Experience" WP1, October 2011

# Wind and demand, dance partners ?



AEMO, Australian Energy Market Operator, “Wind Integration In Electricity Grids: International Practice And Experience” WP1, October 2011

# Load, wind and CO<sub>2</sub> Ireland



# Where does it fit into NAWEA

Charter for the North American Wind Energy Academy

REVIEW COPY v1.0

## Charter for the North American Wind Energy Academy (NAWEA)

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# Educational programme & succession planning



- ❑ **System science and engineering**
- ❑ **Grid integration and management**
- ❑ **Interdisciplinary Research**
  
- ❑ **Social acceptance**
- ❑ **Policy research**
  
- ❑ **Atmospheric sciences**
- ❑ **Environmental science**
- ❑ **Market barriers**
- ❑ **Business and financial**
  
- ❑ **New research**



# Some Research Areas

- Fundamentals of power systems
  - Asynchronous generation
  - Transmission system changing
  
- Flexibility
  - Wind providing control
  - Optimal portfolio & tools
  - Cycling
  - Markets





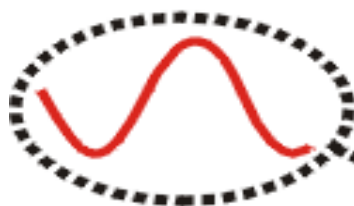


Asynchronous Generation Technologies  
are changing the Grid fundamentally

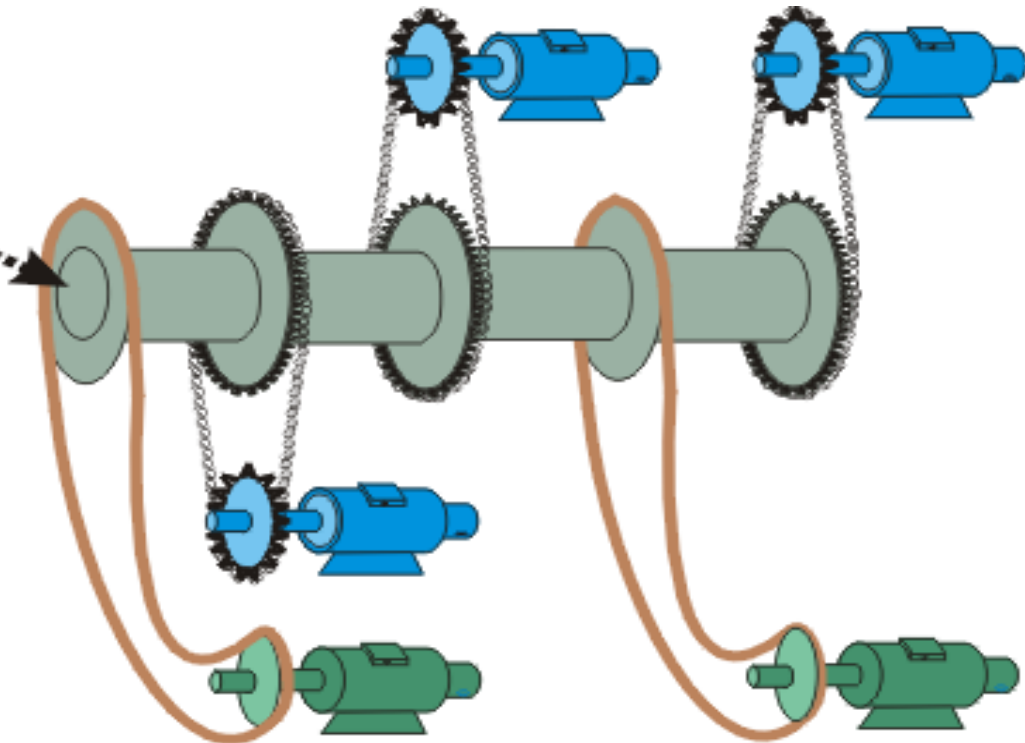
# Simple Model of the Grid



50/60 Hz



Synchronous generator



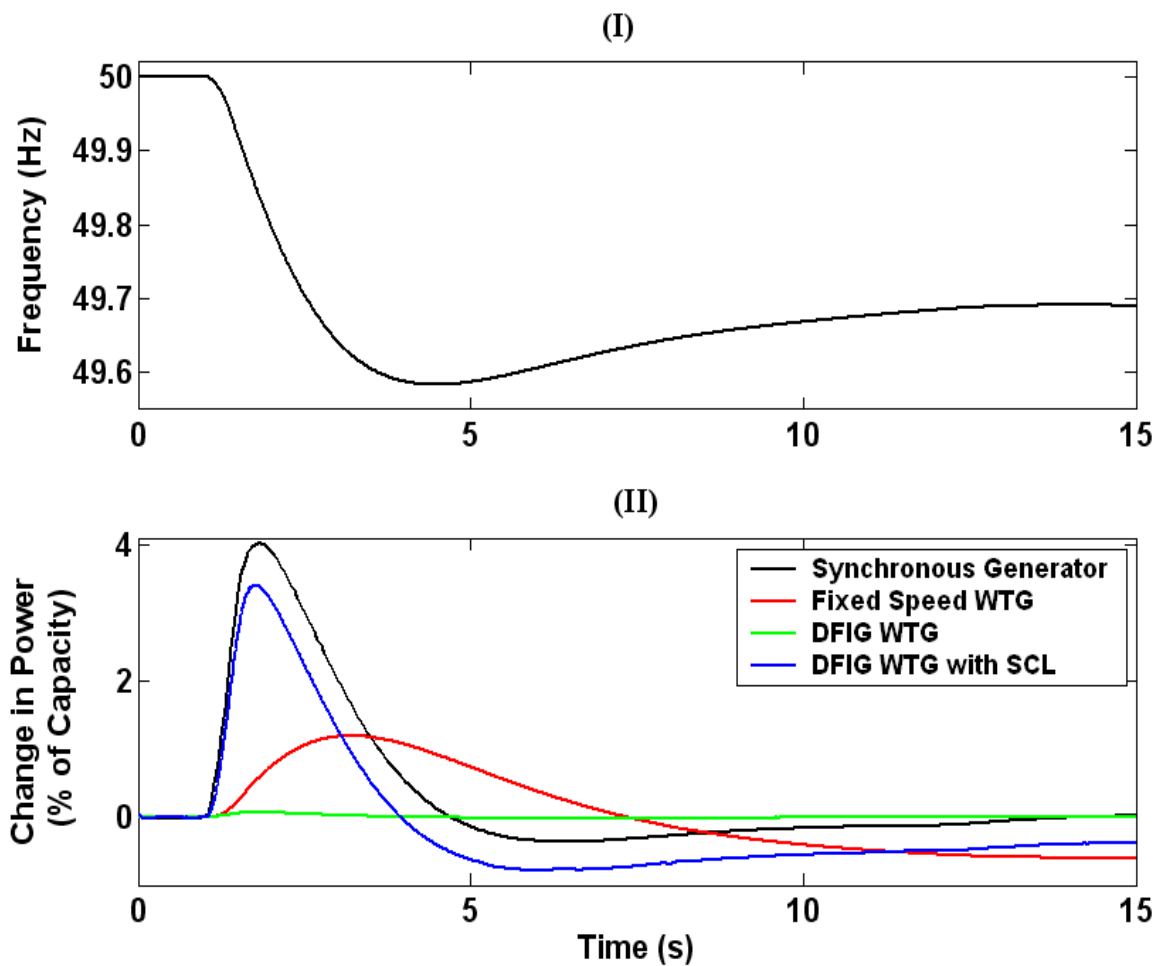
Does not add to system inertia



Doubly fed induction generator wind turbine

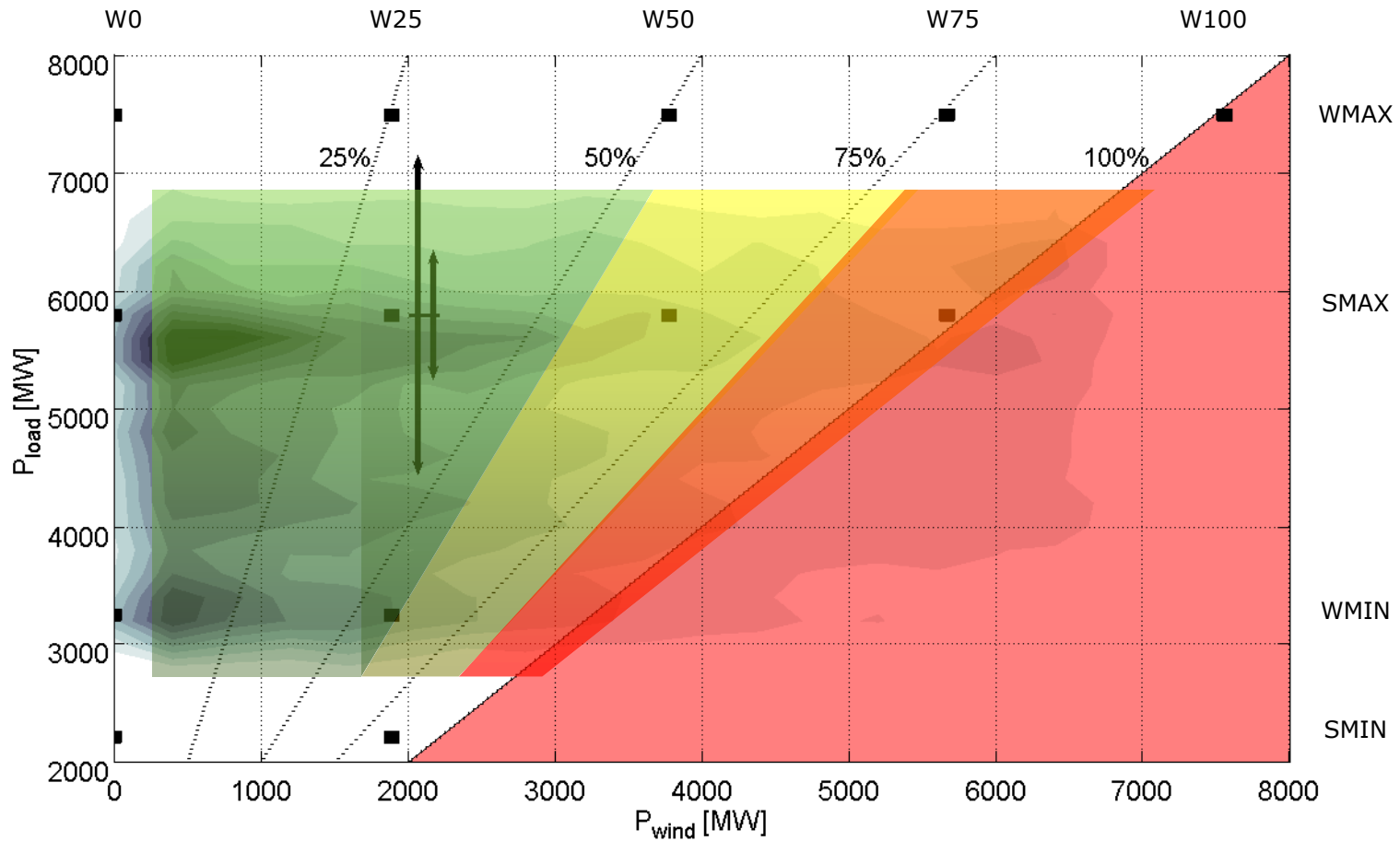
Fixed speed wind turbine generator

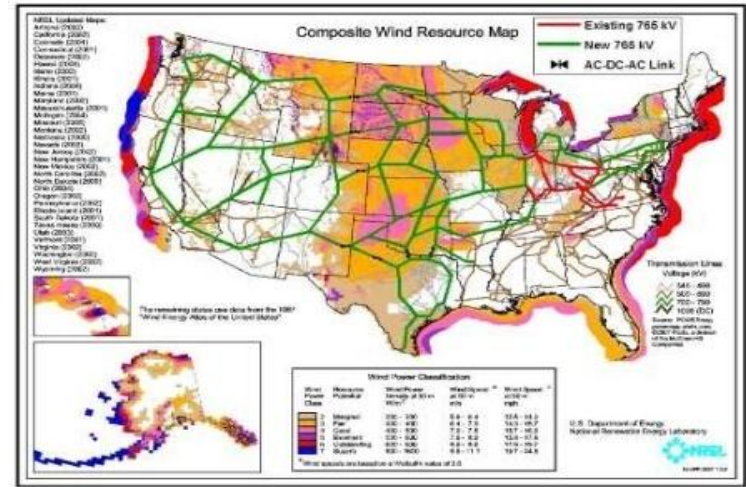
# Wind Turbine Inertial Response



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 .

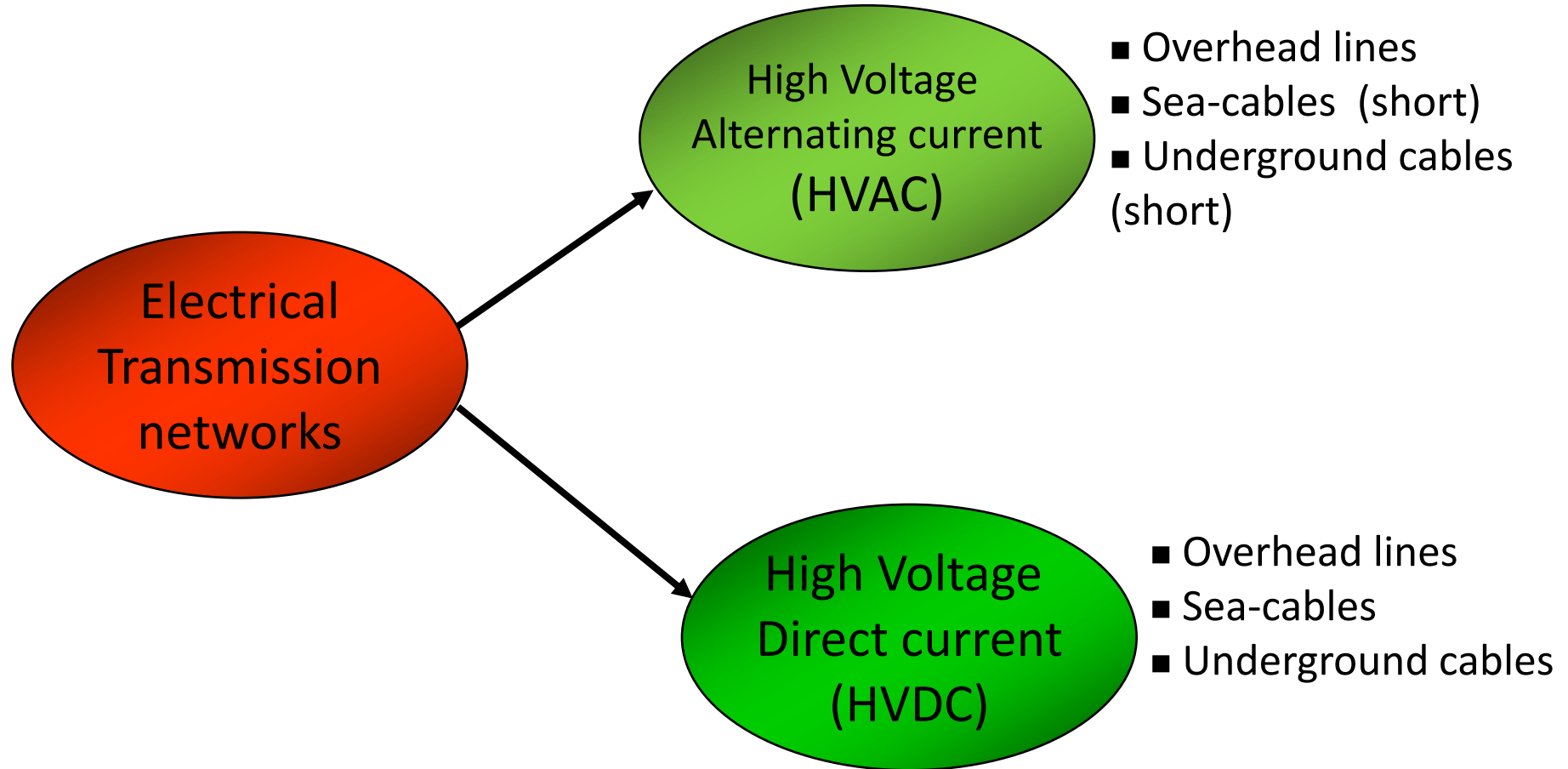
# Operational Boundaries





# Transmission system is expanding and changing

# AC/DC ?





# Public acceptance of Transmission



# Maximising the Capacity of the Grid

TABLE I  
TEST SYSTEM WIND CAPACITY FACTOR INFORMATION (%)

System Node	3	5	7	9	11	13	15	17	25	33
4-year dataset	27.3	29.6	29.7	29.9	30.3	31.0	31.9	31.4	32.4	33.9
1-year dataset	24.0	28.5	28.7	29.5	28.9	29.9	31.5	28.1	30.2	32.3

Burke, D. and O'Malley, M.J., "A Study of Optimal Non-Firm Wind Capacity Connection to Congested Transmission Systems", *IEEE Transactions on Sustainable Energy*, Vol. 2, pp. 167 - 176, 2011.



# Maximising the Capacity of the Grid

TABLE II  
OPTIMAL NONFIRM WIND CAPACITY ALLOCATION (MW)

System Node	3	5	7	9	11	13	15	17	25	33
$\sigma$ (GW)										
1	0	0	0	0	0	0	177	70	432	321
2	0	0	0	0	0	0	308	364	704	624
3	0	0	6	0	65	0	914	563	548	903
4	0	228	157	0	175	325	1087	553	523	952
5	0	730	376	0	338	543	1030	415	582	985
6	508	812	637	0	372	651	854	397	717	1051
7	1145	854	639	60	334	683	889	442	812	1140

Burke, D. and O'Malley, M.J., "A Study of Optimal Non-Firm Wind Capacity Connection to Congested Transmission Systems", *IEEE Transactions on Sustainable Energy*, Vol. 2, pp. 167 - 176, 2011.

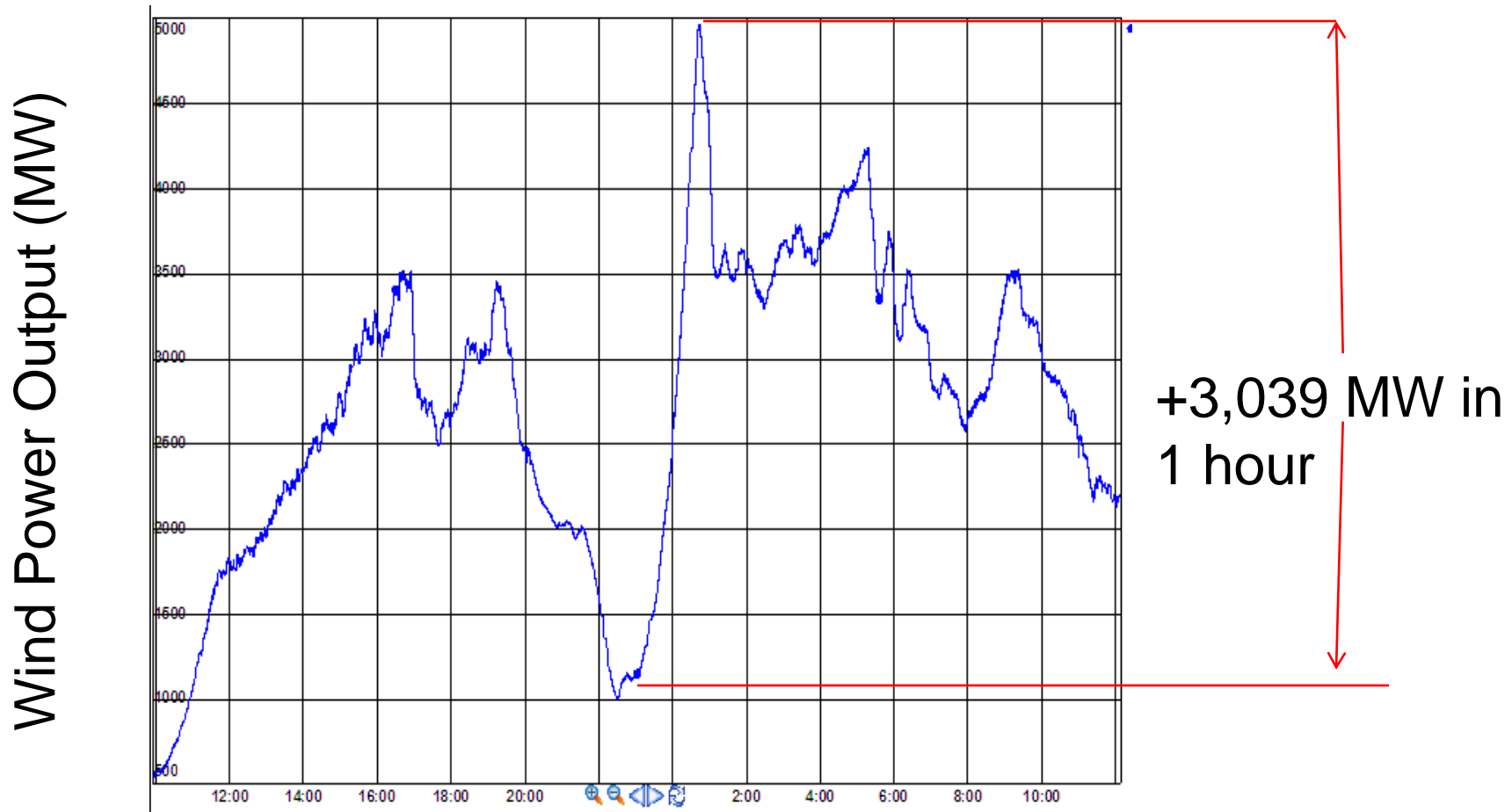


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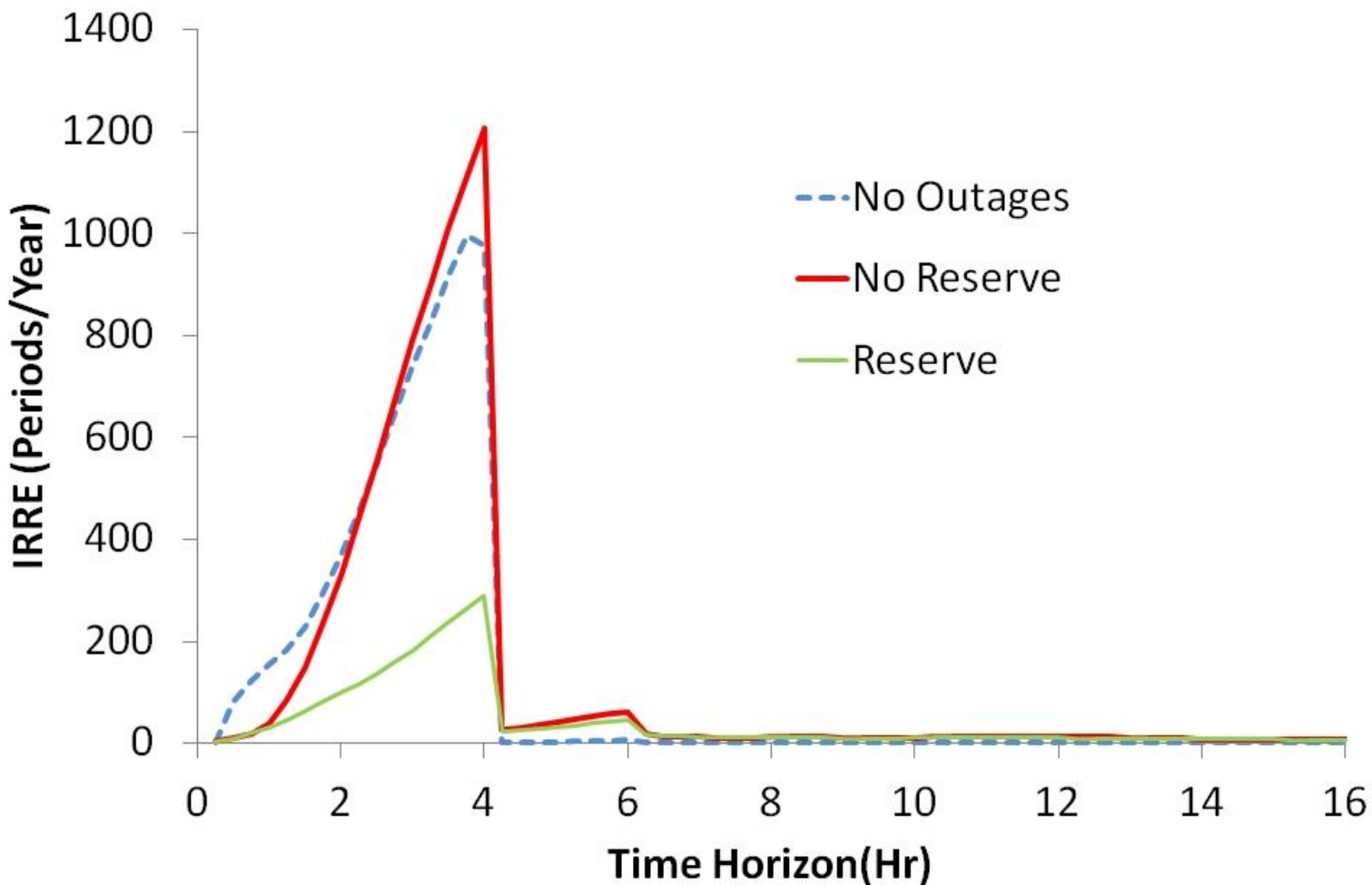
**Flexibility**

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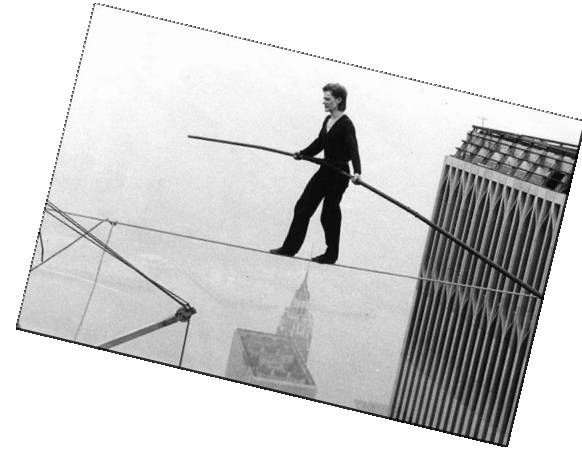
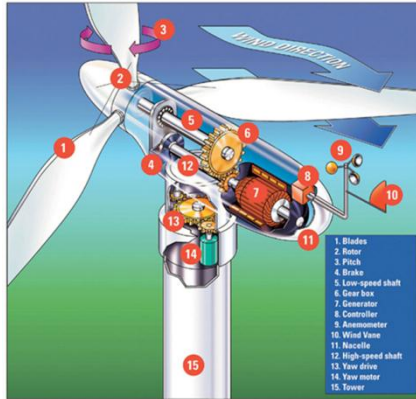
# Ramp ERCOT - 18/19<sup>th</sup> April 2009



# Flexibility metrics



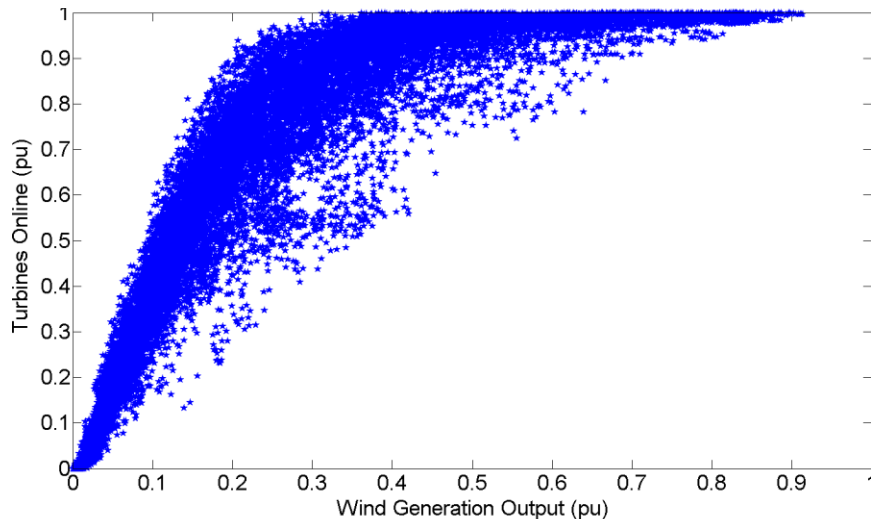
Lannoye, Flynn & O'Malley, *Evaluating Power System Flexibility*, IEEE Trans. Power Systems, Vol. 27, pp. 922 – 931, 2012.



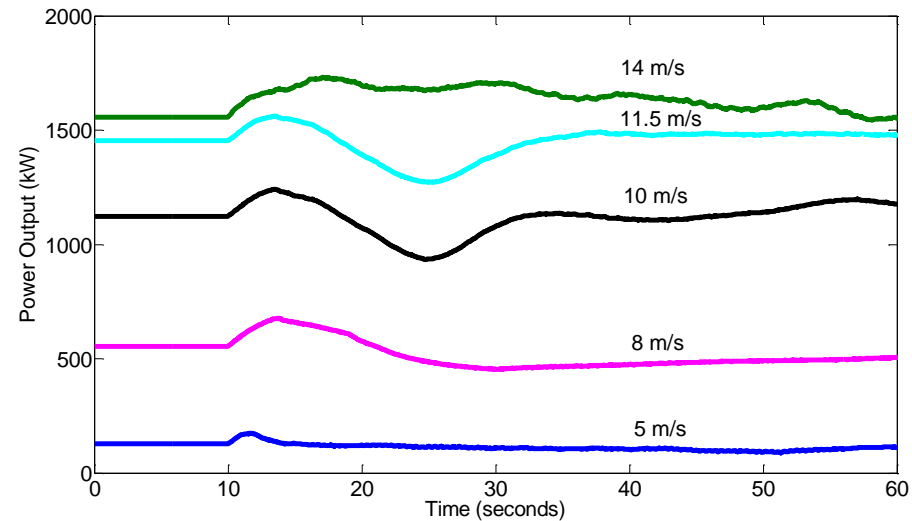
# Wind providing control

# Aggregate Emulated Inertial Response

- Potential response from wind will be stochastic - dependent on:
  - Number of turbines online
  - Operating level of wind turbines



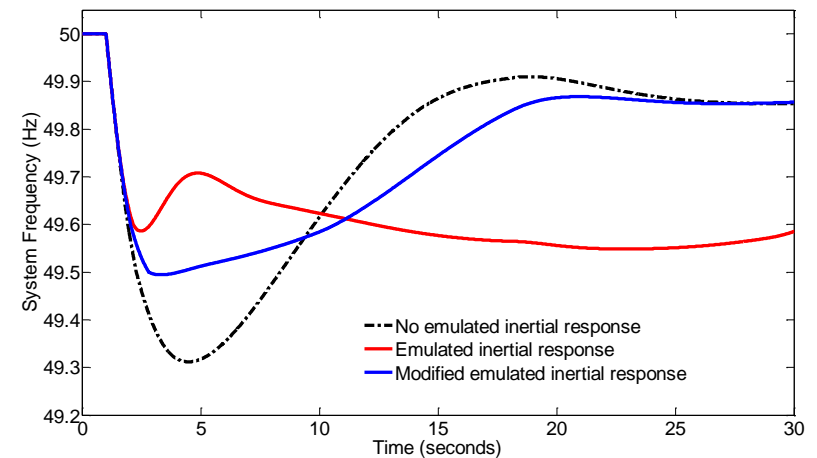
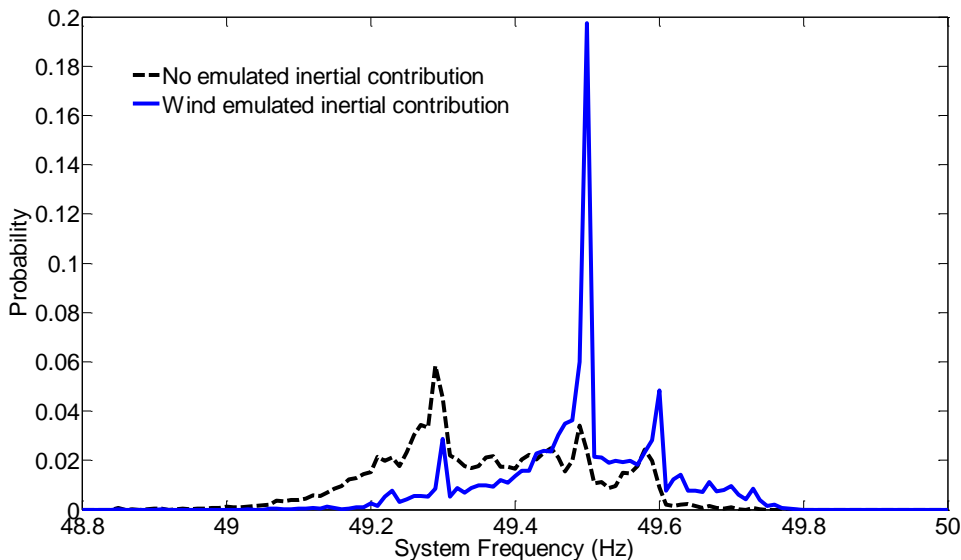
Number of turbines above minimum speed (from wind farm data, across the island of Ireland)



Response at different operating points (GE field tests)

# Emulated Inertia Impact on Frequency Response

- Frequency nadir (lowest point) can be improved
  - Rate of change of frequency (ROCOF) issue may remain on small isolated systems



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

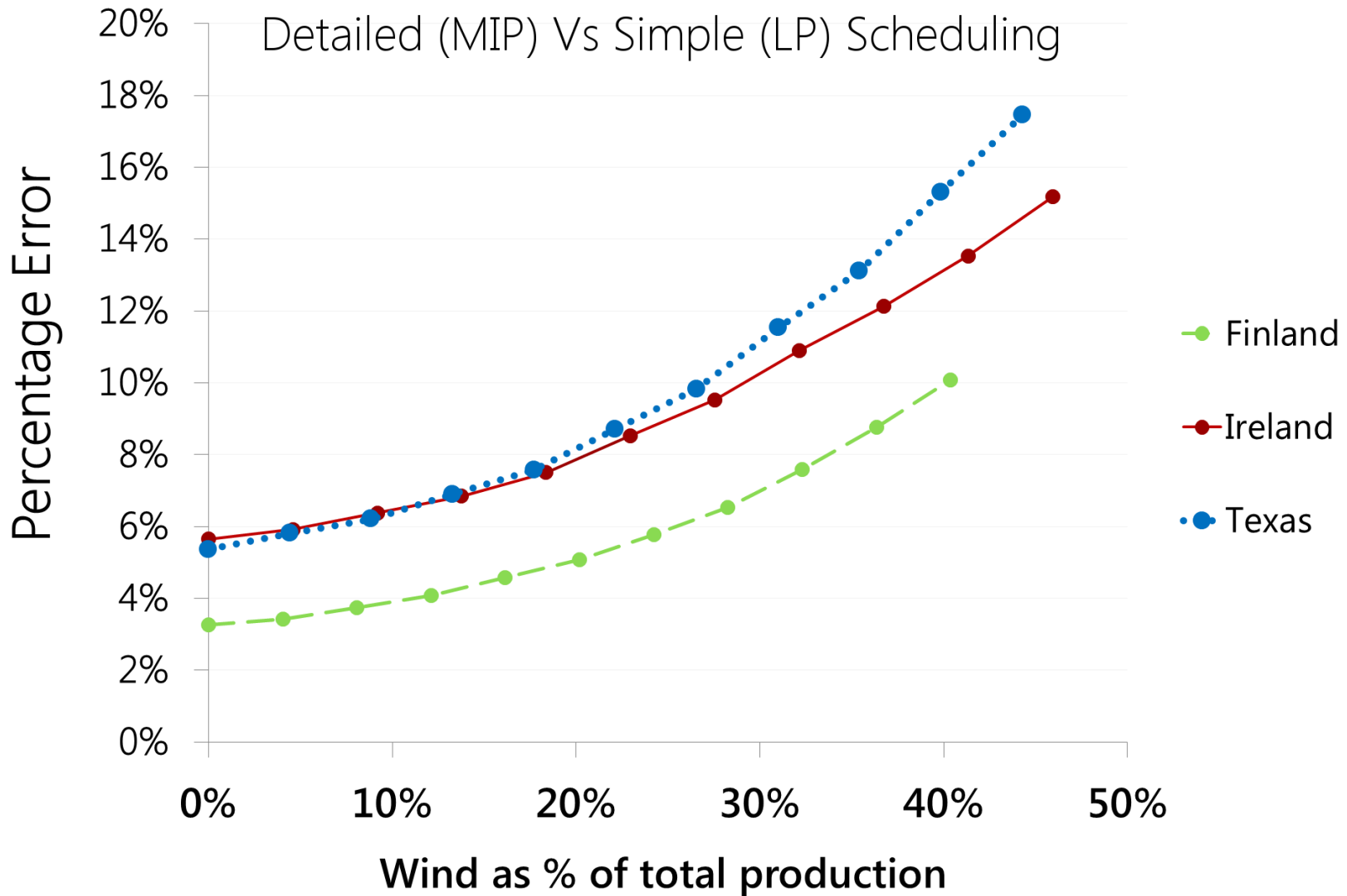


# Optimal Portfolio & Tools





# Variable Renewables and Generation Expansion <sup>25</sup>

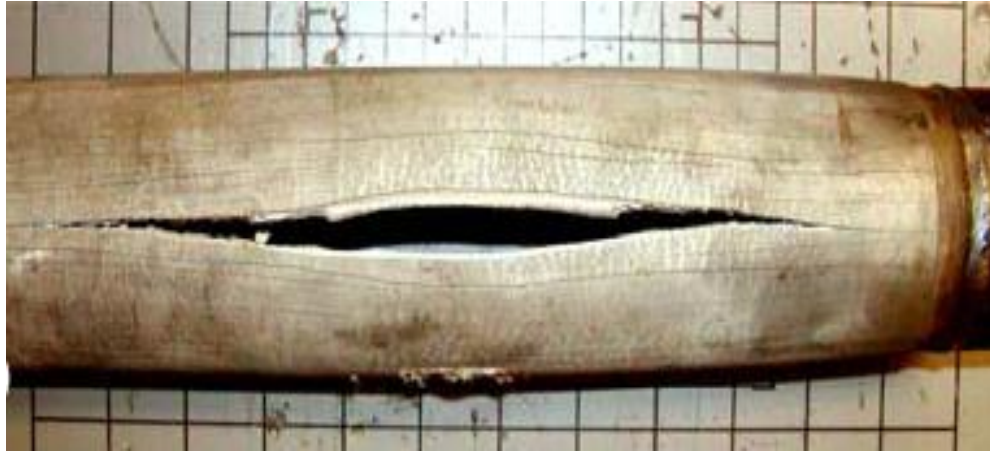


Shortt, A., Kiviluoma, J. and O'Malley, M., "Accommodating Variability in Generation Planning", *IEEE Transactions on Power Systems*, in press, 2012.

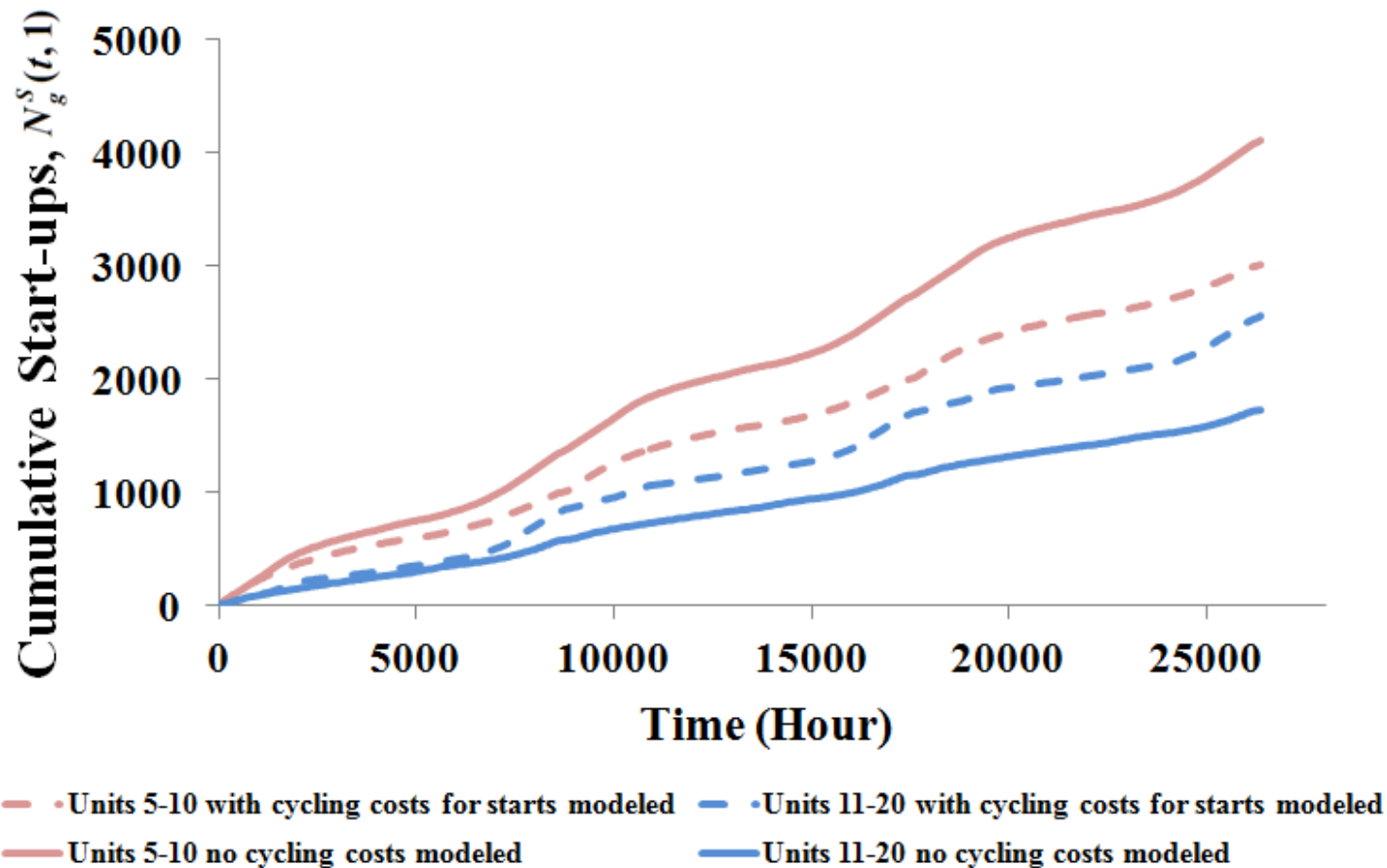


Cycling

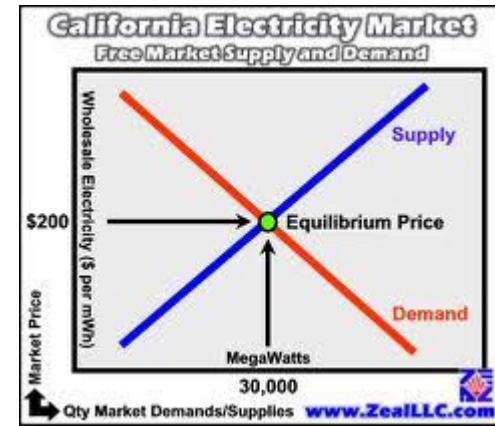
# Effects of Cycling



# Impact of Dynamic Cycling Costs

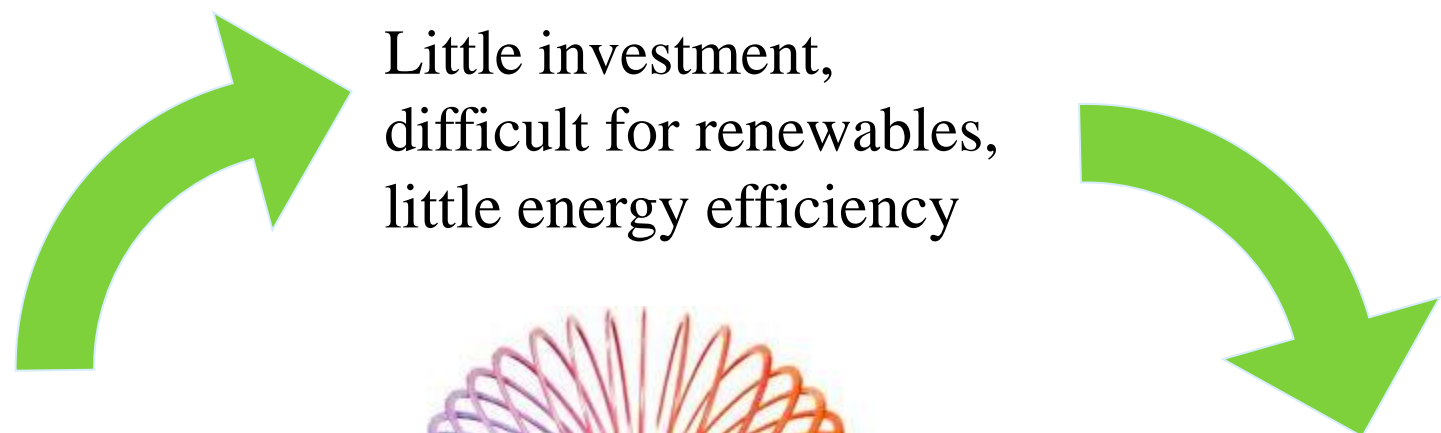


Troy, N., Flynn, D., Milligan, M. and O'Malley, M.J., "Unit commitment with Dynamic Cycling costs", *IEEE Transactions on Power Systems*, in press, 2012.



# Markets

# The Electricity Market Design Lifecycle



Little investment,  
difficult for renewables,  
little energy efficiency

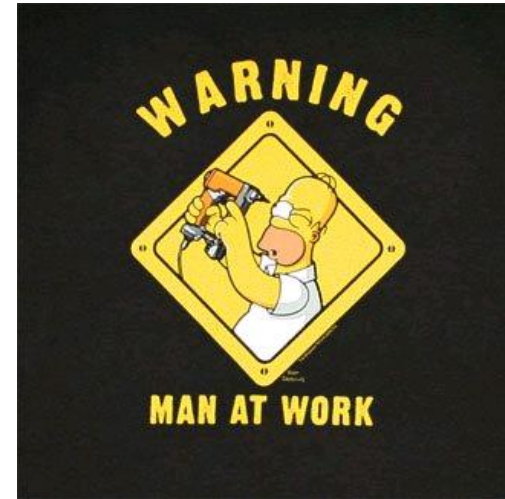


Capacity Payments,  
Green incentives  
→ Raises Prices

Unhappy Consumers  
Accusations of market abuse /  
failure

Regulate for low  
price





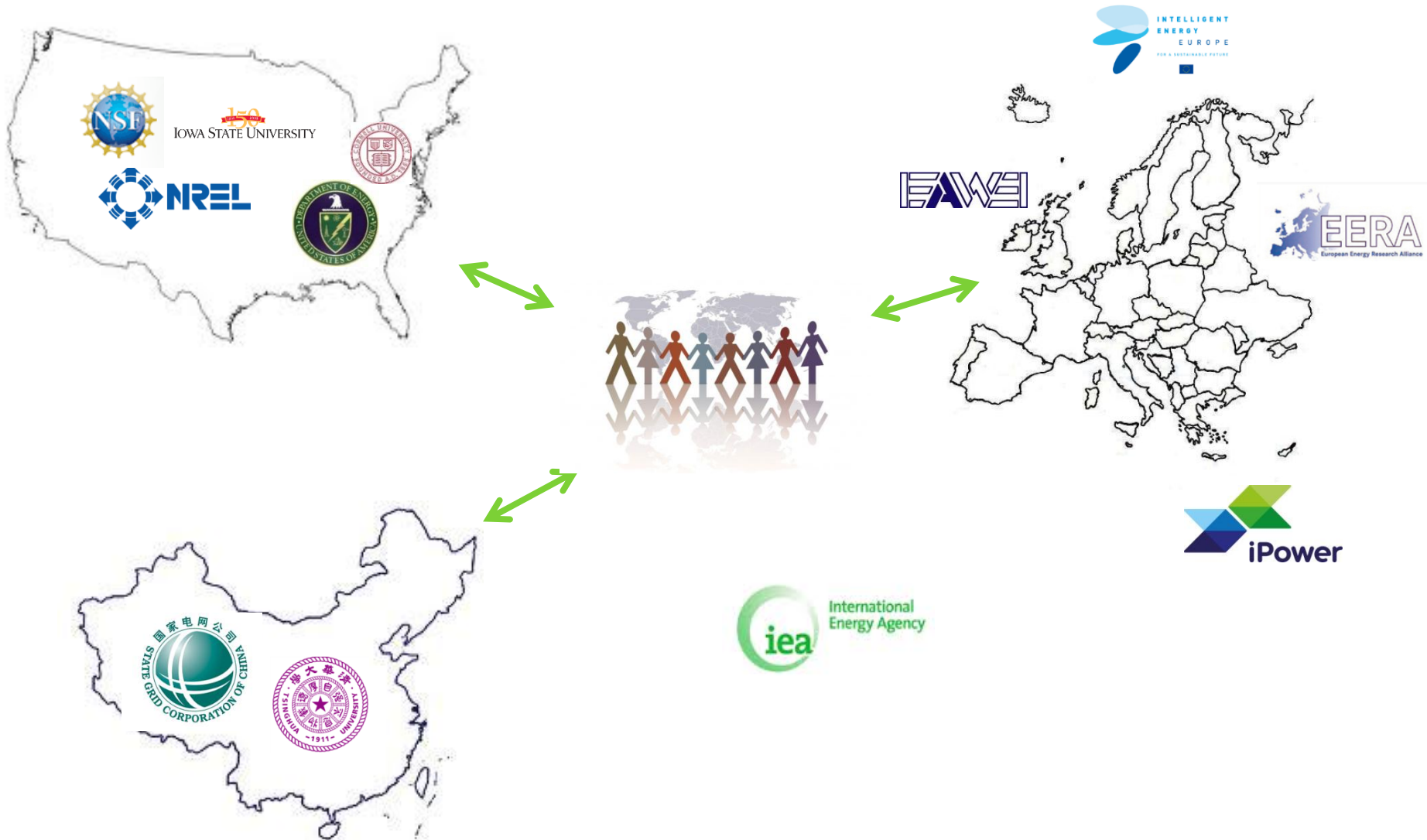
Final thoughts and direction

# Convergence

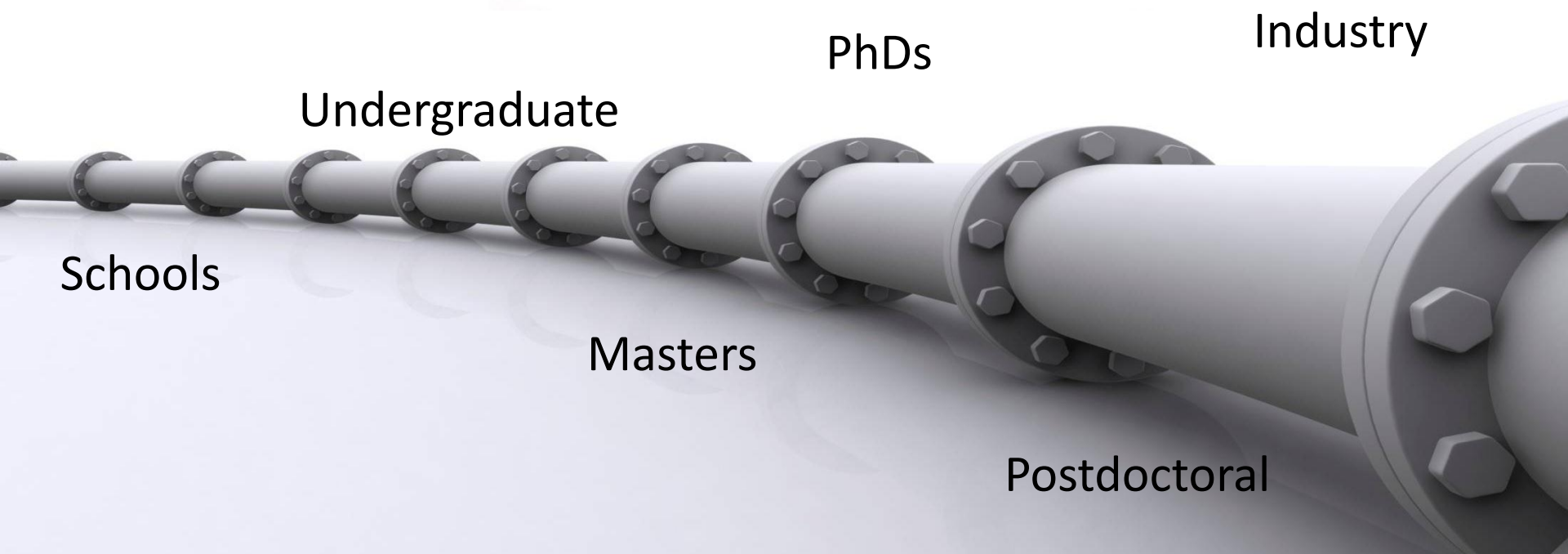




# International Collaboration



# The Pipeline



Schools

Undergraduate

Masters

PhDs

Postdoctoral

Industry

# Conclusions

- International experience
- Fundamental research areas
- Collaboration
- The pipeline is all important



# Acknowledgements

- Matthew A. Lackner and NAWEA
- Jonathan Ruddy, UCD
- Industry: Bord Gais, Bord Na Mona, Commission for Energy Regulation, Cylon Controls, EirGrid, EPRI, ESB Energy International, ESB Networks, ESB Energy Solutions, Gaelectric, Intel, SSE Renewables, United Technologies Research Centre (UTRC), Viridian
- Funding Agencies: Department of Communications Energy and Natural Resources, Electricity Research Centre (ERC), Enterprise Ireland, EU, Irish Research Council for Science, Engineering & Technology, Science Foundation Ireland, Sustainable Energy Ireland, Teagasc, IRCHSS, PRTL
- Current research Team: Dr. Damian Flynn, Dr. Eleanor Denny, Dr. Andrew Keane, Dr. Ciara O'Connor, Mr. Alan Taylor, Dr. Roisin Duignan, Dr. Niamh Troy, Dr. Eknath Vittal, Mr. Paul Smith, Mr. Michael Power, Mr. Batsaikhan Nyamdash, Dr. Peter Richardson, Mr. Aonghus Short, Ms. Amy O'Mahoney, Mr. Paul Cuffe, Mr. Eamonn Lannoye, Mr. David Kavanagh, Mr. Colm Lowery, Mr. Stefano Verde, Ms. Lisa Rutledge, Ms. Muireann Lynch, Mr. Eamon Keane, Mr. David Fletcher, Mr. Lasantha Meegahapola, Mr. Erik Ela, Mr. Mario Džamarija, Dr. Andrej Gubina, Ms. Ciara O'Dwyer, Mr. Olivier Neu, Mr. James Ryan, Mr. Noel Cunniffe, Mr. Hassan Wajahat Qazi, Dr. Reza Tavakoli, Ms. Ellen Diskin, Mr. Mostafa Bakhtvar, Ms. Allison O'Connell, Mr. Fabiano Pallonetto, Ms. Despiona Christantoni, Ms. Claudia Aravena, Mr. James Carroll, Ms. Fiona D'Rosario, Mr. Jonathan Ruddy, Ms. Magda Szczepanska, Ms. Grace O'Shea
- Graduated PhDs: Dr. Peter Richardson, Dr. Niamh Troy, Dr. Eknath Vittal, Dr. Daniel Burke, Dr. Aidan Tuohy, Dr. Garth Bryans, Dr. Eleanor Denny, Dr. Ronan Doherty, Dr. Meadhbh Flynn, Dr. Andrew Keane, Dr. Gill Lator, 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 etc.

# Recent Relevant Journal Publications

- Kiviluoma, J., Meibom, P., Tuohy, A., Milligan, M., Lange, B., Gibescu, M. and O'Malley, M.J. "Optimal short term energy balance with increasing levels of wind energy", *IEEE Transactions on Sustainable Energy*, in press, 2012
- Lowery, C. and O'Malley, M.J. "Impact of wind forecast error statistics upon unit commitment", *IEEE Transactions on Sustainable Energy*, in press, 2012.
- Söder, L., Abildgaard, H., Estanqueiro, A., Hamon, C., Holttinen, H., Lannoye, E, Gómez Lázaro, E., O'Malley, M.J. and Zimmermann, U. "Experience and challenges with short term balancing in systems with large penetration of wind power", *IEEE Transactions on Sustainable Energy*, in press, 2012.
- Shortt, A., Kiviluoma, J. and O'Malley, M., "Accommodating Variability in Generation Planning", *IEEE Transactions on Power Systems*, in press, 2012.
- Burke, D., A. Tuohy and O'Malley, M. "Should Unit Commitment be Endogenously Included in Wind Power Transmission Planning Optimisation Models?", *IET Renewable Power Generation*, in press, 2012.
- Troy, N., Flynn, D., Milligan, M. and O'Malley, M.J., "Unit commitment with Dynamic Cycling costs", *IEEE Transactions on Power Systems*, in press, 2012.
- Ela, E and O'Malley, M.J., "A Flexible Power System Operations Model for Studying Variable Generation Integration", *IEEE Transactions on Power Systems*, in press, 2012.
- Lannoye, E., Flynn, D., O'Malley, M., "Evaluation of Power System Flexibility" *IEEE Transactions on Power Systems*, Vol. 27, pp. 922 – 931, 2012.
- Troy, N., Flynn, D. and O'Malley, M.J., "Multi-mode Operation of Combined-Cycle Gas Turbines with Increasing Wind Penetration", *IEEE Transactions on Power Systems*, Vol. 27, pp. 484 - 492, 2012.
- Vittal, E., O'Malley, M.J. and Keane, A., "Rotor Angle Stability with High Penetrations of Wind Generation", *IEEE Transactions on Power Systems*, Vol. 27, 353 – 362, 2012.
- Burke, D.J., and O'Malley M.J. "A Study of Principal Component Analysis Applied to Statistical Distributed Wind Power", *IEEE Transactions on Power Systems*, Vol. 26, pp. 2084 - 2092, 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*, Vol. 26, pp. 1367 - 1379, 2011.
- Doherty, R. and O'Malley, M.J. "The Efficiency of Ireland's Renewable Energy Feed-In Tariff (REFIT) for Wind Generation", *Energy Policy*, Vol. 39, pp. 4911 - 4919, 2011.
- Keane, A, Tuohy, A., Meibom, P., Denny, E., Flynn, D., Mullane, A. and O'Malley, M.J., "Demand side resource operation on the Irish power system with high wind power penetration", *Energy Policy*, Vol. 39, 2925 - 2934, 2011.
- Keane, A., Milligan, M., D'Annunzio, C., Dent, C., Dragoon, K., Hasche, B., Holttinen, H., 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", *Energy Policy*, Vol. 39, pp. 1965-1974, 2011.
- Burke, D.J., and O'Malley M.J. "Factors influencing wind energy curtailment", *IEEE Transactions on Sustainable Energy*, Vol. 2, pp. 185-193, 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*, Vol. 2, pp. 167 - 176, 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*, Vol. 14, pp. 179-192, 2011.
- Hasche, B., Keane, A. and O'Malley, M.J. "Capacity value of wind power: calculation and data requirements: The Irish power system case", *IEEE Transactions on Power Systems*, Vol. 26, pp. 420 - 430, 2011.



# Grid Integration Challenges and Solutions

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Amherst, MA, USA

August 8<sup>th</sup>, 2012



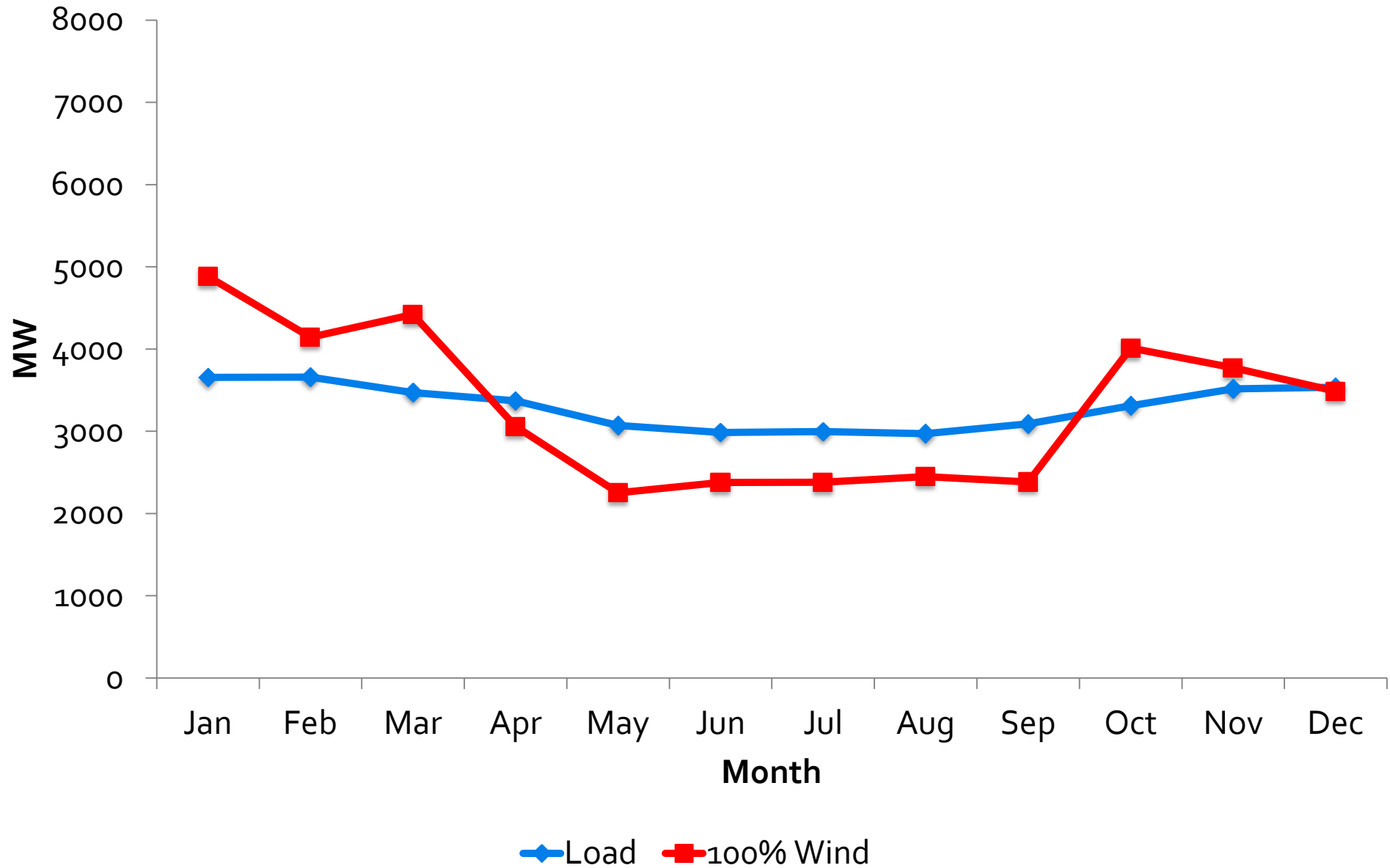
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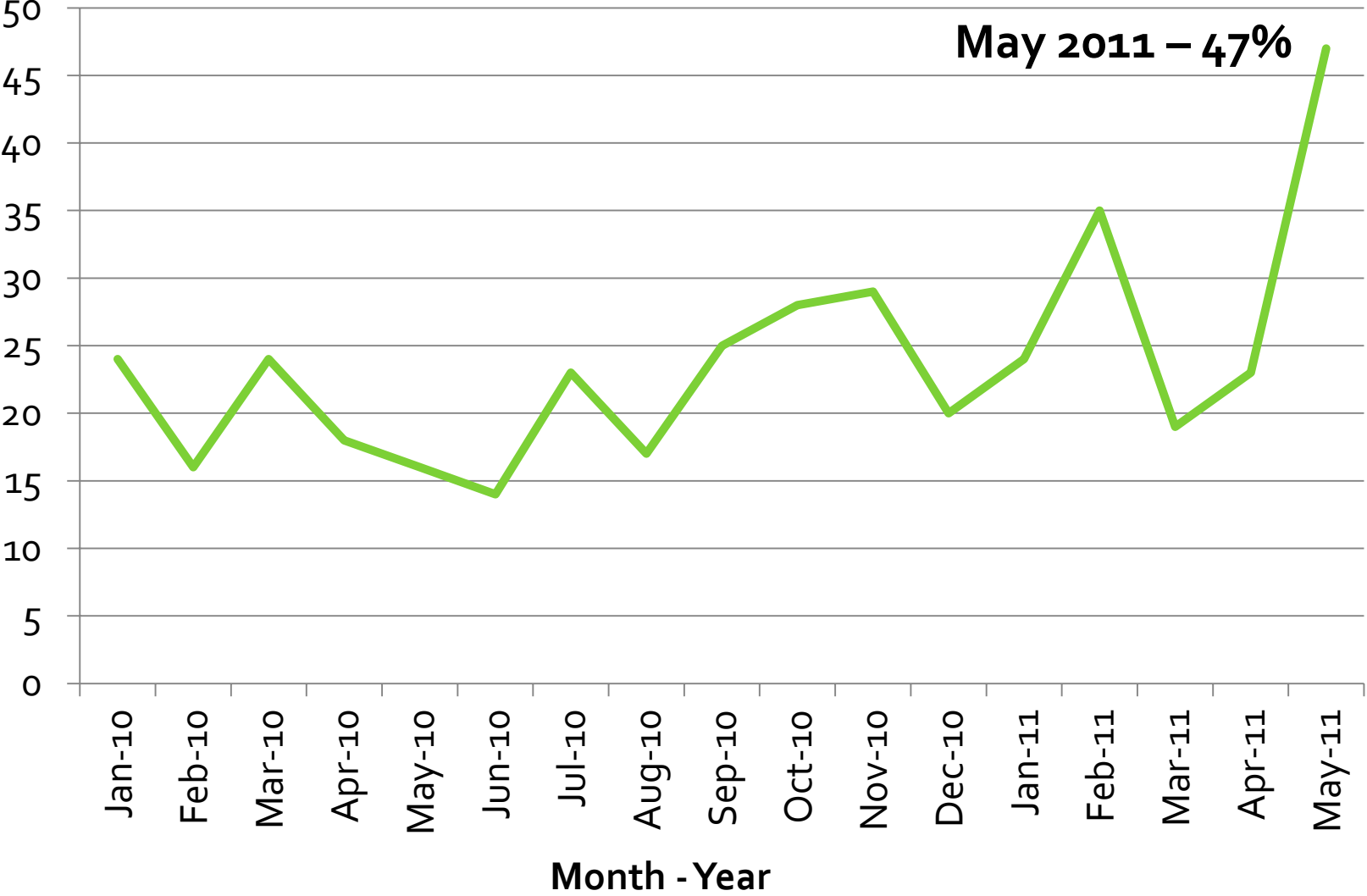
The following slides were used  
subsequent to the presentation at the  
panel session

# Yearly load & 100 % Wind (Ireland)





# Monthly Capacity Factor – Ireland



# Yearly Capacity Factor - Ireland

