Low Carbon Integrated Energy Systems: Challenges and Opportunities

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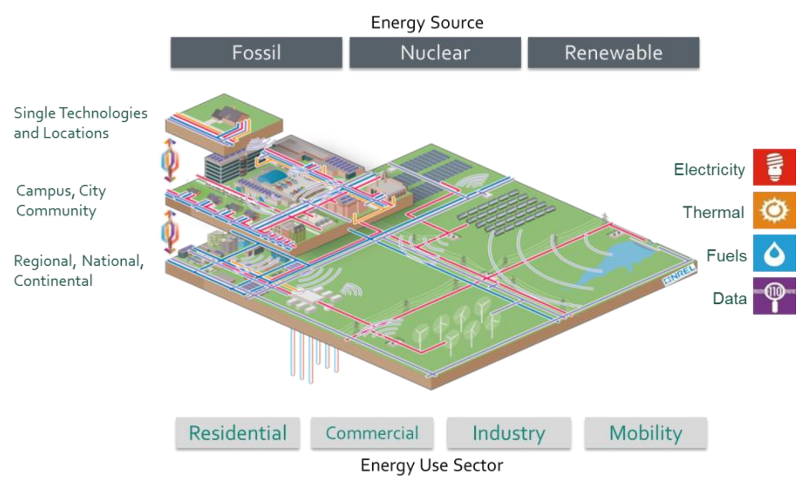
Andlinger Center for Energy and the Environment
Princeton, New Jersey, 8th May 2015

Low Carbon Integrated Energy Systems: Challenges and Opportunities

Abstract: Globally, there is an undeniable trend towards low carbon integrated energy systems. These systems have some **unique characteristics that will be highlighted in particular with respect to variable renewable energy technologies (e.g. wind and solar photovoltaic).** High penetrations of these variable renewables can be achieved by increasing the levels of **integration across the energy system** (e.g. heat in the form of demand management in electricity). The challenges and opportunities of highly integrated energy systems will be explored.

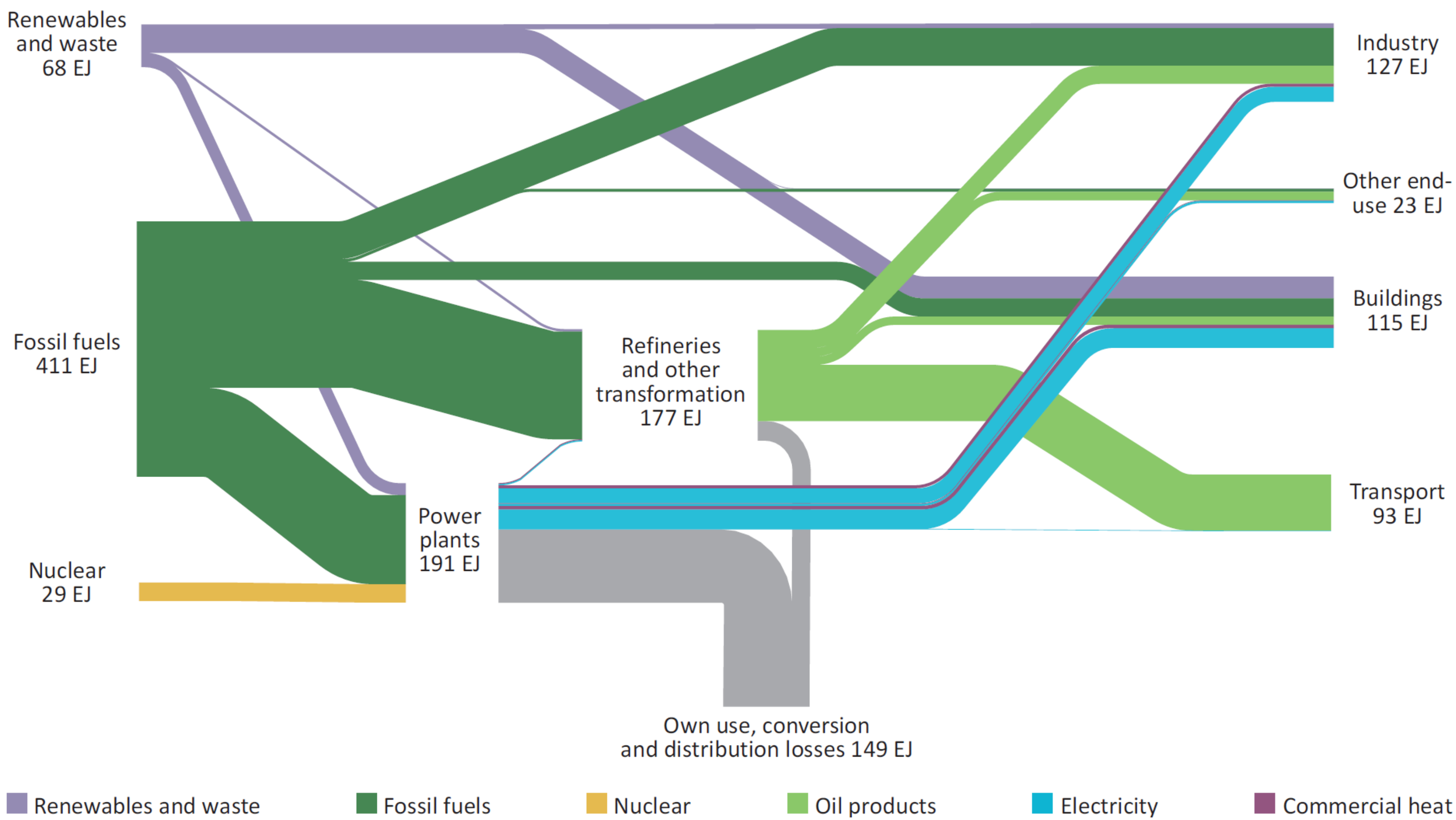


Outline

- What is this and why is it important
- Variable renewable energy:
  - Technical Characteristics
    - Non synchronous nature
  - Resource Characteristics
    - Flexibility
- Energy Systems Integration
- Conclusions

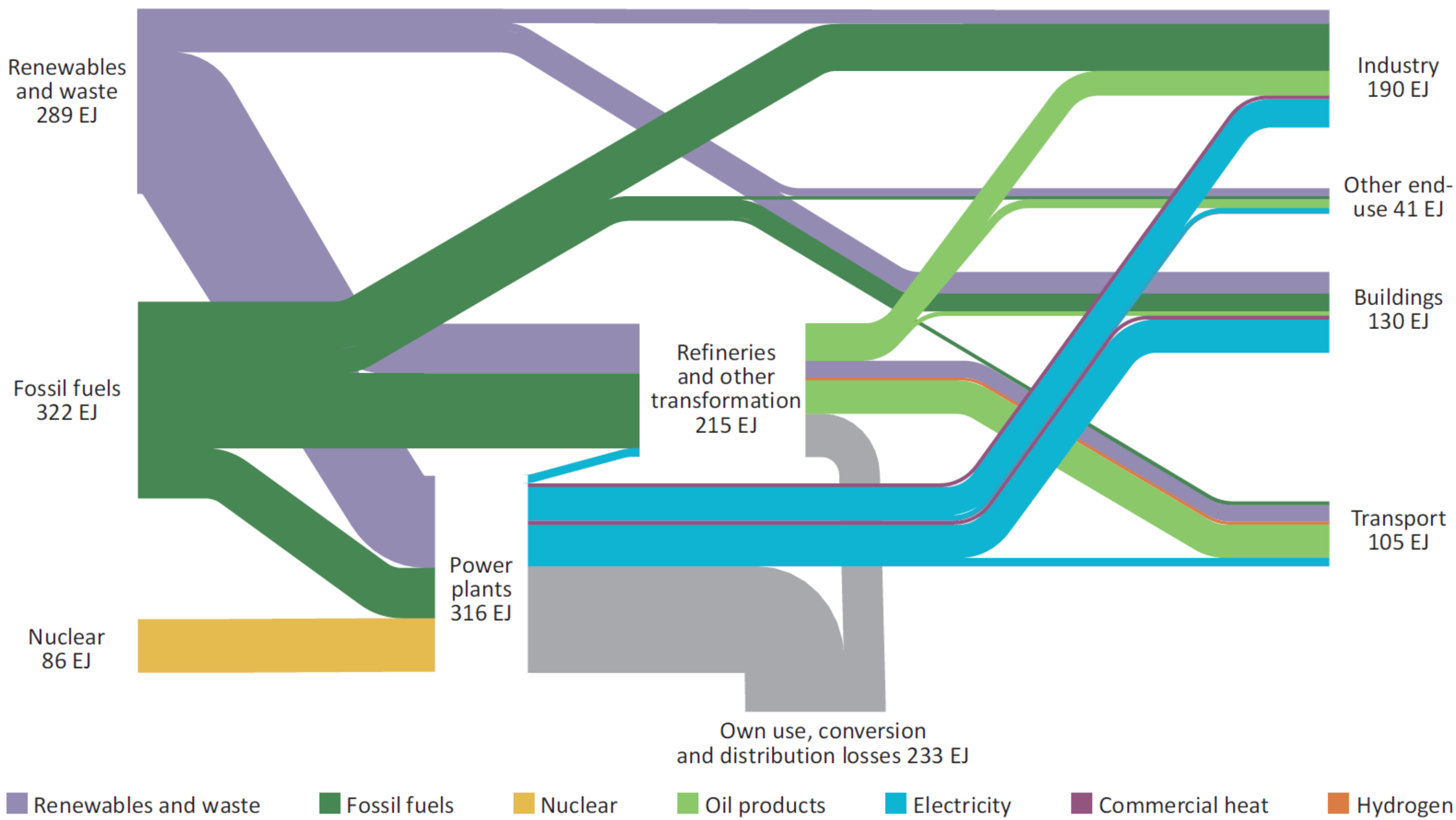
What is this and why is it important

The global energy system today

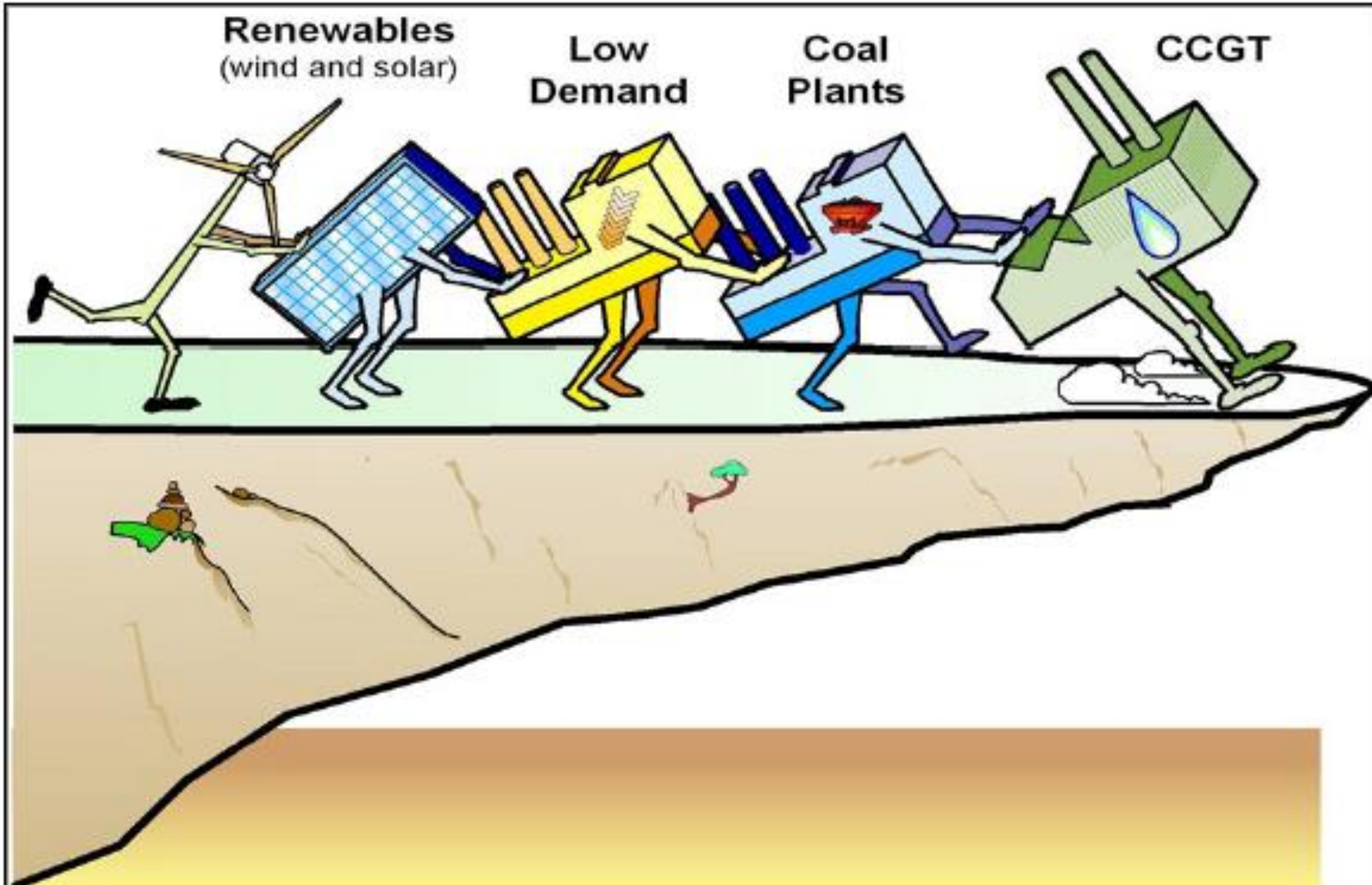


Dominated by fossil fuels in all sectors: (Source IEA)

The future low-carbon energy system



The 2DS in 2050 shows a dramatic shift in energy sources and demands: (Source IEA)

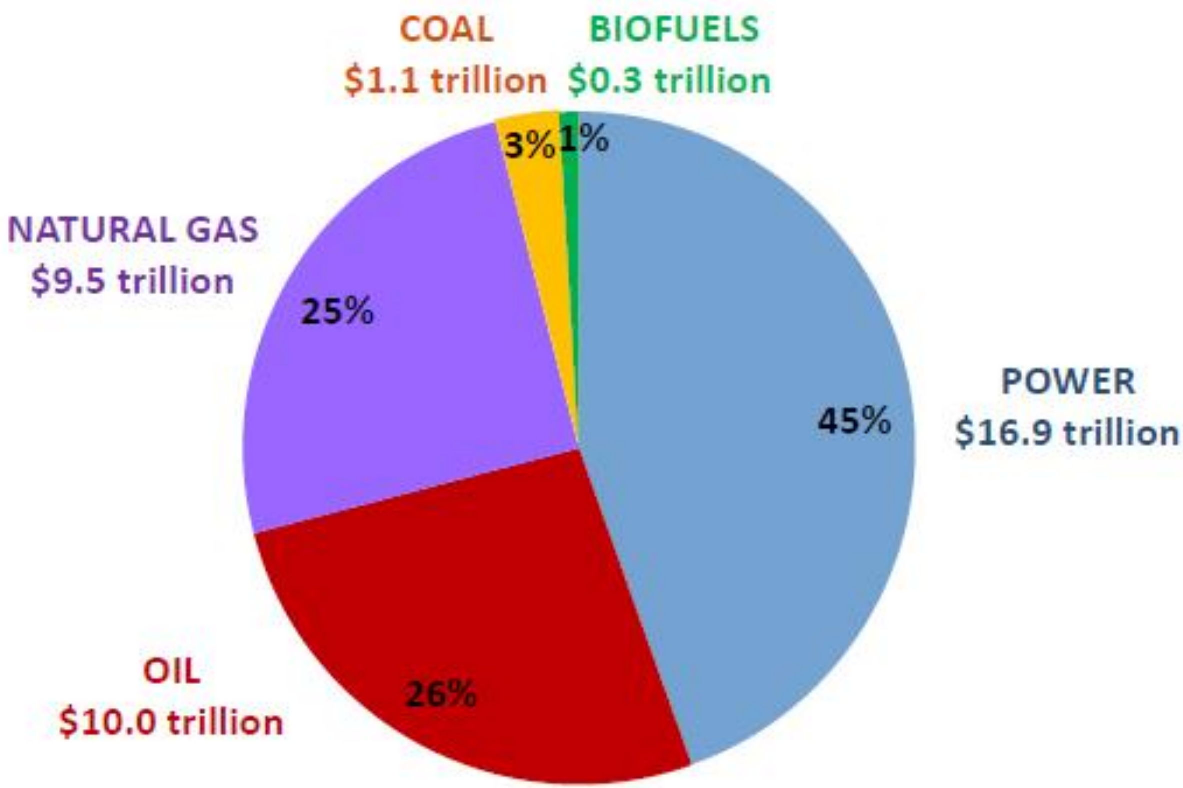


Renewables
(wind and solar)
Low
Demand
Coal
Plants
CCGT

Investment: the essence of energy

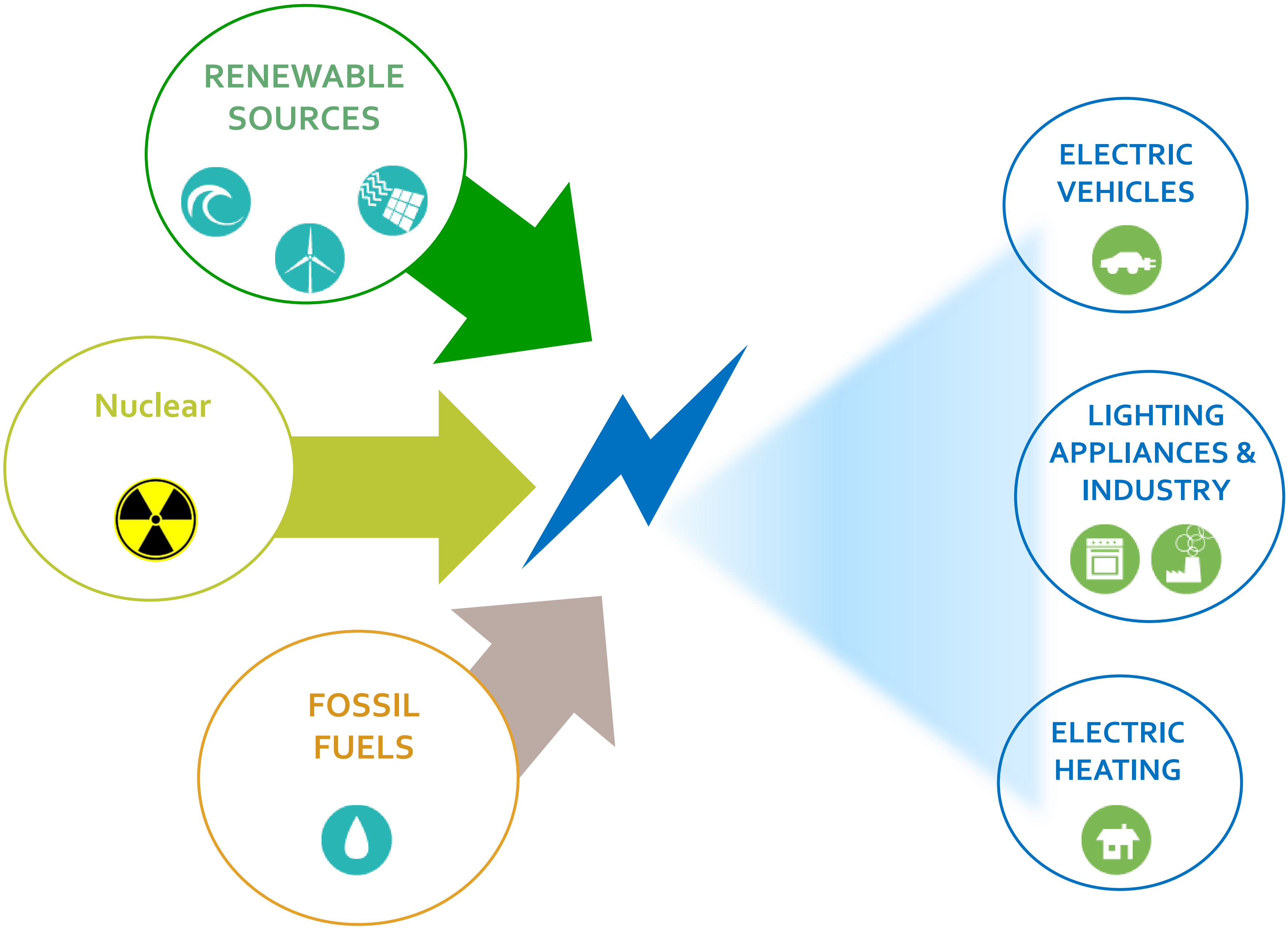
WORLD ENERGY OUTLOOK 2011

Cumulative investment in energy infrastructure, *2011-2035*



WEO-2011 will show that <u>$38 trillion</u> of investment is required to meet projected energy demand through to 2035 and that investors in energy projects are facing a multitude of risks

The Electric Future



Greatest Engineering Achievements OF THE 20TH CENTURY

• About • Timeline • The Book

Welcome!

How many of the 20th century's greatest engineering achievements will you use today? A car? Computer? Telephone? Explore our list of the top 20 achievements and learn how engineering shaped a century and changed the world.

1. Electrification
2. Automobile
3. Airplane
4. Water Supply and Distribution
5. Electronics
6. Radio and Television
7. Agricultural Mechanization
8. Computers
9. Telephone
10. Air Conditioning and Refrigeration
11. Highways
12. Spacecraft
13. Internet
14. Imaging
15. Household Appliances
16. Health Technologies
17. Petroleum and Petrochemical Technologies
18. Laser and Fiber Optics
19. Nuclear Technologies
20. High-performance Materials

21st Century Innovation Topics

1. Energy conservation
2. Resource protection
3. Food and water production and distribution
4. Waste management
5. Education and learning
6. Medicine and prolonging life
7. Security and counter-terrorism
8. New technology
9. Genetics and cloning
10. Global communication
11. Traffic and population logistics
12. Knowledge sharing
13. Integrated electronic environment
14. Globalization
15. AI, interfaces and robotics
16. Weather prediction and control
17. Sustainable development
18. Entertainment
19. Space exploration
20. "Virtualization" and VR
21. Preservation of history
22. Preservation of species

Greatest Achievements

 Printer-Friendly Version. Text-Only Version. Contact Us.

Trilemma

"Difficult task for investors to navigate policy and market uncertainties", (IEA WEO, 2014)

Competiveness

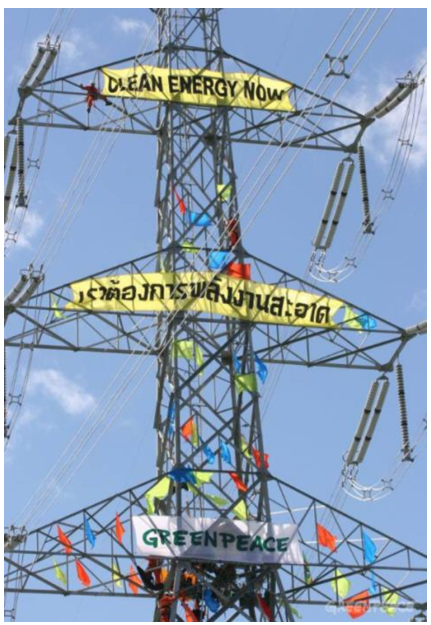
Security of supply

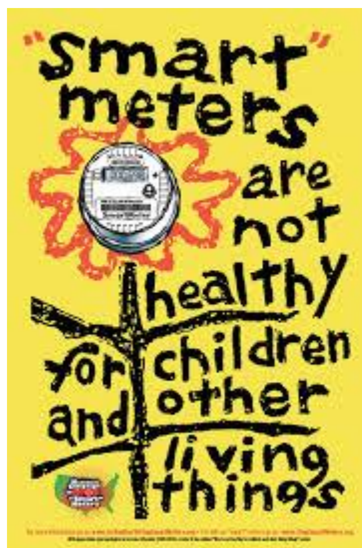
Sustainability

The consumer

“Engineers (and economists) tend to be ignorant and arrogant about customers”

Source: Janusz Bialek, Durham University





The “consumer”

The human dimensions of sustainable energy transitions

Research agenda

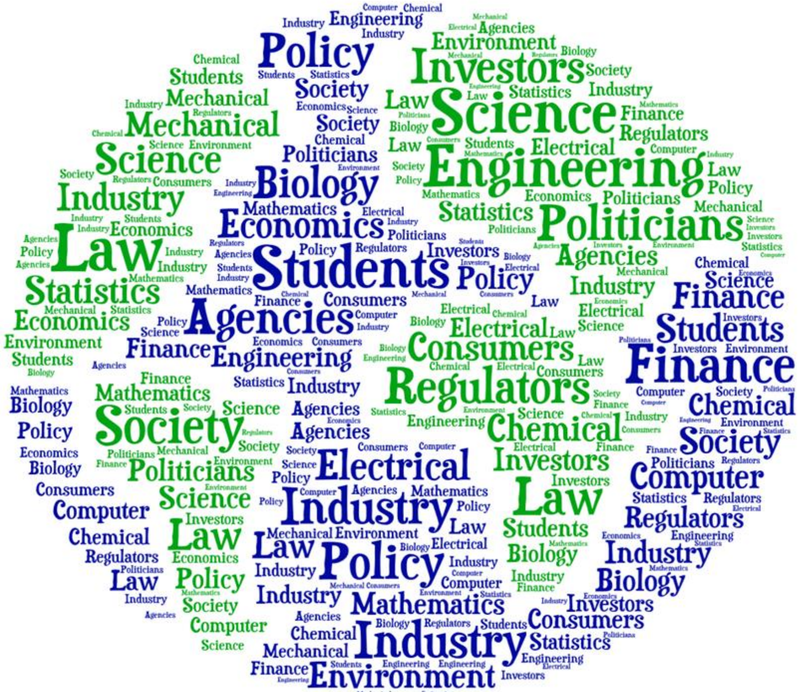
Platform for Energy Research in the Socio-economic Nexus (PERSON)

November 2014

Trilemma plus the “consumer”

Key Take Away

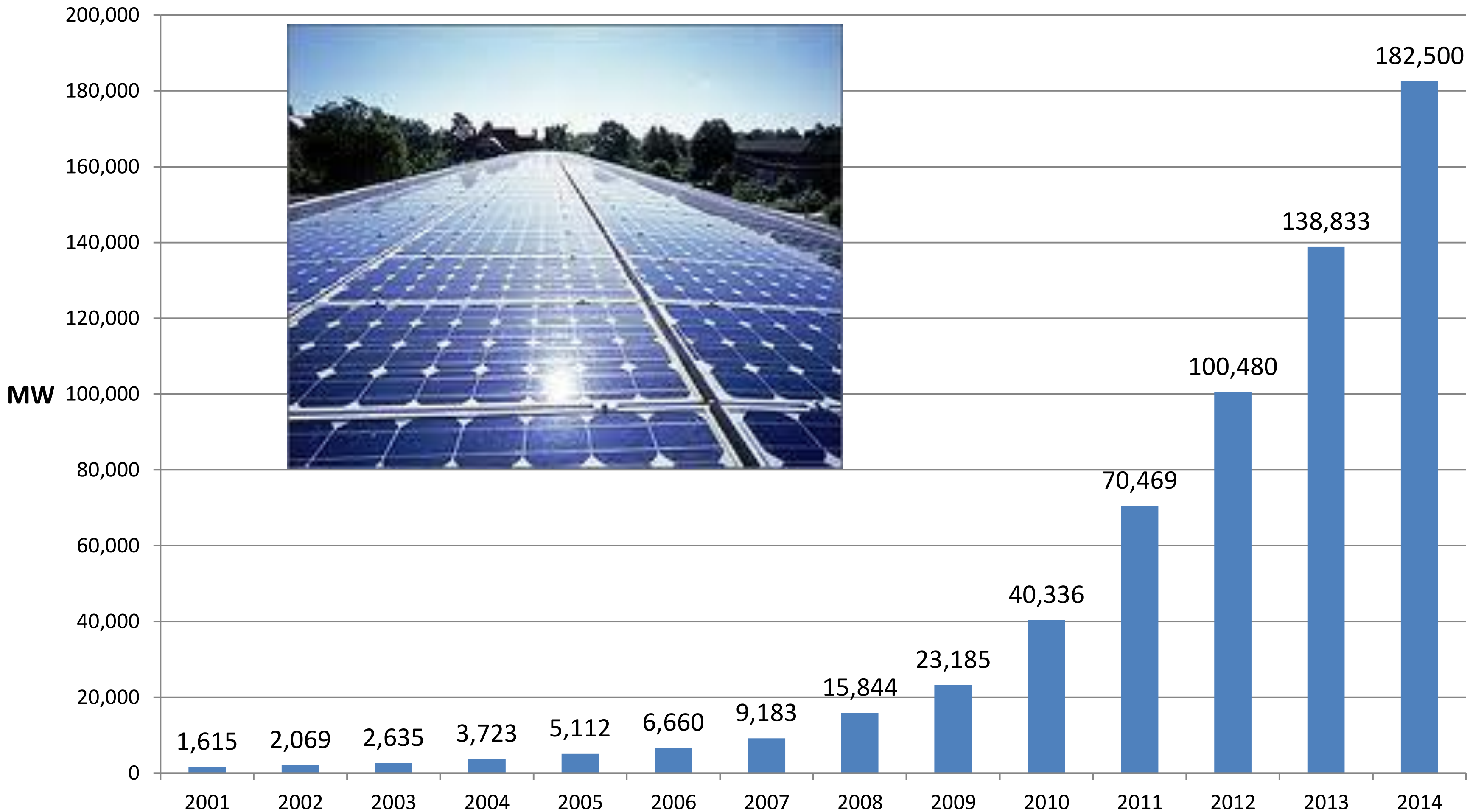
- It is about an energy transition, electricity, money, environment, consumer, security of supply, politics etc.
    - and it is all very uncertain



Variable Renewable Energy Technical Characteristics

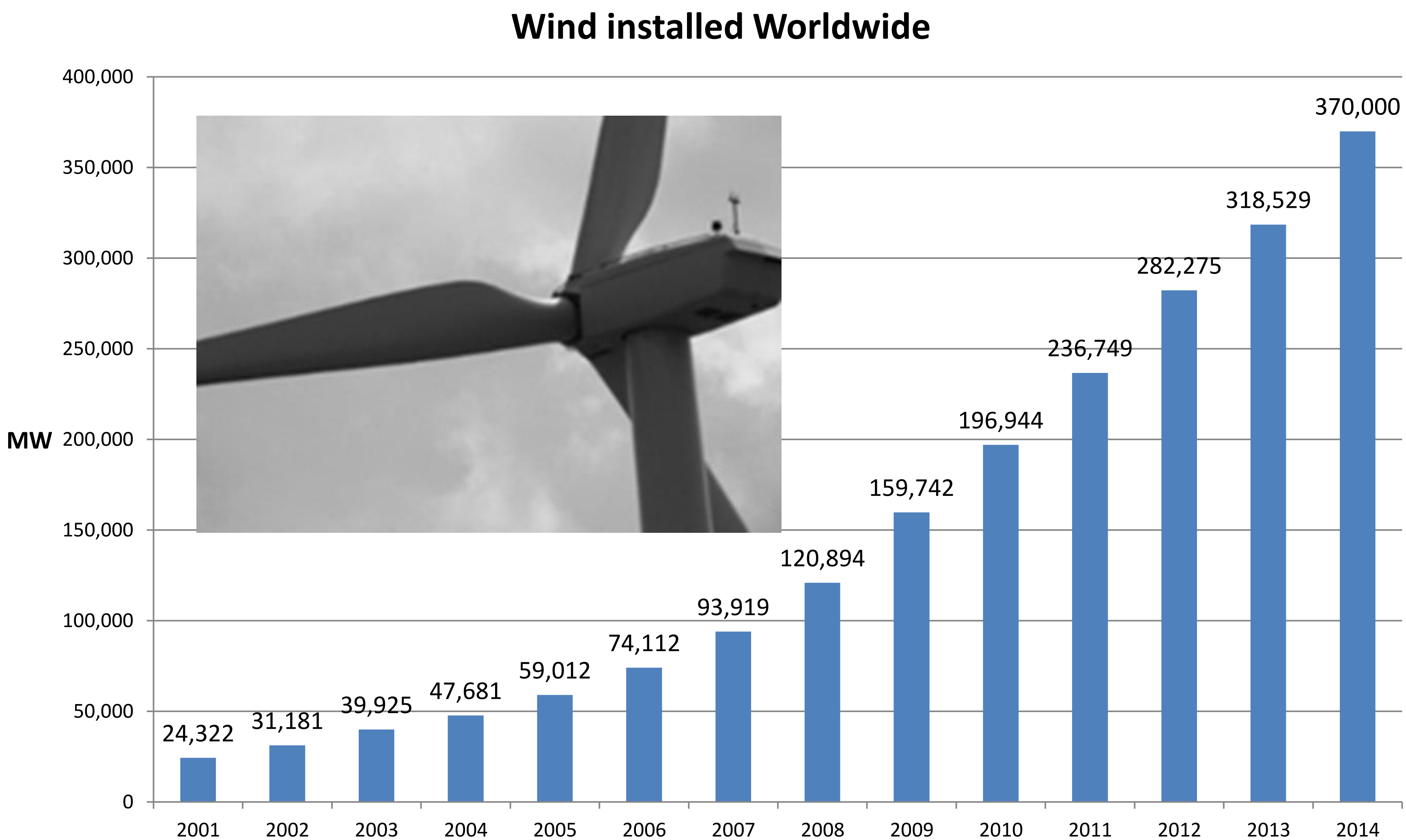
PV Installed Worldwide

Global PV Cumulative Installed Capacity



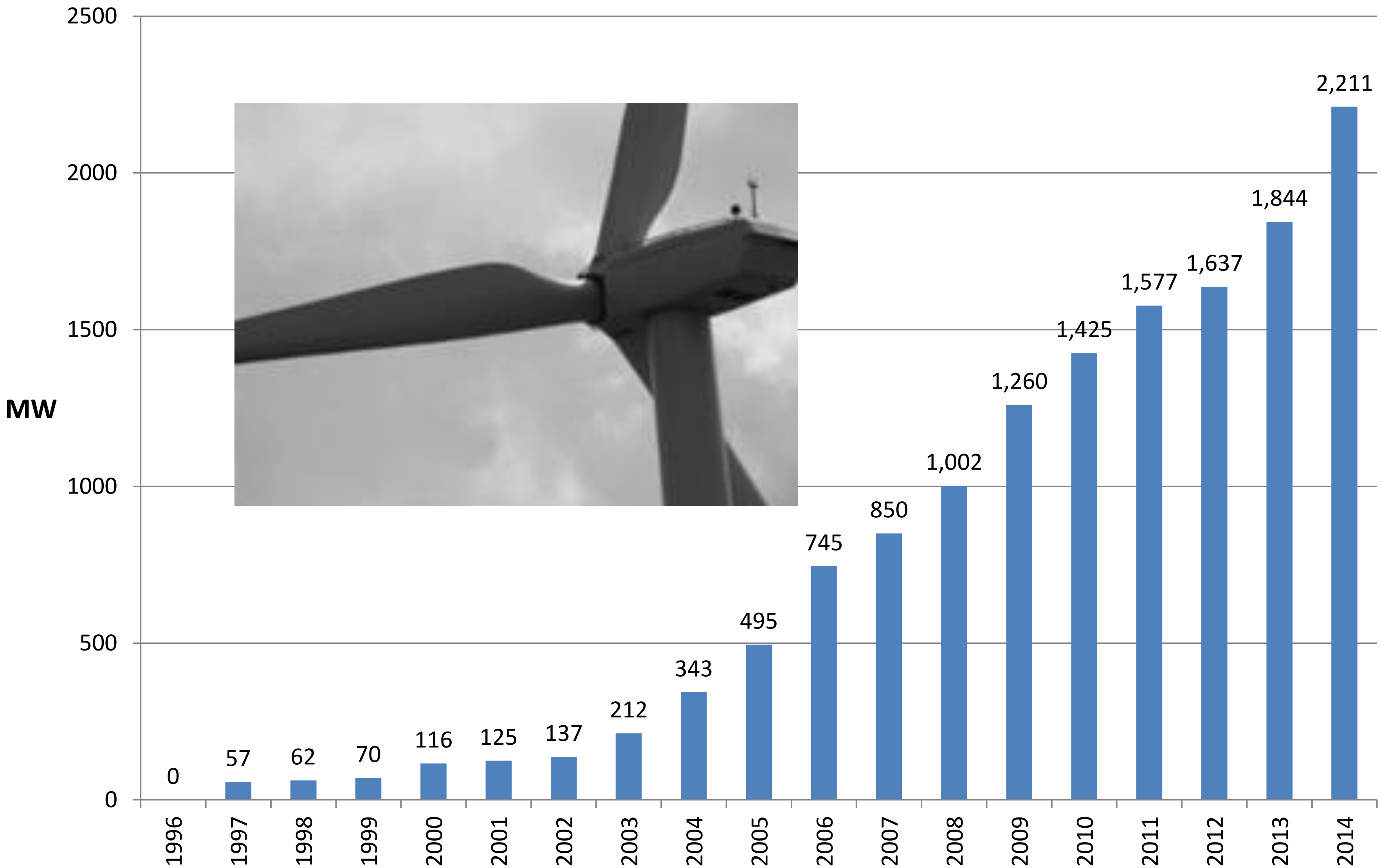
Sources: European Photovoltaic Industry Association (EPIA), International Energy Agency (IEA), IHS Technology (2014 figure)

Wind Installed Worldwide



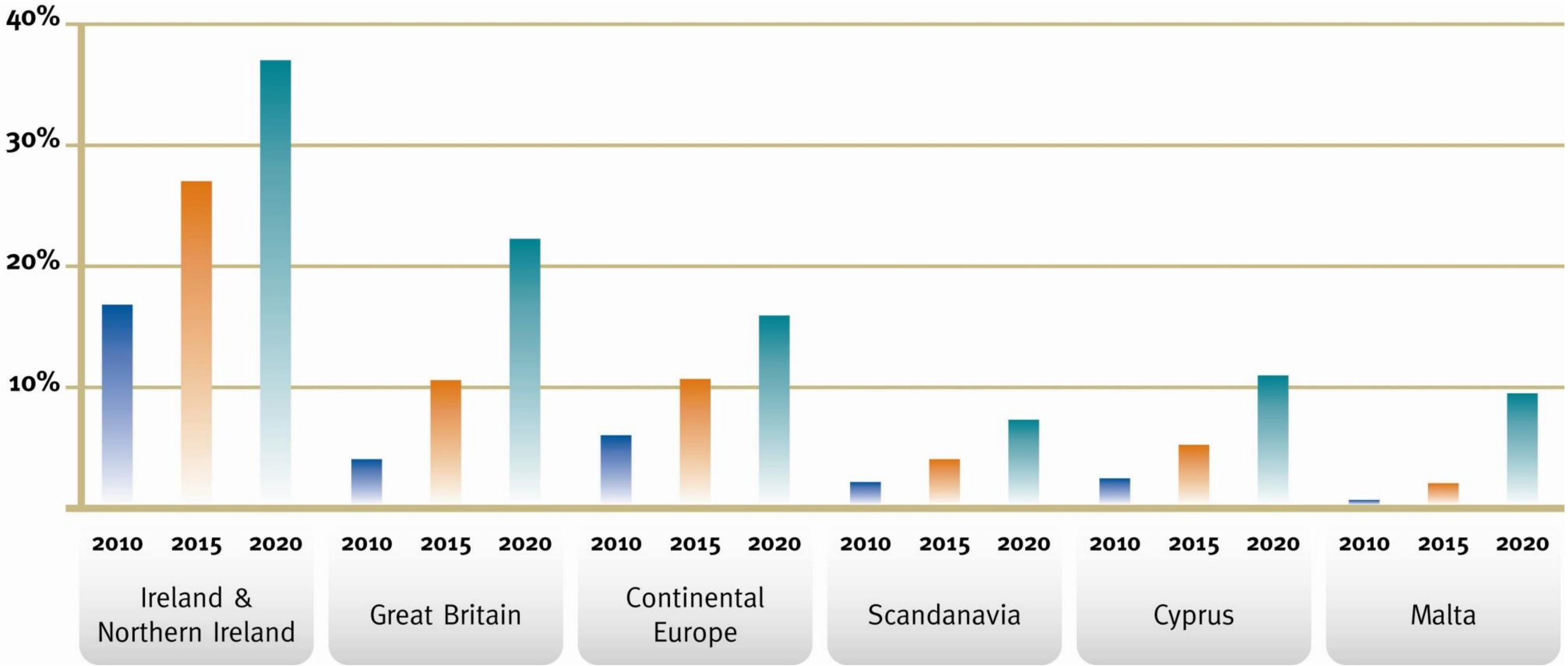
Data from http://www.wwindea.org/home/index.php

Wind Installed in Republic of Ireland



Source: EirGrid http://www.eirgrid.com/operations/systemperformancedata/all-islandwindandfuelmixreport/

Targets for non-synchronous sources in European Systems



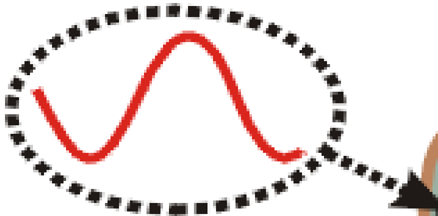
http://www.eirgrid.com/operations/ds3/

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

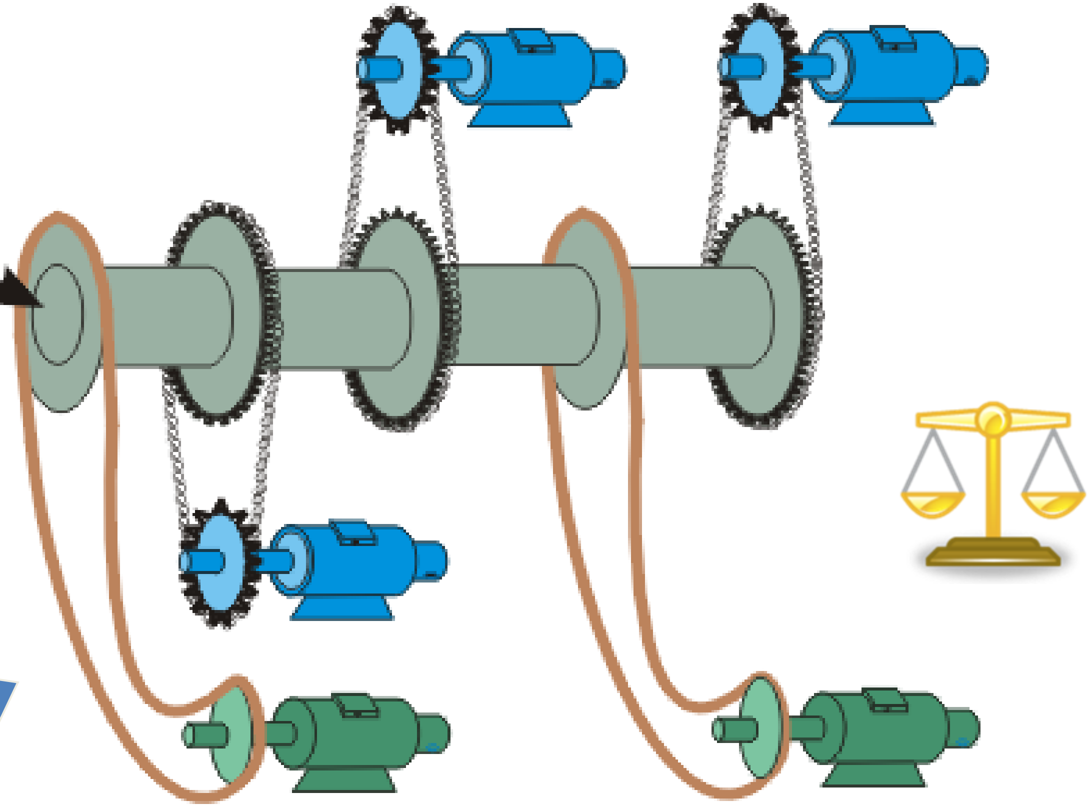
Synchronous systems in Europe

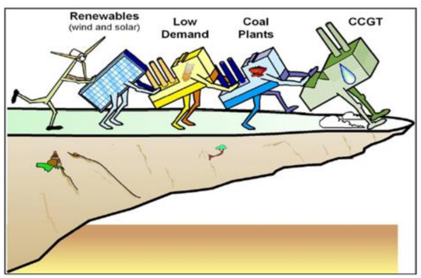
Adding non-synchronous generation

50/60 Hz



Synchronous generator



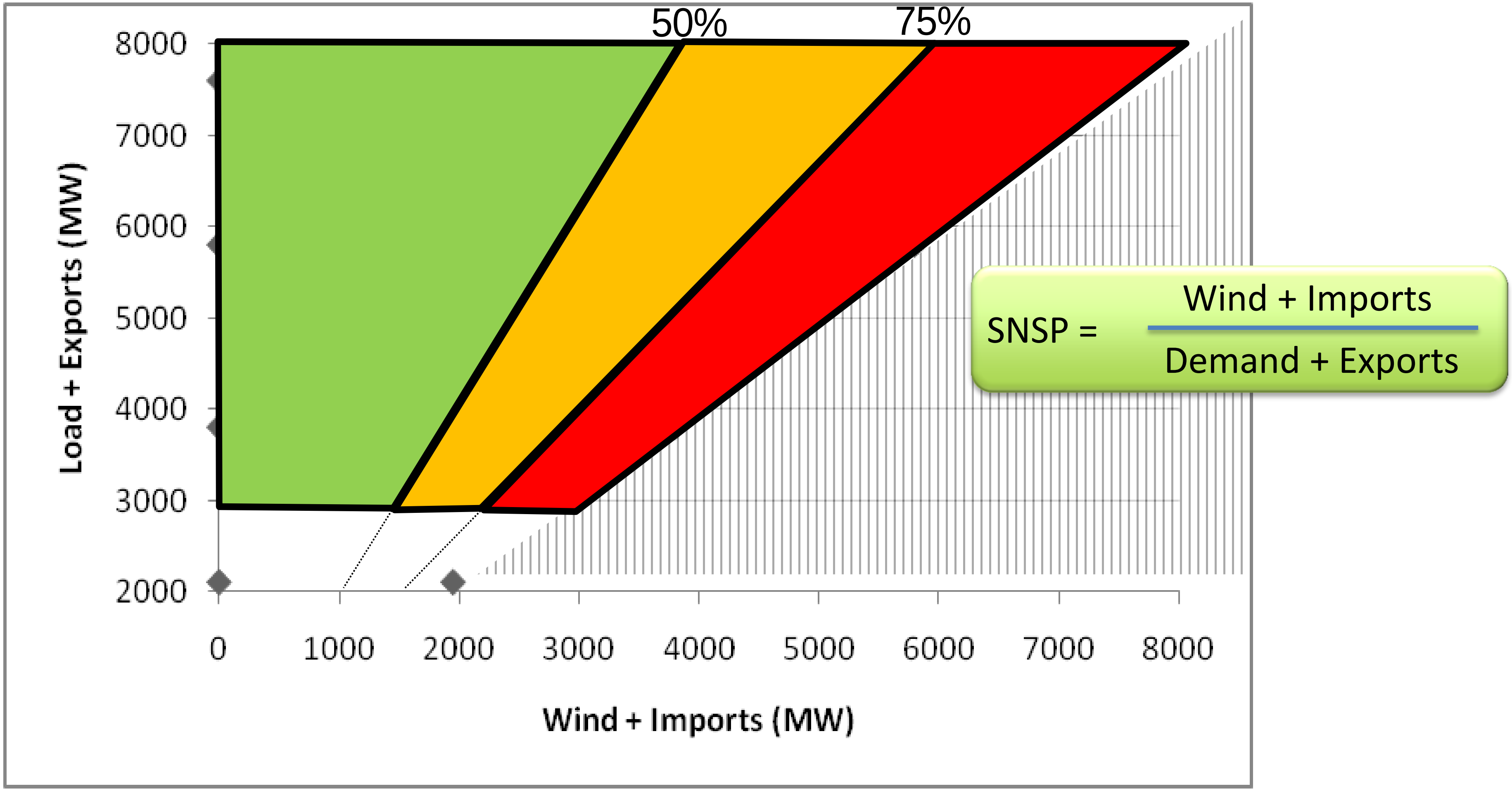


Does not add
to system inertia

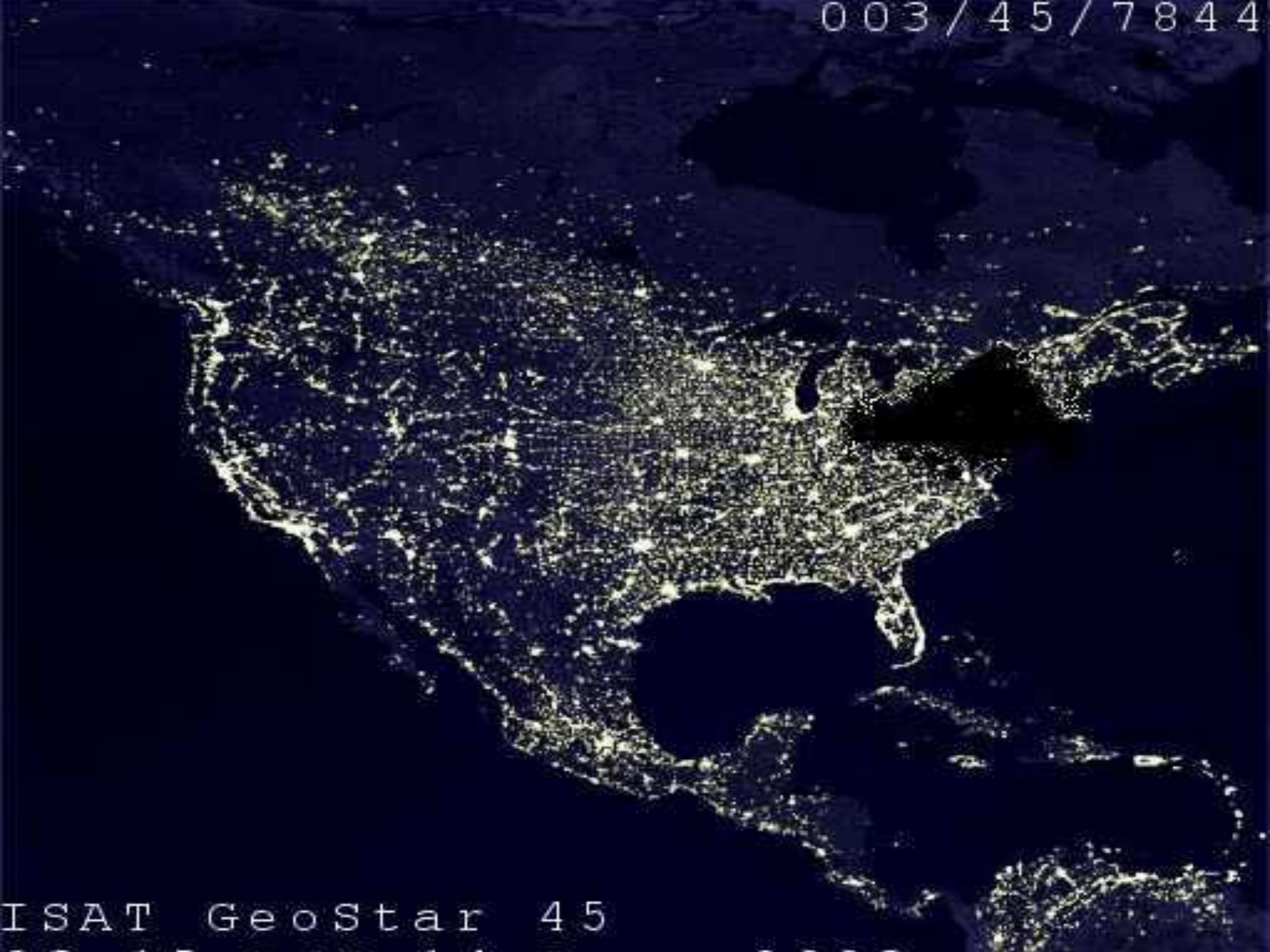
Doubly fed induction generator wind turbine

Fixed speed wind turbine generator

System Non-Synchronous Penetration (SNSP)



O'Sullivan, J., Rogers, A., Flynn, D., Smith, P., Mullane, A., and O'Malley, M.J., "Studying the Maximum Instantaneous Non-Synchronous Generation in an Island System – Frequency Stability Challenges in Ireland", *IEEE Transactions on Power Systems*, Vol. 29, pp. 2943 – 2951, 2014.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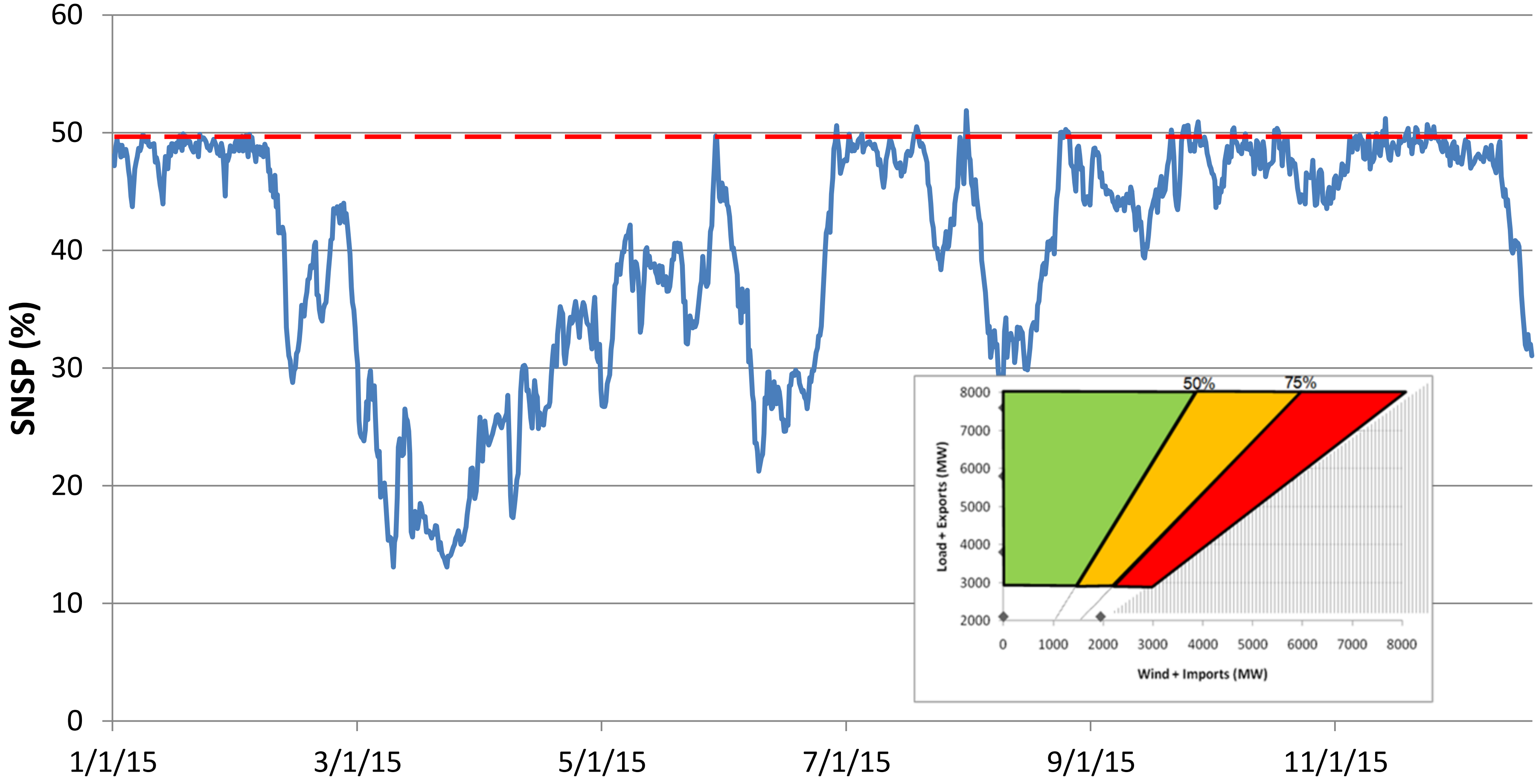
SNSP – Early 2015



Mainland Europe & US

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Western Wind and Solar Integration Study Phase 3 – Frequency Response and Transient Stability

N.W. Miller, M. Shao, S. Pajic, and R. D'Aquila
GE Energy Management
Schenectady, New York

NREL Technical Monitor: Kara Clark

Link to Executive Summary

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Subcontract Report
NREL/SR-5D00-62906
December 2014

Contract No. DE-AC36-08GO28308

http://www.nrel.gov/docs/fy15osti/62906.pdf

Pushing the Limits

Europe's New Grid: Innovative Tools to Combat Transmission Bottlenecks and Reduced Inertia

By Wilhelm Winter, Katherine Elkington, Gabriel Bareux, and Jan Kostevc

Digital Object Identifier 10.1109/MPE.2014.2363534
Date of publication: 7 January 2015

IN THE FUTURE A GROWING AMOUNT OF POWER electronics will lead to a transition of the power system to a structure with very low synchronous generation. Due to large transit power flows and uncertainties, transmission systems are being operated under increasingly stressed conditions and are close to their stability limits. Together with the integration of large amounts of renewable generation with power electronic interfaces and the addition of high-voltage direct current (HVdc) links into the power system, these challenges will necessitate a review of the operation and control of transmission networks. This article will demonstrate the need for R&D performed by network operators and explain a set of challenges, focusing on three main areas: transmission grid operation in a new power system environment, the need to increase overhead line (OHL) utilization, and the impact of reduced inertia on power system frequency.

Transmission Grid Operation in a New Power System Environment

The tools currently in use by transmission system operators (TSOs) for operational planning and system operation must evolve significantly to work in an environment characterized by large-scale integration of renewable energy sources with low predictability and limited controllability as well as one that is close to its stability limits. The insertion of new equipment such as phase shifters and HVdc lines and the development of an integrated European electricity market with huge power flows over large distances will bring further challenges. These challenges are unprecedented, but fortunately the European Wind Integration Study (EWIS) project, finalized in 2010

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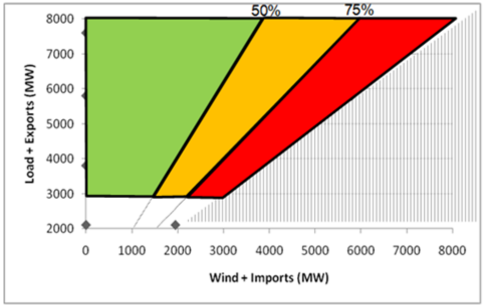
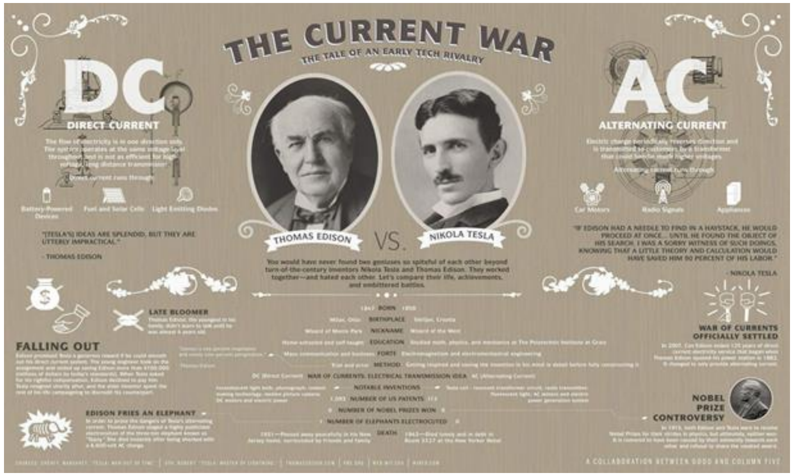
Future > 75 % SNSP



50/60 Hz ?



6124 IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 29, NO. 11, NOVEMBER 2014

Synchronization of Parallel Single-Phase Inverters With Virtual Oscillator Control

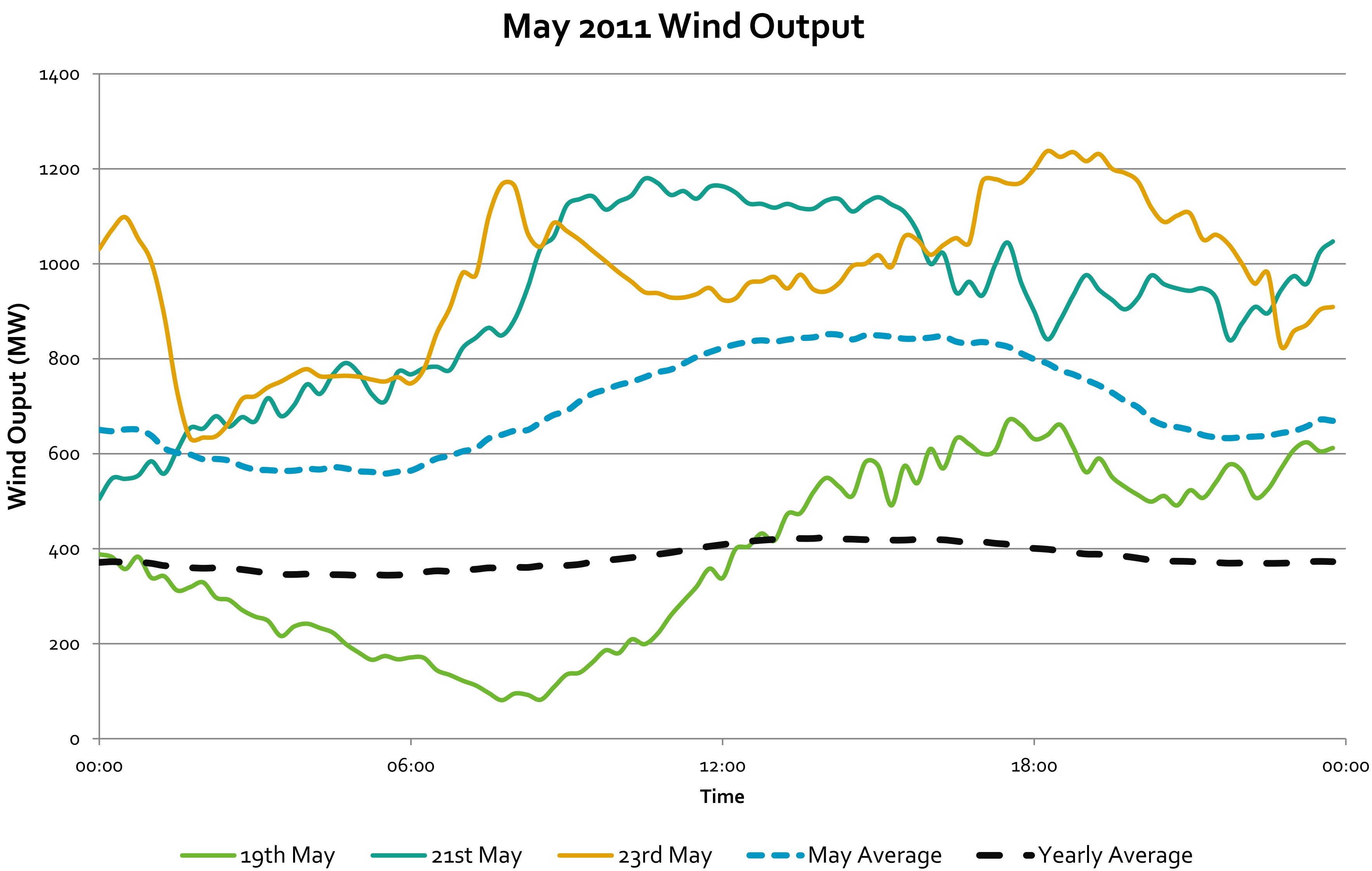
Brian B. Johnson, *Member, IEEE*, Sairaj V. Dhople, *Member, IEEE*, Abdullah O. Hamadeh, and Philip T. Krein, *Fellow, IEEE*

Key Take Aways

- Ireland has the highest penetration of non-synchronous generation in the "world"
  - Power system dynamics is the limitation
  - We will get to 75 % SNSP soon
  - Going beyond 75 % SNSP – game changing

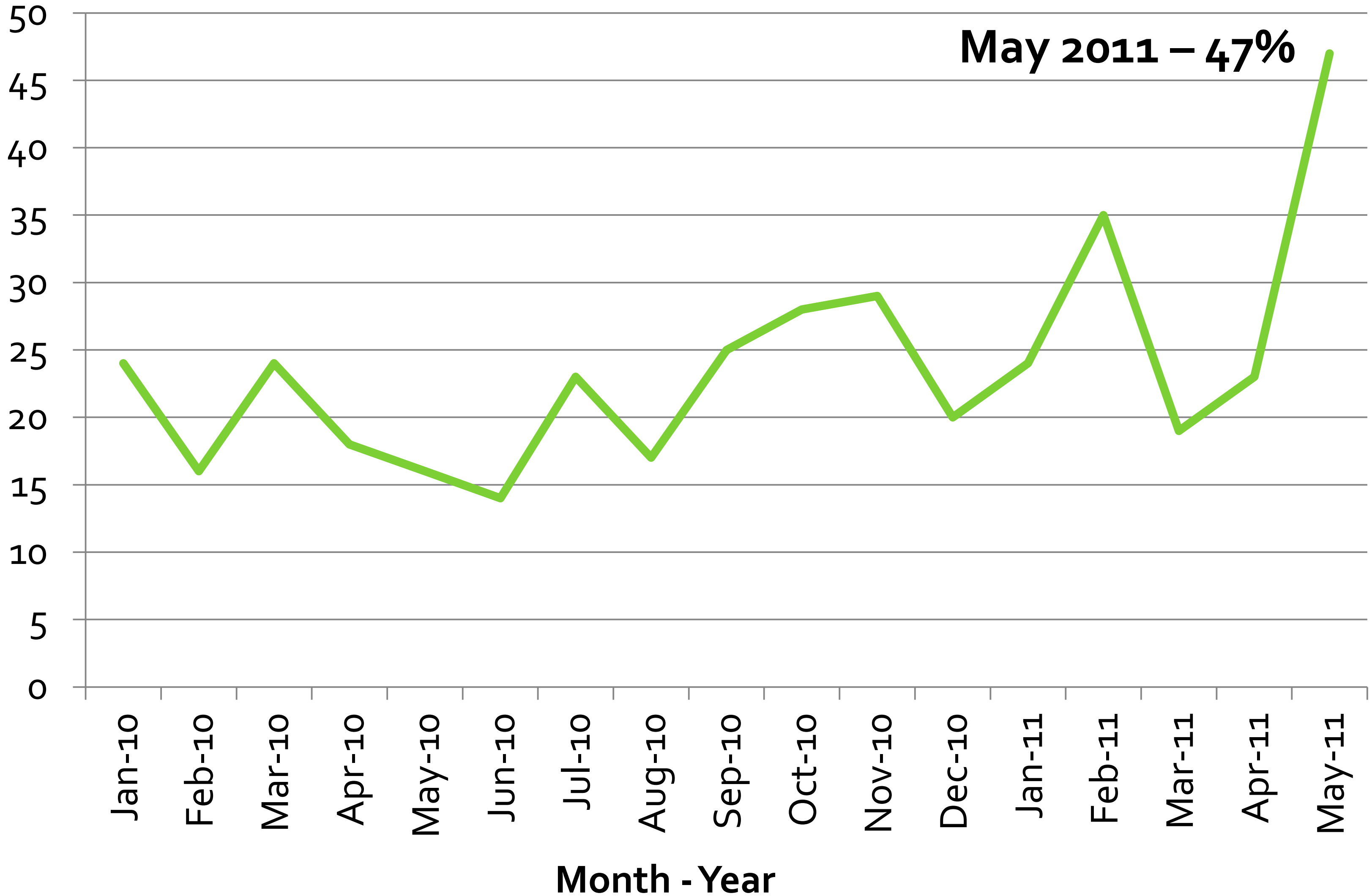
Variable Renewable Energy Resource Characteristics

Wind Generation Hourly Variability



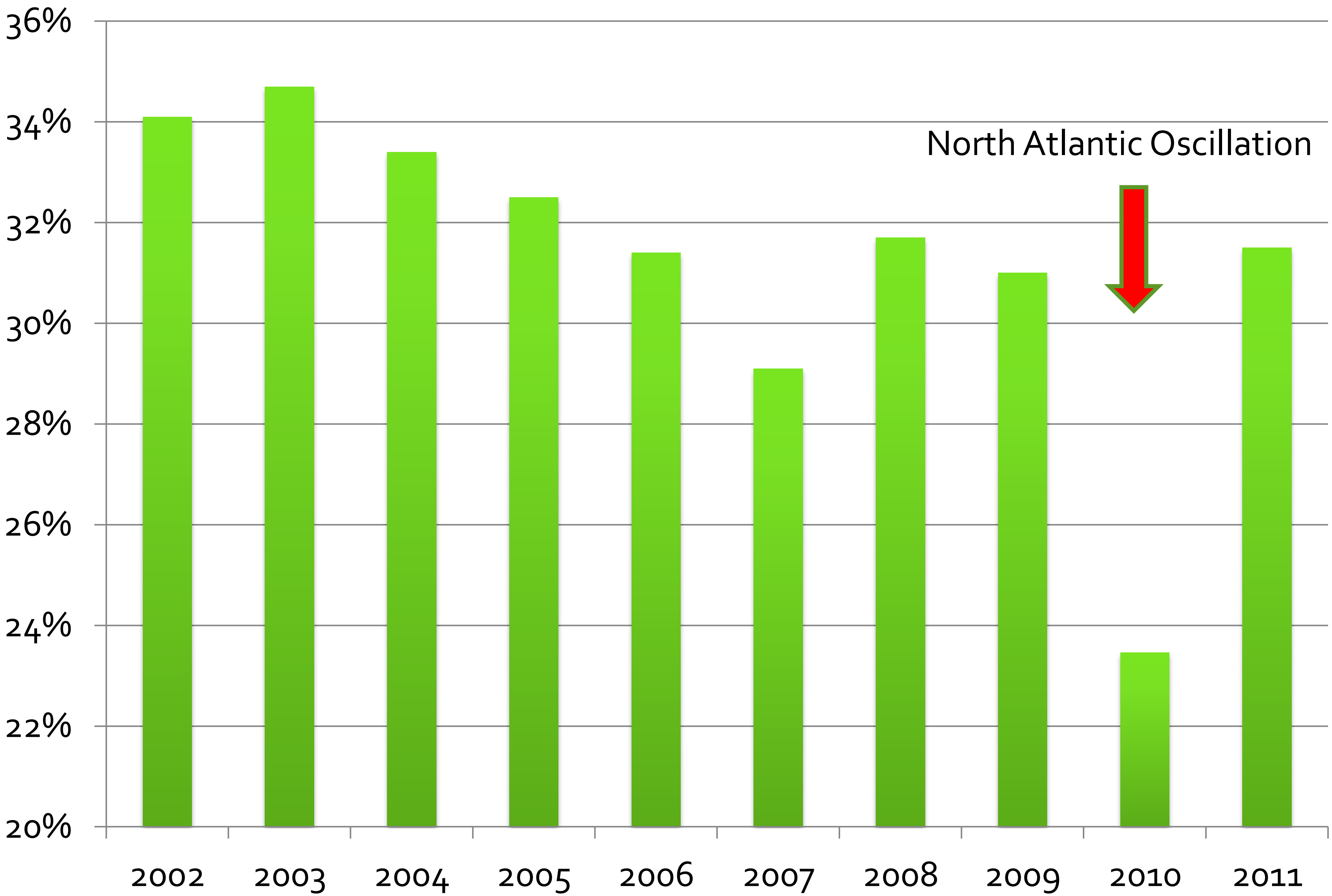
Source: EirGrid

Monthly Variability Capacity Factor – Ireland



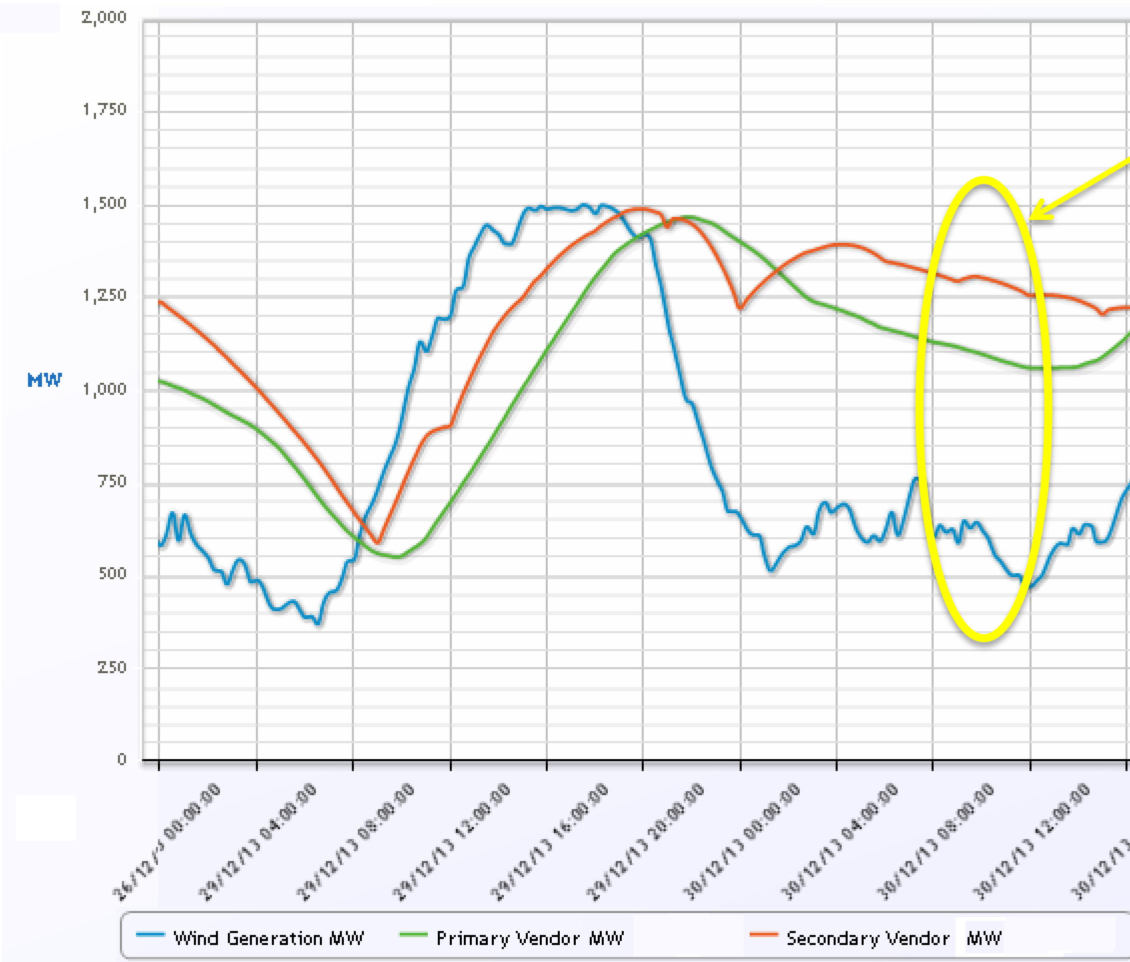
Source: EirGrid

Yearly Variability - Capacity Factor - Ireland



Source: EirGrid

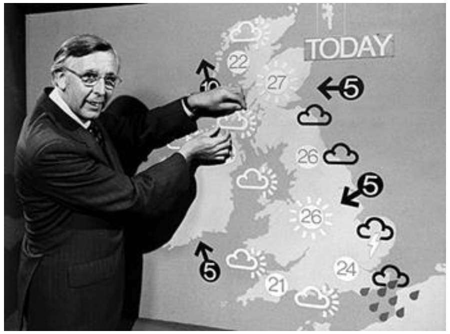
Wind Forecasting



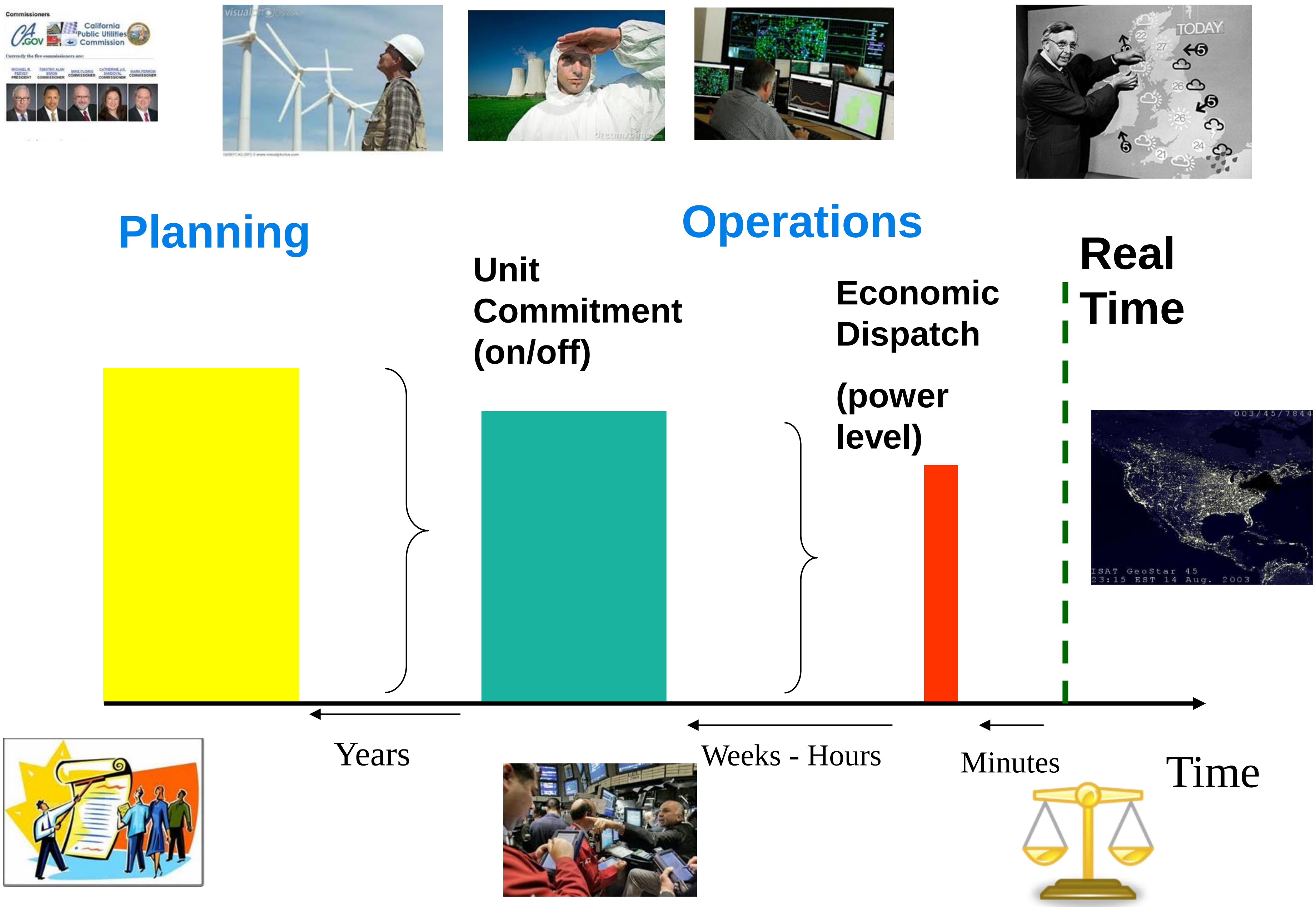
07:00 on 30th Dec

- Forecasted Values:
  Primary – 1150 MW
  Secondary – 1340 MW

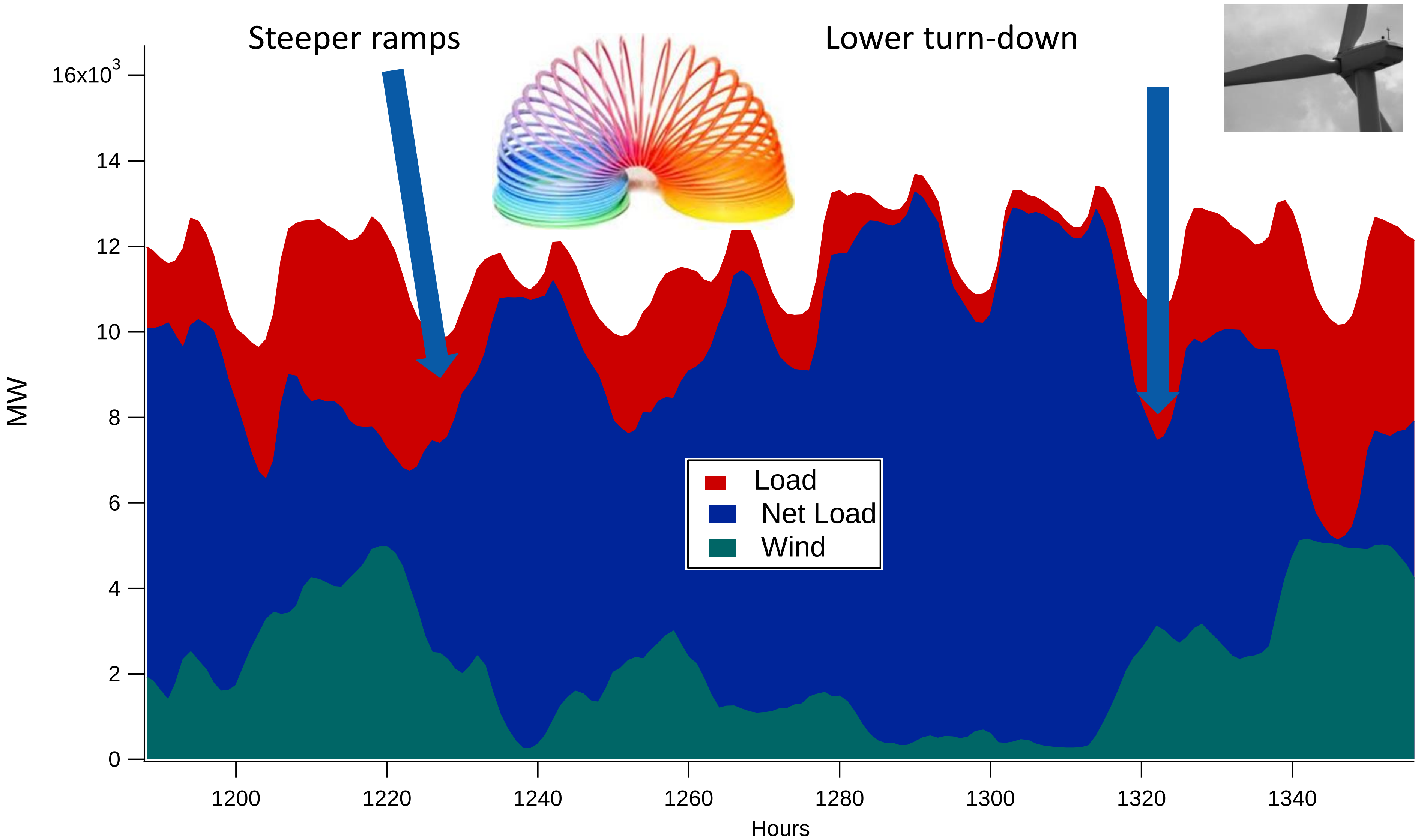
- Actual Wind: 725 MW



Uncertain across all time scales

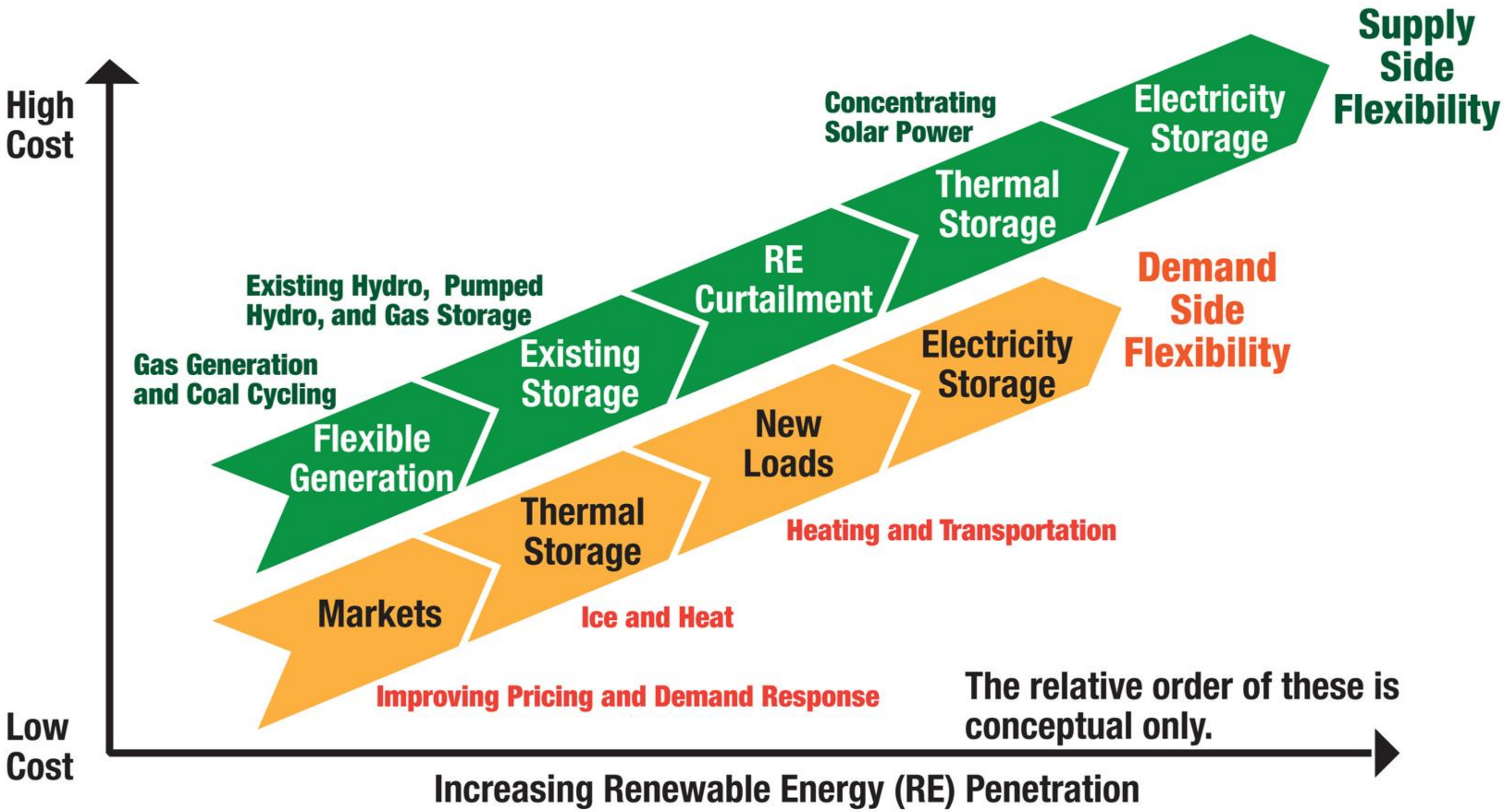


With Variable Renewables More Flexibility is Needed



Source: Michael Milligan , NREL

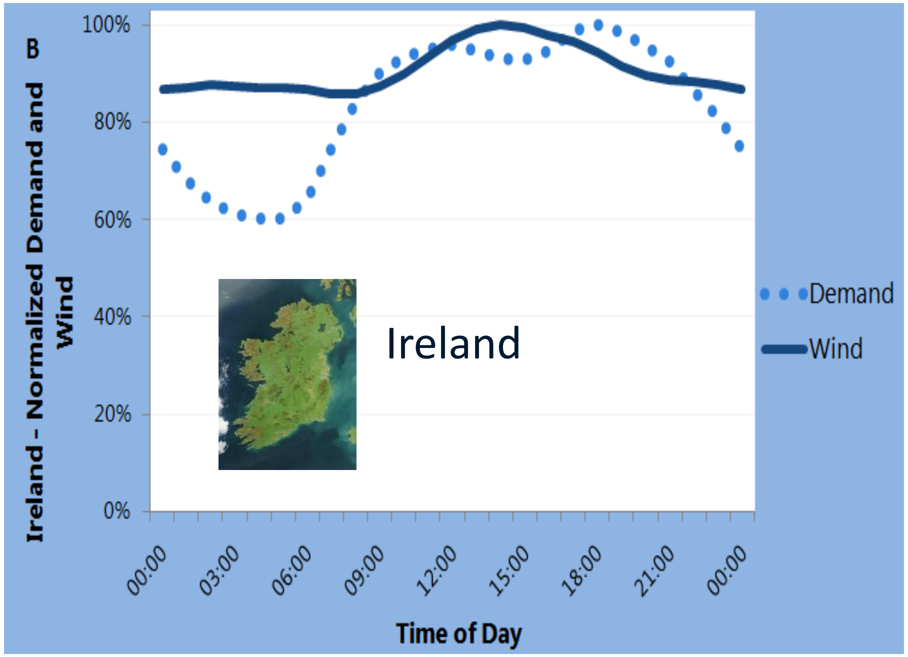
System Flexibility Supply Curve

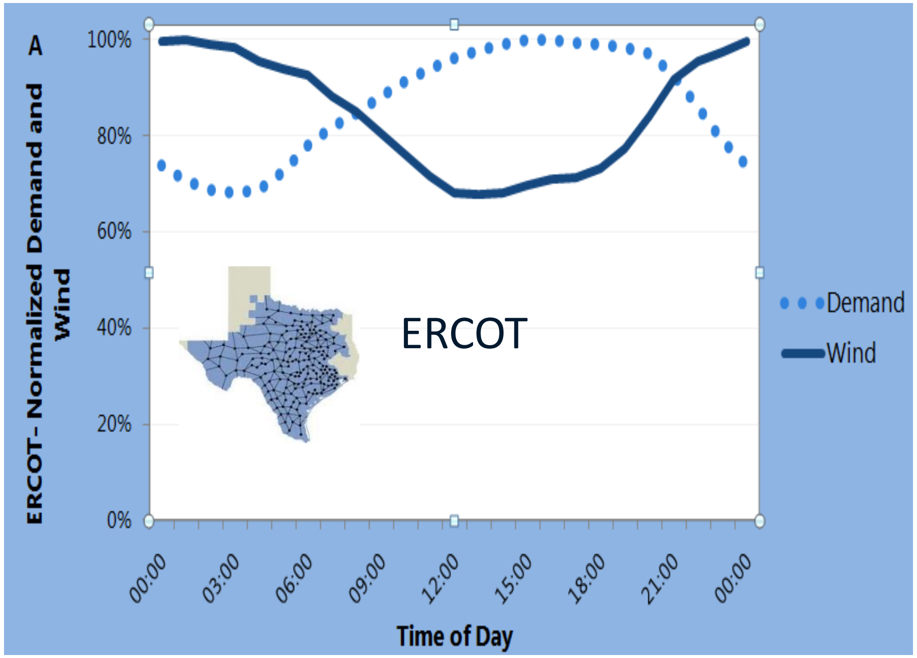


How do we choose the optimum mix of flexibility resources?

Renewable energy and load (demand) characteristics

Dance partners

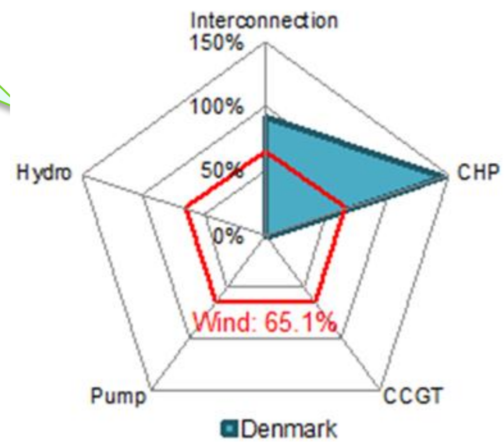




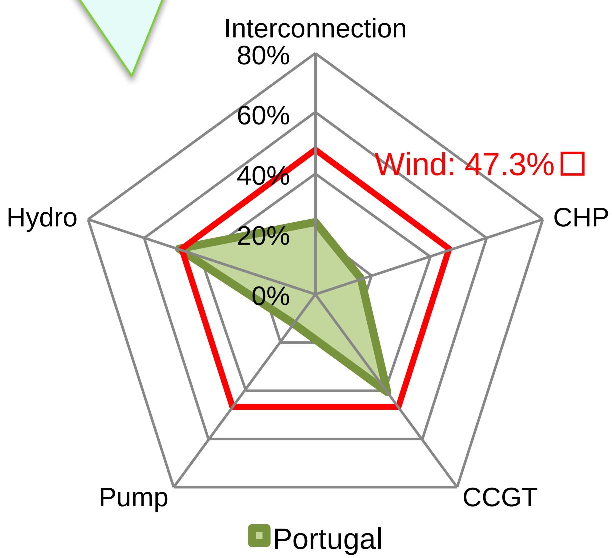
AEMO, Australian Energy Market Operator, “Wind Integration In Electricity Grids: International Practice And Experience” Work Package 1, 2011.
http://www.aemo.com.au/~/media/Files/Other/planning/0400-0049%20pdf.pdf

Flexibility chart

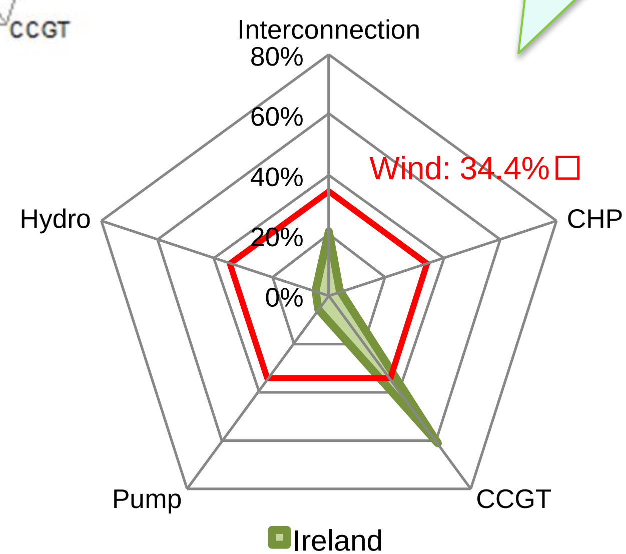
Denmark(Interconnection-oriented)



Portugal (Hydro-oriented)

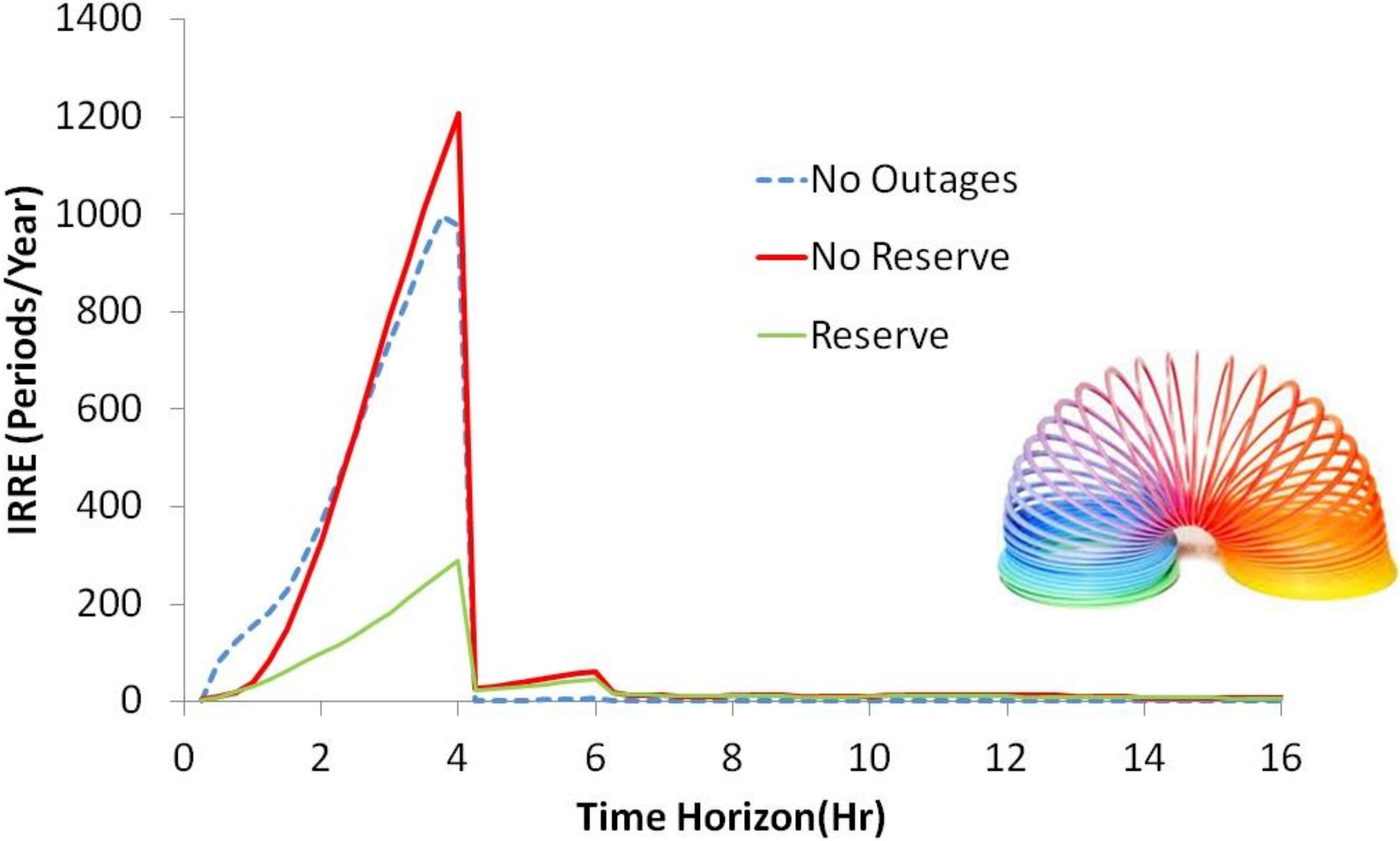


Ireland (CCGT-oriented)



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

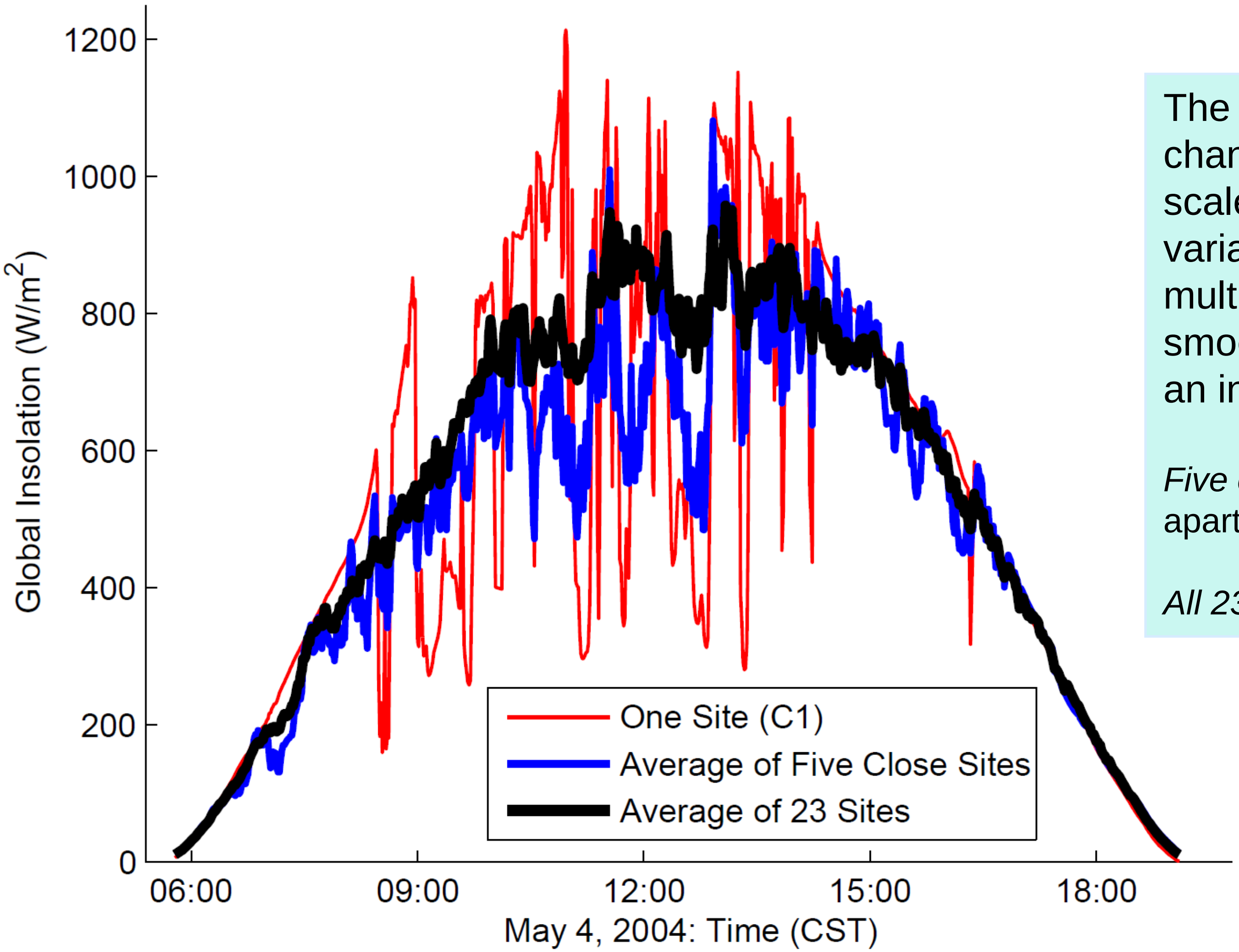
Flexibility Metric



Lannoye, E., Flynn, D. and O'Malley, M.J. "Transmission, variable generation and power system flexibility”, *IEEE Transactions on Power Systems*, Vol. 30, pp. 57 – 64, 2014.
Lannoye, E., Flynn, D., O’Malley, M., “Evaluation of Power System Flexibility” *IEEE Transactions on Power Systems*, Vol. 27, pp. 922 – 931, 2012.

If you love wind/solar you have to at least like Transmission

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.

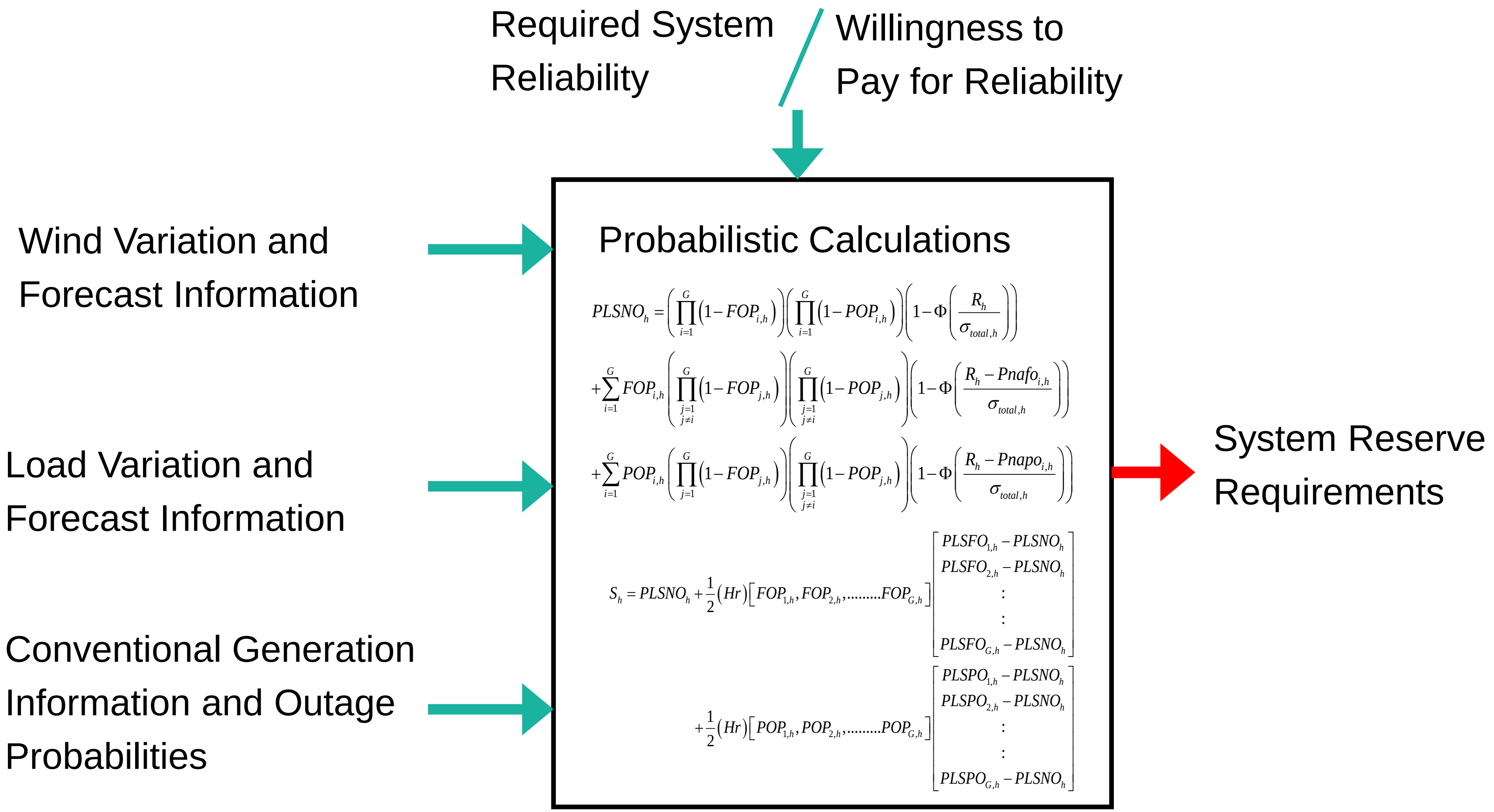
Five closest sites: 50 – 170 km apart

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

Reserve calculations



$$PLSNO_h = \left(\prod_{i=1}^{G}\left(1-FOP_{i,h}\right)\right)\left(\prod_{i=1}^{G}\left(1-POP_{i,h}\right)\right)\left(1-\Phi\left(\frac{R_h}{\sigma_{total,h}}\right)\right)$$

$$+\sum_{i=1}^{G} FOP_{i,h}\left(\prod_{\substack{j=1\\ j\neq i}}^{G}\left(1-FOP_{j,h}\right)\right)\left(\prod_{\substack{j=1\\ j\neq i}}^{G}\left(1-POP_{j,h}\right)\right)\left(1-\Phi\left(\frac{R_h - Pnafo_{i,h}}{\sigma_{total,h}}\right)\right)$$

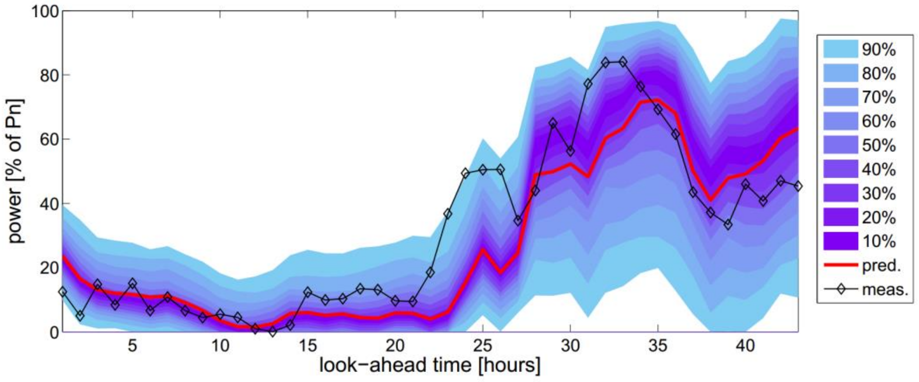
$$+\sum_{i=1}^{G} POP_{i,h}\left(\prod_{j=1}^{G}\left(1-FOP_{j,h}\right)\right)\left(\prod_{\substack{j=1\\ j\neq i}}^{G}\left(1-POP_{j,h}\right)\right)\left(1-\Phi\left(\frac{R_h - Pnapo_{i,h}}{\sigma_{total,h}}\right)\right)$$

$$S_h = PLSNO_h + \frac{1}{2}(Hr)\left[FOP_{1,h}, FOP_{2,h}, ...FOP_{G,h}\right]\begin{bmatrix} PLSFO_{1,h} - PLSNO_h \\ PLSFO_{2,h} - PLSNO_h \\ : \\ : \\ PLSFO_{G,h} - PLSNO_h \end{bmatrix}$$

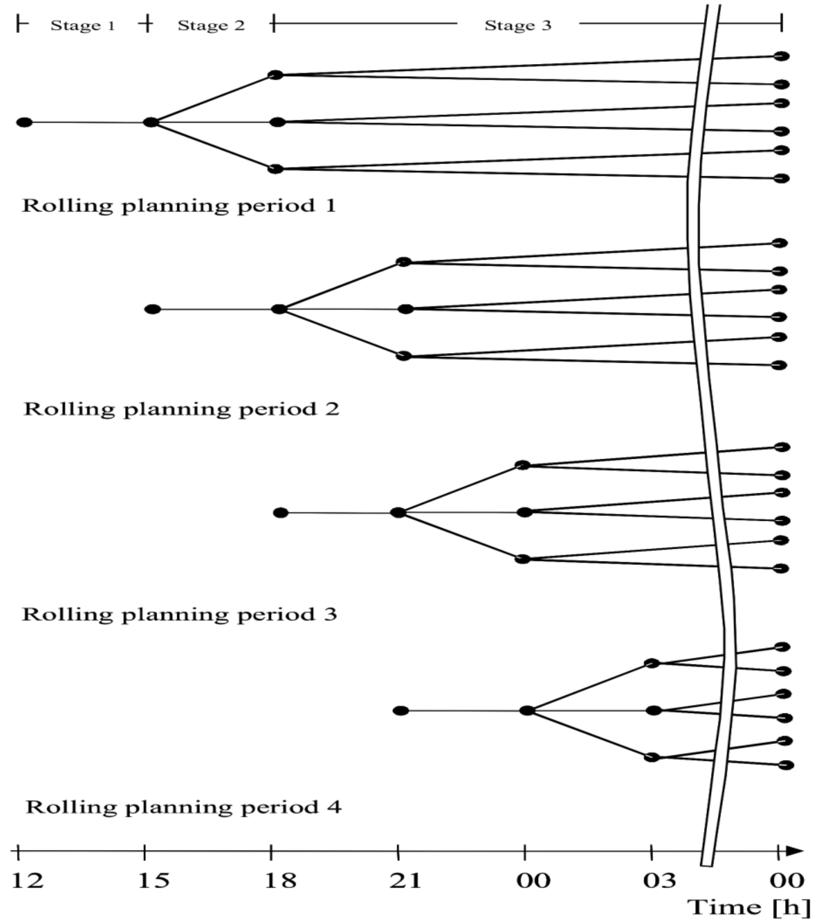
$$+\frac{1}{2}(Hr)\left[POP_{1,h}, POP_{2,h}, ...POP_{G,h}\right]\begin{bmatrix} PLSPO_{1,h} - PLSNO_h \\ PLSPO_{2,h} - PLSNO_h \\ : \\ : \\ PLSPO_{G,h} - PLSNO_h \end{bmatrix}$$

Doherty, R. and O'Malley, M.J., "New approach to quantify reserve demand in systems with significant installed wind capacity", *IEEE Transactions on Power Systems*", Vol. 20, pp. 587 -595, 2005.

Forecasting & Stochastic Unit Commitment



Pinson, P., Madsen, H, Nielsen, H., Papaefthymiou, G. and Klöckl, B., From probabilistic forecasts to statistical scenarios of short-term wind power production, Wind Energy, volume 12, issue 1, January 2009



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.

Scheduling for uncertainty and variability

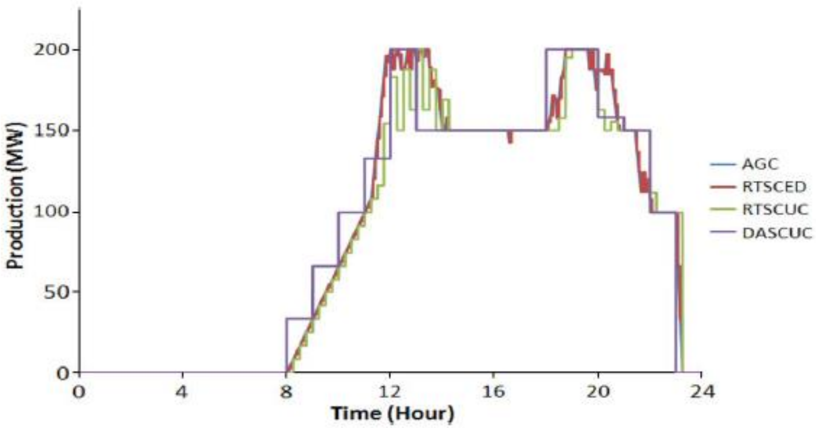
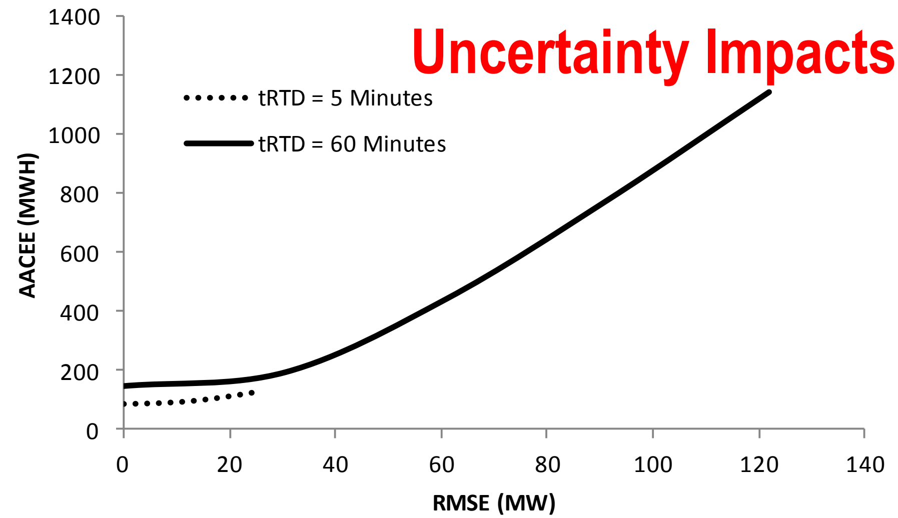
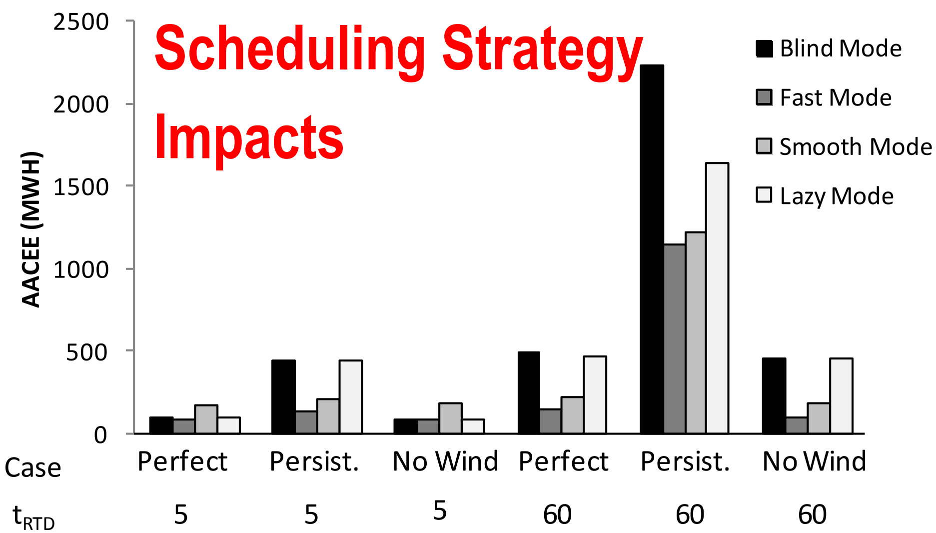
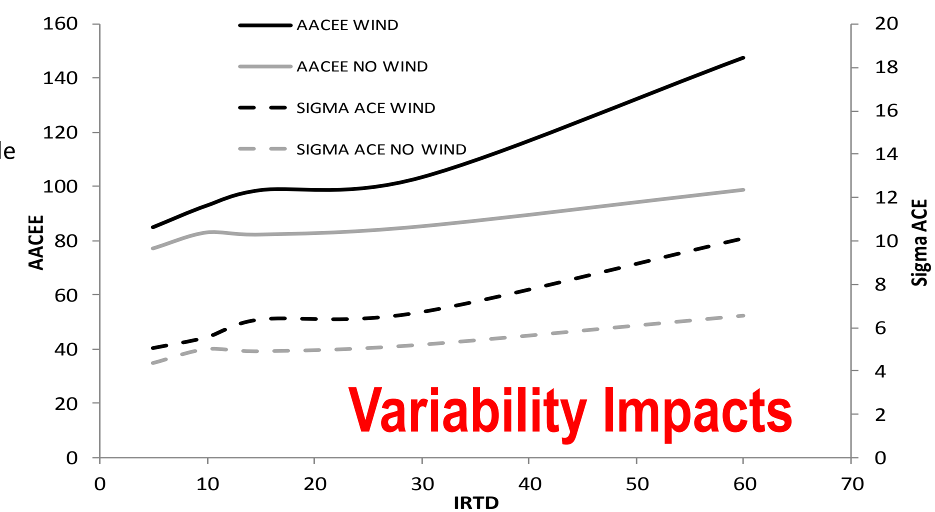


Fig. 3. Example generation production for all sub-models.



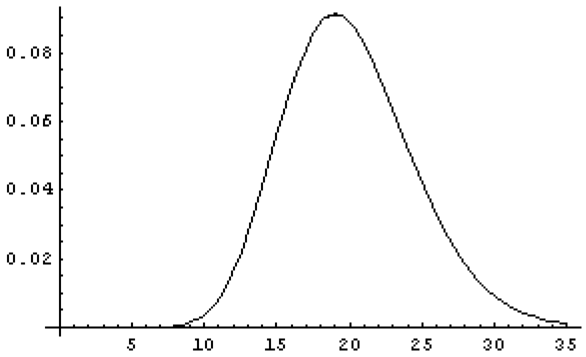




Ela, E and O'Malley, M.J., "A Flexible Power System Operations Model for Studying Variable Generation Integration", *IEEE Transactions on Power Systems*, Vol. 27, pp. 1324 – 1333, 2012.

Curtailment – what is healthy

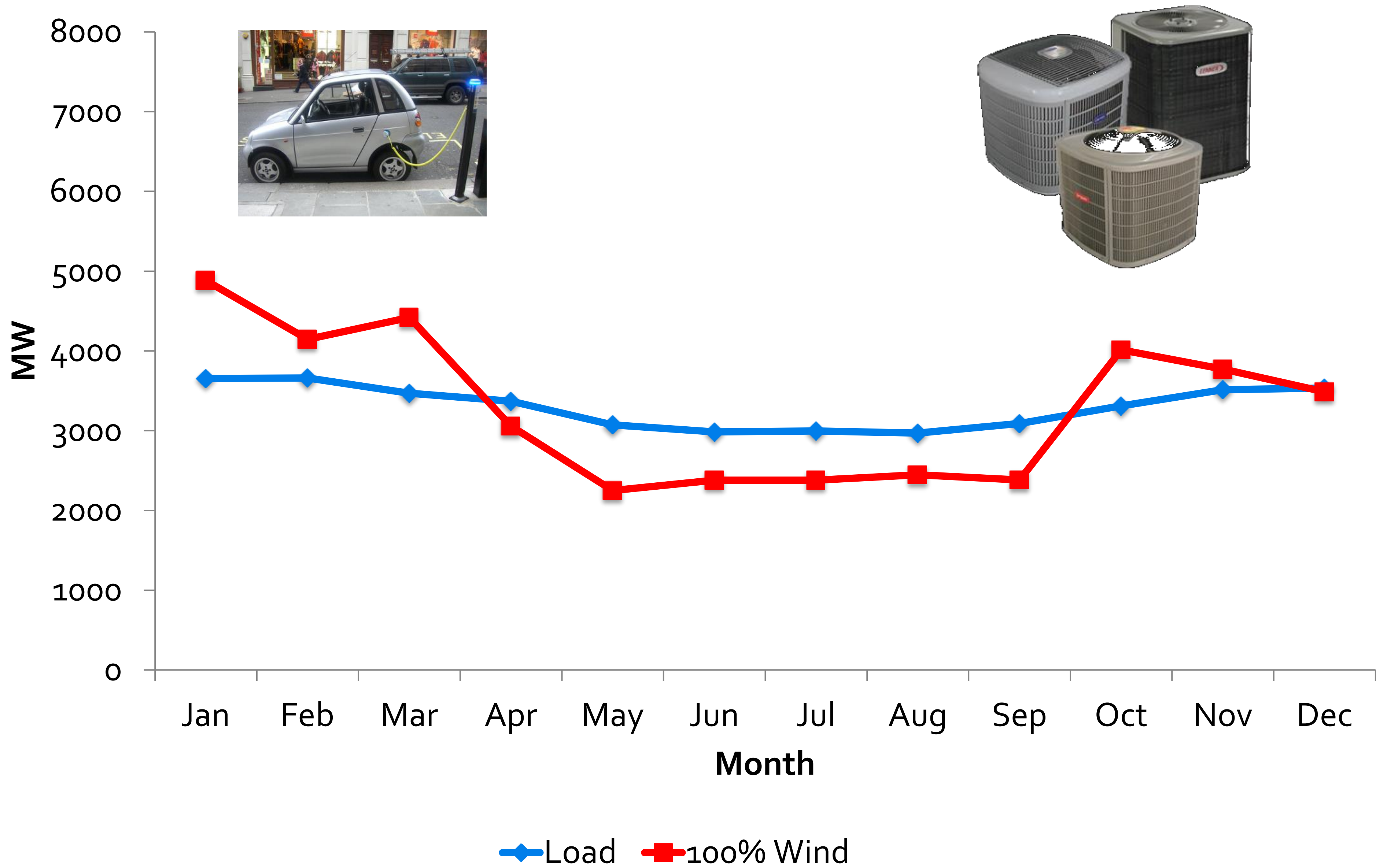
- Wind curtailment in Texas was 8 % in 2010 and 17 % in 2009 mainly due to lack of transmission (Wiser and Bollinger, 2011). It was this type of high levels of curtailment in the early part of the century that spurred Texas to initiate a proactive scheme to alleviate this problem.



- 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

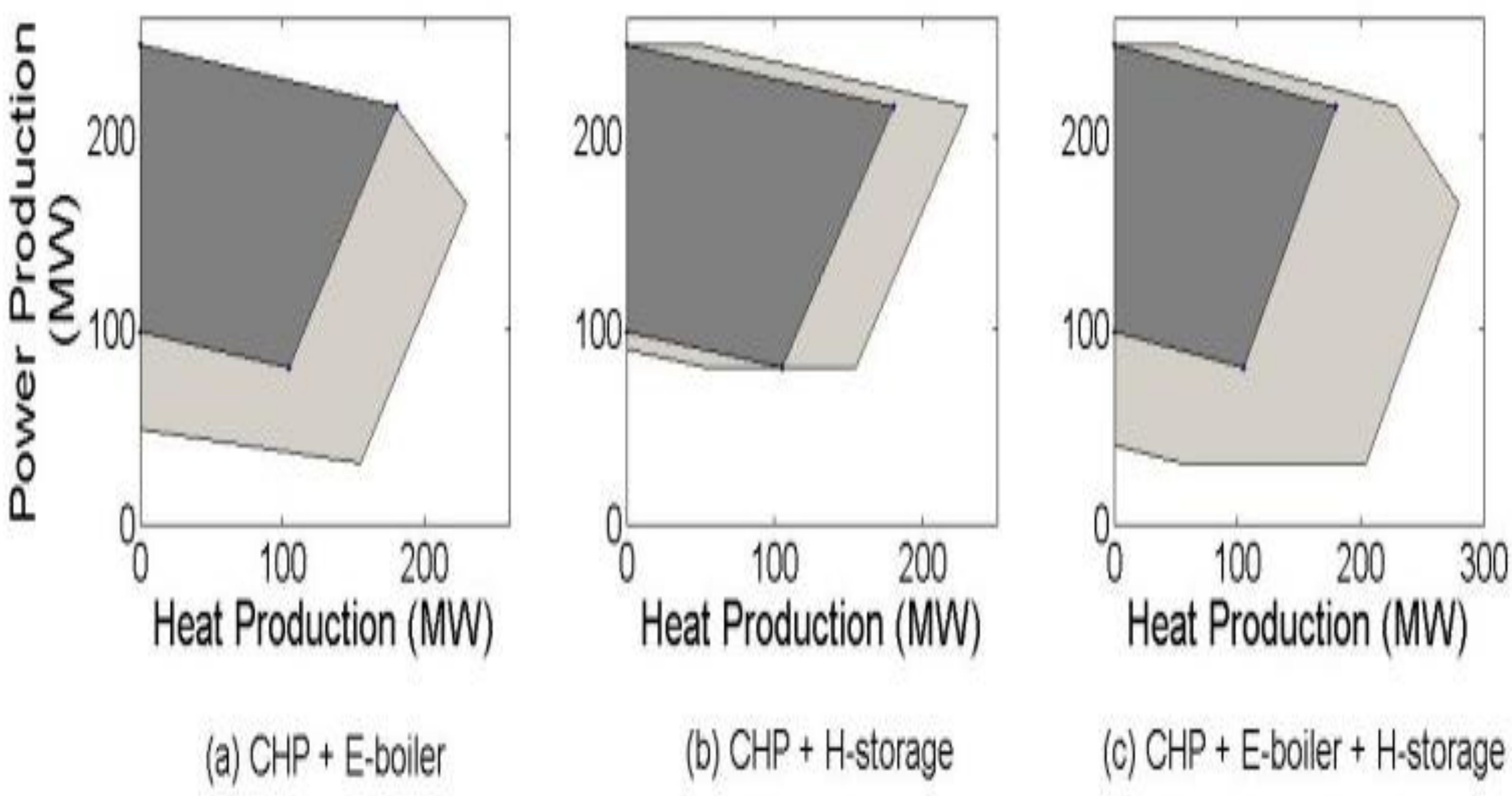
100 % Wind we will have to change how we live



Storage Applications & Competitors

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.

Combined heat and power (CHP) can be made flexible



X. Chen, C. Kang, Q. Xia, B. Jianhua, L.Chun, L. Ji, R. Sun, L. Hui and M.J. O'Malley, "Increasing the Flexibility of CHP with Heat Storage and Electrical Boilers for Wind Power Integration in China: Modeling and Implications", *IEEE Transactions on Power Systems*, in press, 2014.

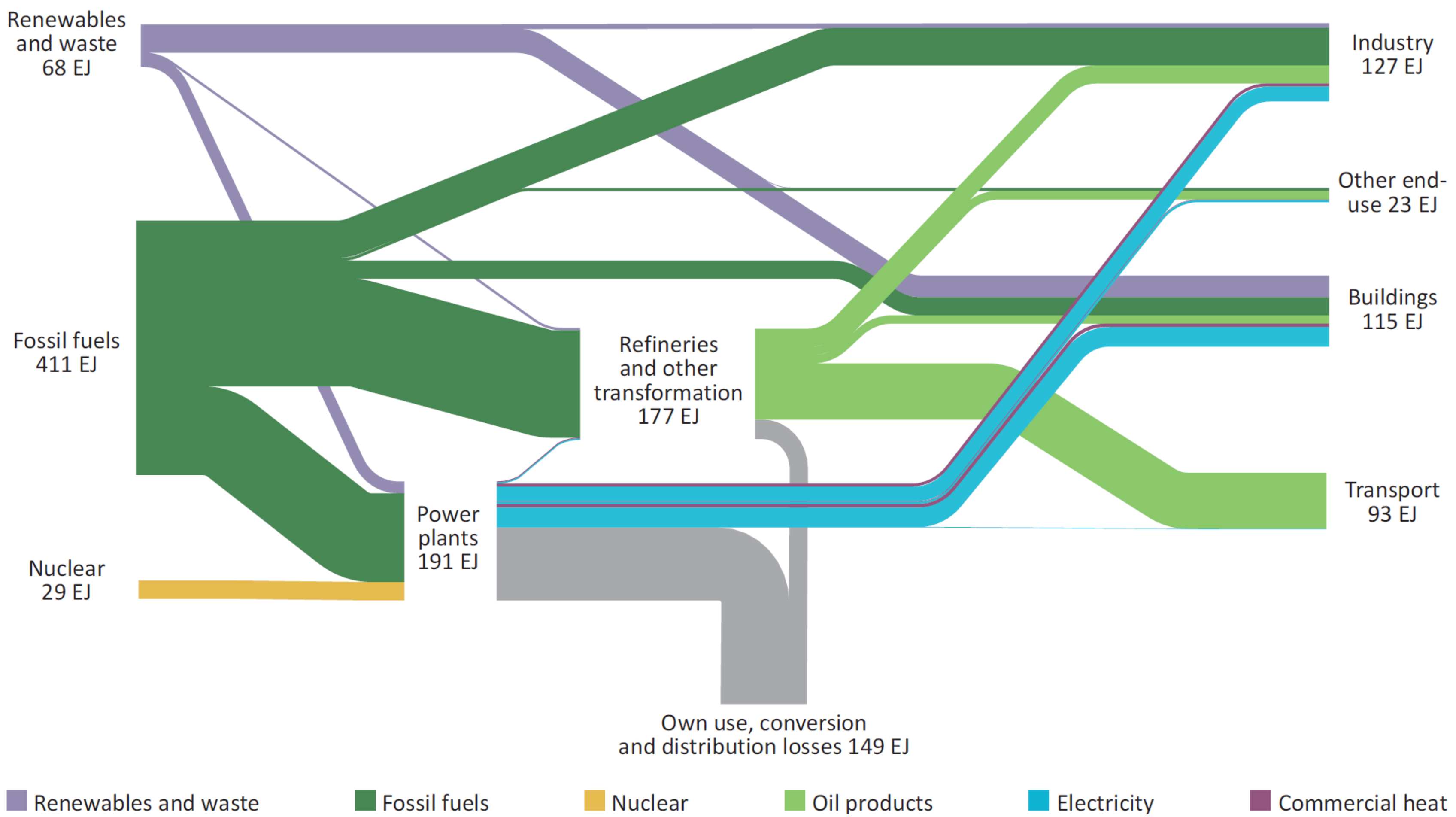
Key Take Away

- Variable renewables uncertain across all time scales
  - Supply demand balance is critical

- Flexibility is the key characteristic to integration variable renewable energy
  - Very difficult to quantify
  - Transmission is the critical element
  - Some curtailment is healthy
  - Correlation of the resource with load
  - Flexibility is not just physical
  - Demand side flexibility may impact on how we organize society
  - Storage is still expensive and has competition
  - Sources of flexibility for electricity can be in other parts of the energy system

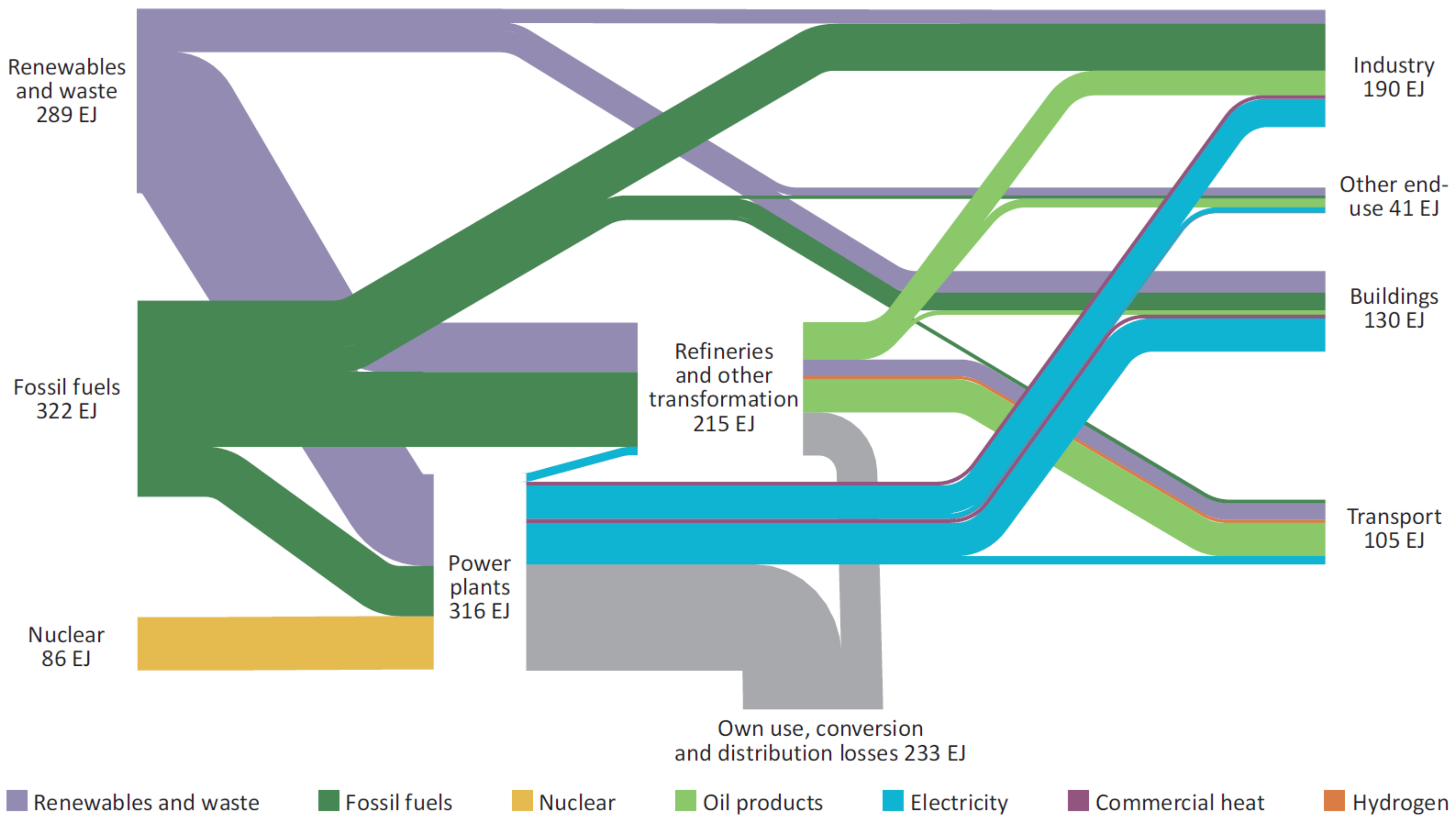
Energy Systems Integration

The global energy system today



Dominated by fossil fuels in all sectors: (Source IEA)

The future low-carbon energy system



The 2DS in 2050 shows a dramatic shift in energy sources and demands: (Source IEA)

Energy Systems Integration (ESI)

Optimizes the integrated suite of electrical, thermal, and fuels pathways at all scales

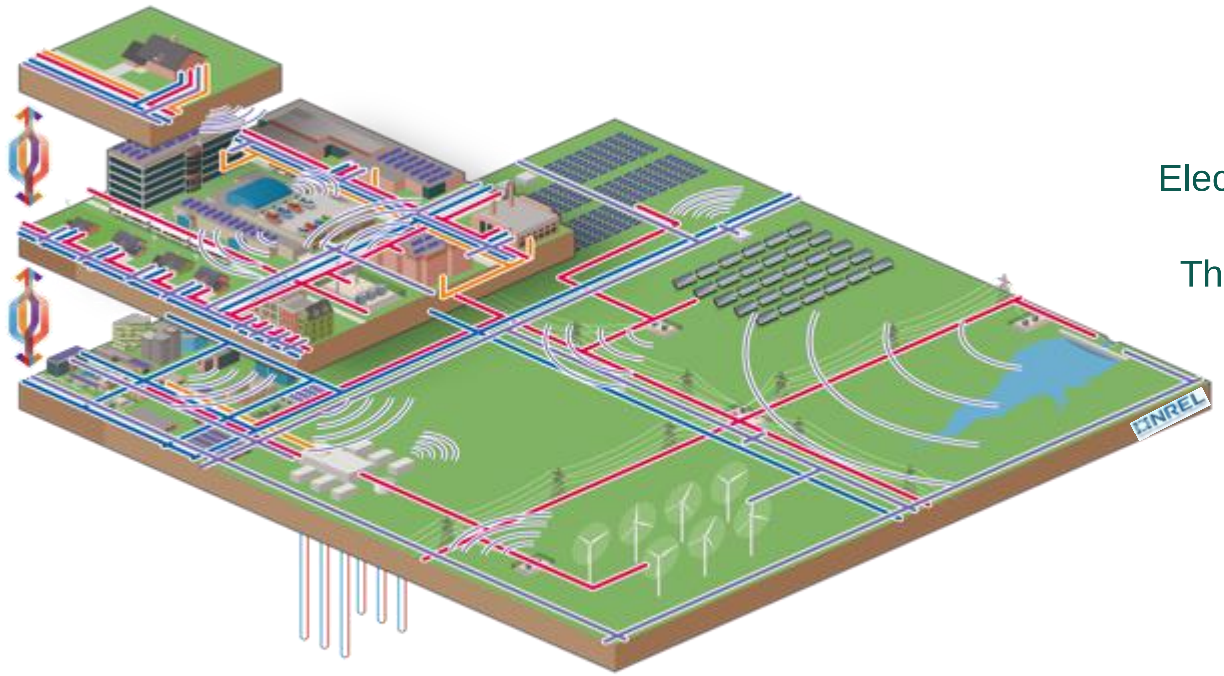
Energy Source

Fossil | Nuclear | Renewable

Single Technologies and Locations

Campus, City Community

Regional, National, Continental



Electricity

Thermal

Fuels

Data

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Residential | Commercial | Industry | Mobility

Energy Use Sector

focused on the interfaces where the coupling and interactions are strong and represent a challenge and/or an opportunity.

Energy Systems & Water

Part 2

Energy Systems

Part 2 analyses, from three different angles, the interdependency of energy technologies, and the value of increased integration for the energy system as it is decarbonised. Chapter 5 focuses on heating and cooling with the link between heat and electricity

International Energy Agency

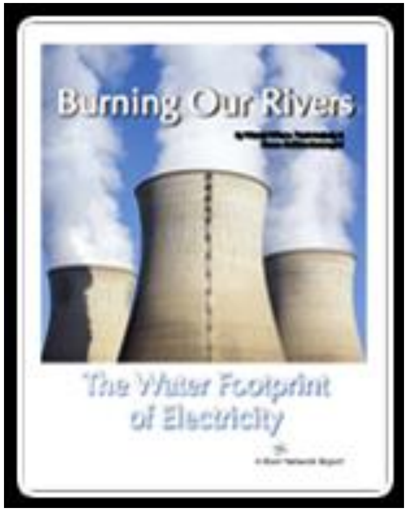
Chapter 17

Water for energy

Is energy becoming a thirstier resource?

Highlights

- Energy depends on water – for power generation, the extraction, transport and processing of fossil fuels, and the irrigation of biofuels feedstock crops – and is vulnerable to physical constraints on its availability and regulations that might limit access to it. A more water-constrained future, as population and the global economy grow and climate change looms, will impact energy sector reliability and costs.
- Global water withdrawals for energy production in 2010 were estimated at 583 billion cubic metres (bcm), or some 15% of the world's total water withdrawals. Of that, water consumption – the volume withdrawn but not returned to its source – was 66 bcm. In the New Policies Scenario, withdrawals increase by about 20% between 2010 and 2035, but consumption rises by a more dramatic 85%. These trends are driven by a shift towards higher efficiency power plants with more advanced cooling



EIP Water

Boosting opportunities – Innovating water

EIP Water Action Group

W4EF

A framework for evaluation and reporting of the energy impacts on water

EIP Water Conference 2013

Networking & interacting – Innovating water

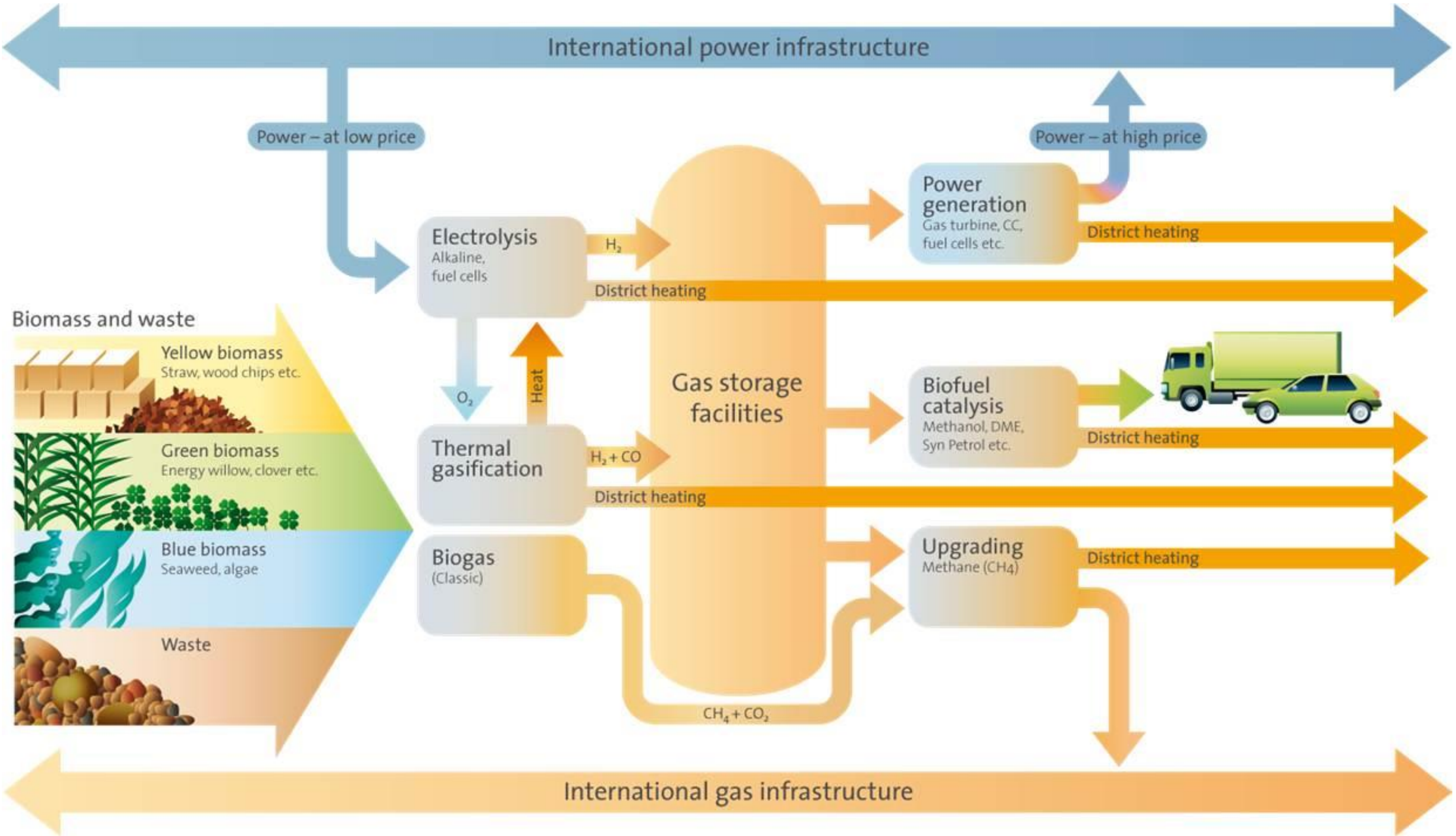
21 November 2013

EU Parliament, Brussels

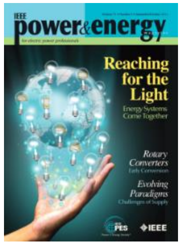
EDF

EPRI ELECTRIC POWER RESEARCH INSTITUTE

ESI in Denmark



Meibom, P.; Hilger, K.B.; Madsen, H.; Vinther, D., "Energy Comes Together in Denmark: The Key to a Future Fossil-Free Danish Power System," *Power and Energy Magazine, IEEE* , vol.11, no.5, pp.46,55, Sept. 2013. doi: 10.1109/MPE.2013.2268751



Policy Failures because they are not holistic

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Windmills Overload East Europe's Grid Risking Blackout: Energy

By Ladka Bauerova and Tino Andresen - Oct 26, 2012 12:01 AM GMT

15 COMMENTS QUEUE

Sean Gallup/Getty Images

Germany is dumping electricity on its unwilling neighbors and by wintertime the feud should come to a head.

Germany is dumping electricity on its unwilling neighbors and by wintertime the feud should come to a head.

- http://ec.europa.eu/energy/gas_electricity/studies/doc/electricity/201310_loop-flows_study.pdf

THEMA CONSULTING GROUP

Loop flows – Final advice

Prepared for The European Commission

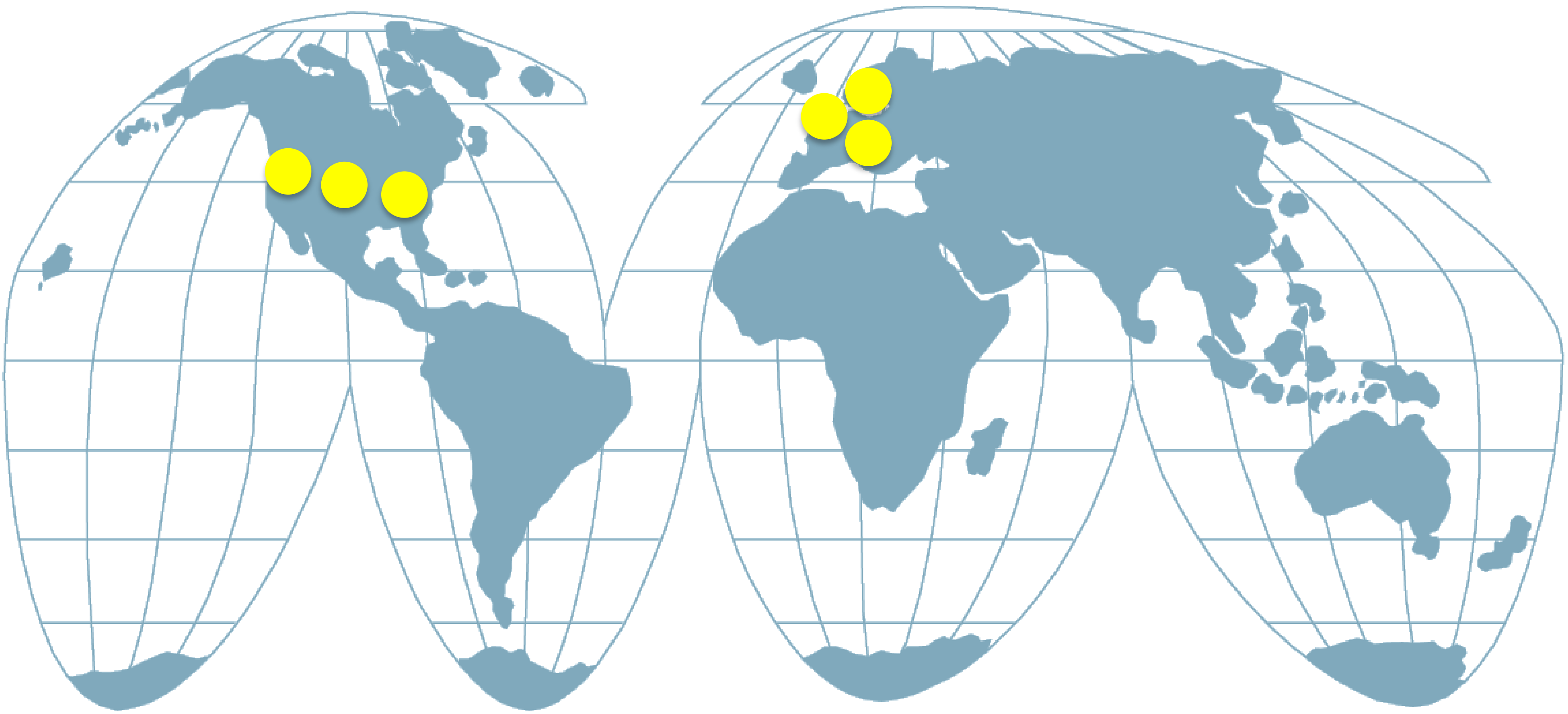
October 2013

THEMA Report 2013-36

iiESI International Institute for Energy Systems Integration

www.iiESI.org
iiesi@ucd.ie

Addressing energy challenges through global collaboration



NREL NATIONAL RENEWABLE ENERGY LABORATORY

Pacific Northwest NATIONAL LABORATORY

EPRI ELECTRIC POWER RESEARCH INSTITUTE

UCD DUBLIN

DTU

KU LEUVEN

Recently

International Institute for Energy Systems Integration

Summary of iiESI Workshop on ESI Research Challenges in London

March 30th and 31st

Imperial College London

The workshop brought together an experienced group of international research active people with a diverse range of expertise (see list of attendees below). The workshop was open and vibrant, (see agenda and briefing documents below) and while **the focus of the workshop was on identifying the research challenges in Energy Systems Integration (ESI),**

http://iiesi.org/assets/pdfs/iiesi_london_summary.pdf

Coming Soon

International Institute for Energy Systems Integration

Energy Systems Integration – Research Challenges

NREL, Colorado, USA
August 3rd to 7th, 2015

The International Institute of Energy Systems Integration presents a course on Energy Systems Integration (ESI). The course is informed by a recent workshop held in Imperial College London to identifying the key research challenges in ESI, hence the course is particularly suited for those with an interest in the future research challenges. The course also builds on previous courses held at NREL and KU Leuven, but are not deemed to be prerequisites.

Key Take Away

- It is more about the whole integrated energy system than ever before
  - Energy Systems Integration can reduce cost and uncertainty etc.
  - Consumer is central to it all - difficult

Conclusions

- Variable renewables (wind & solar PV) are uncertain (& variable) over all time scales

- Can integrate large amounts of variable renewable energy without much trouble
  - It is just good engineering

- Energy Systems Integration is critical to integrate very large amounts of variable renewable energy

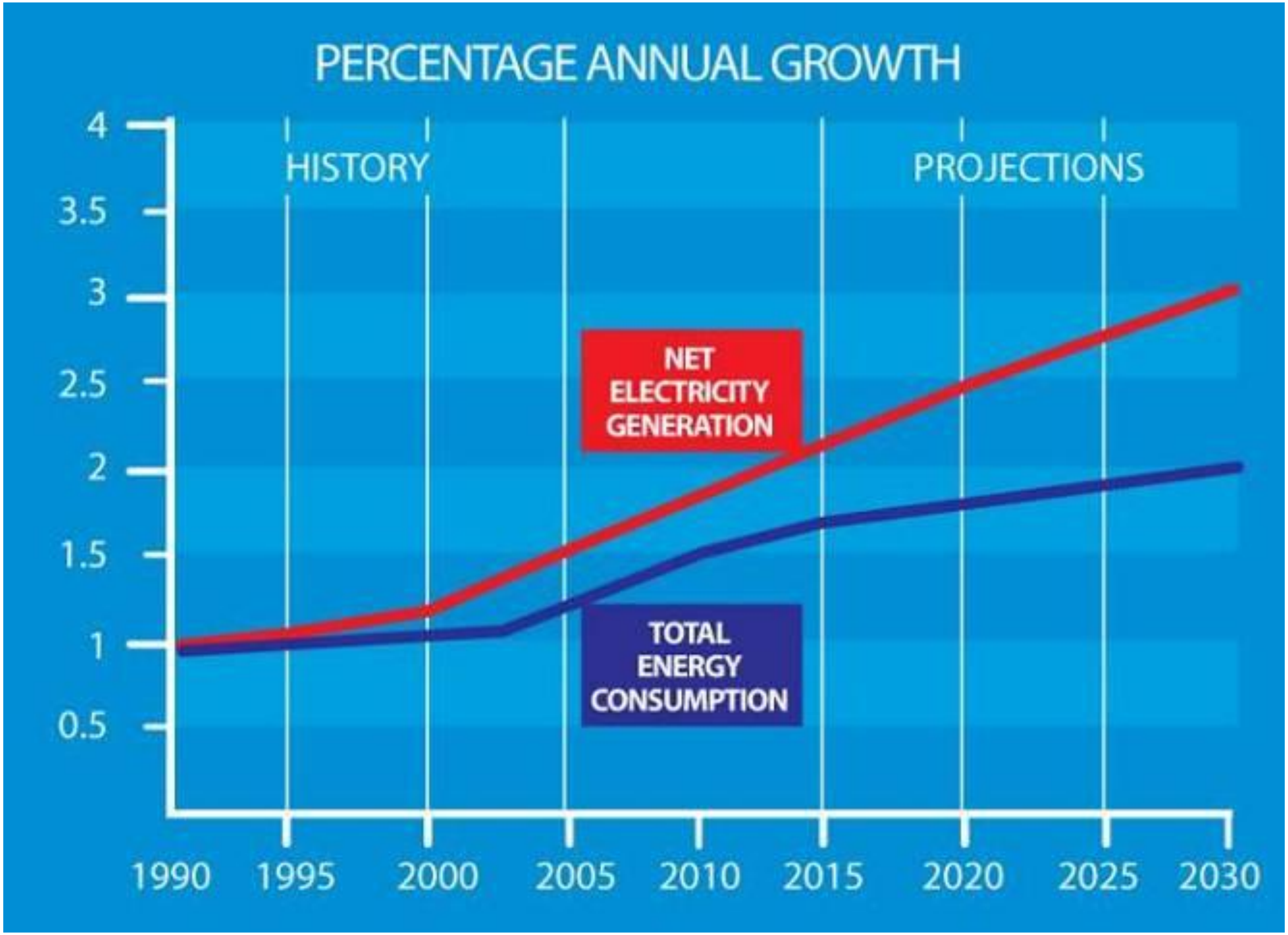
- It will be a power system dynamics issue in the end

- The consumer is key – but I have no idea what that means do you ?

Acknowledgements

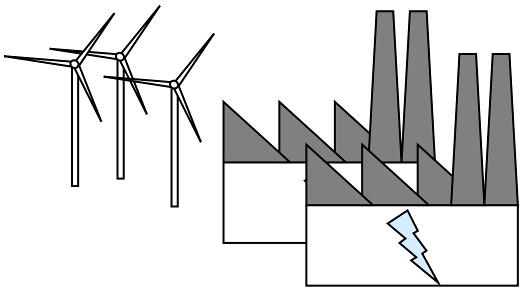
- Princeton
  - Andlinger Center for Energy and the Environment
  - Emily Carter
  - Robert E. Eich
  - Robert Socolow
- My colleagues for many of the slides – NREL, EirGrid, UVIG, DTU etc.

The Future is Electric



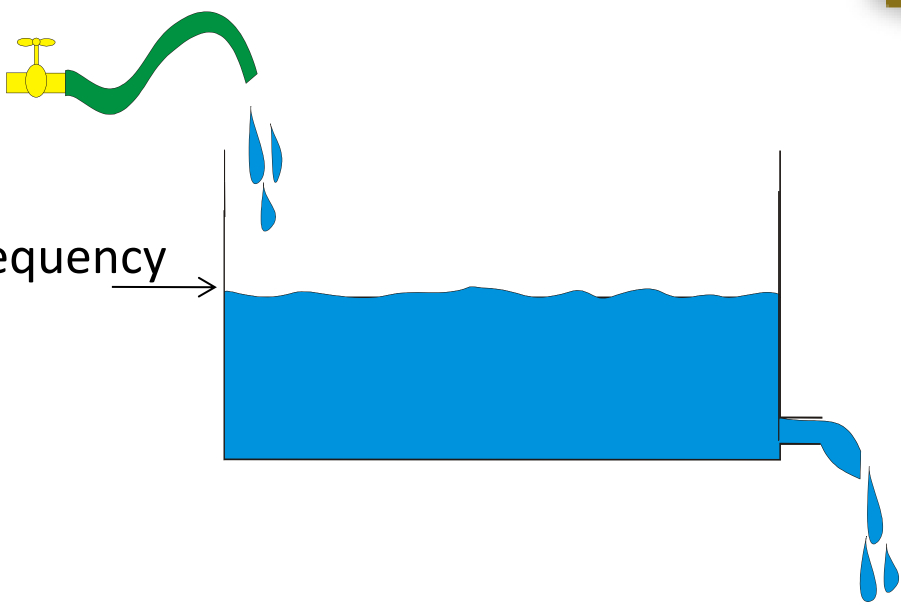
Source: Energy Information Administration (EIA), 2008.

Why: Grid Frequency Control

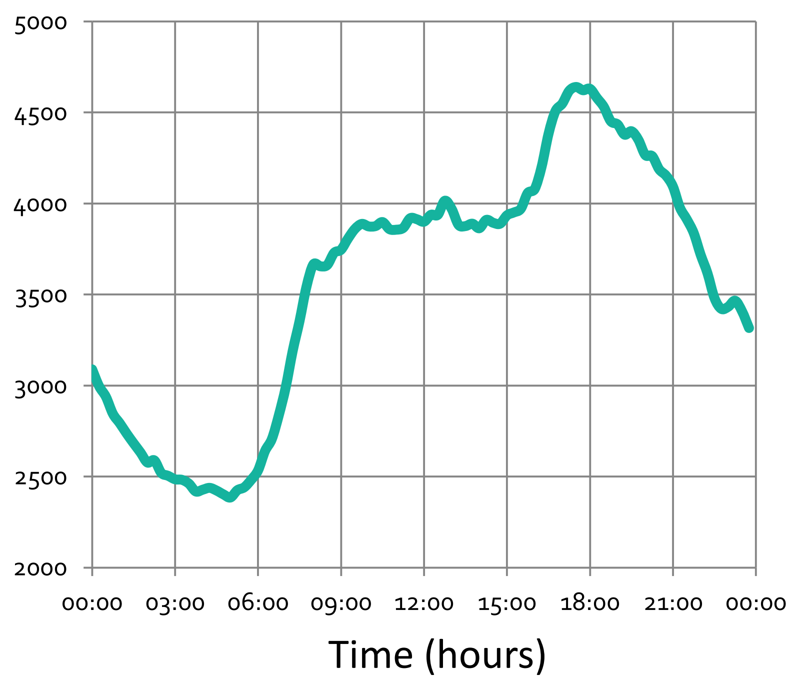


Supply

Frequency



Demand (MW)



Markets for Inertial Response ?

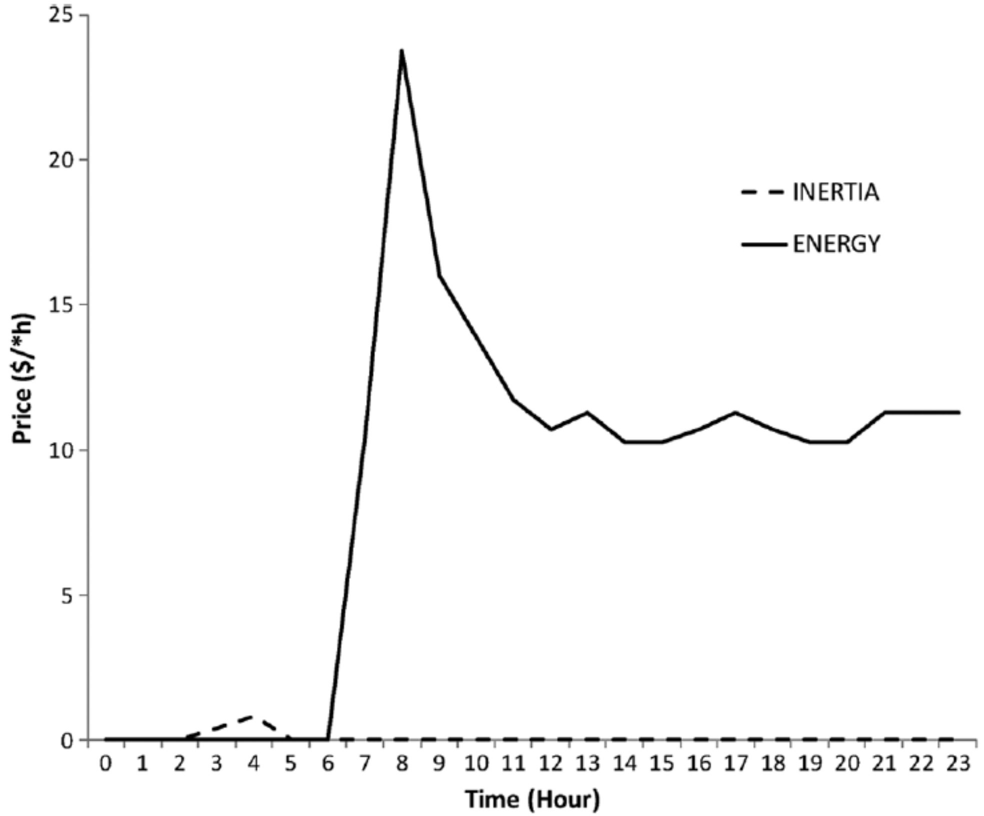


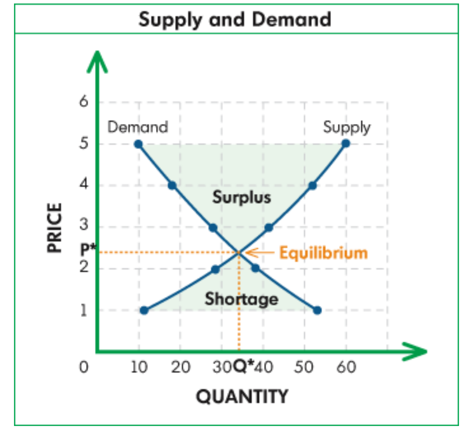
Fig. 10. Prices for energy and synchronous inertia for 50% wind penetration system with all other PFR constraints eliminated. Prices are in ($/MVAs-h) for inertia and ($/MW-h) for energy.

Ela, E., Gevorgian, V, Tuohy, A., Kirby, Milligan, M. and O'Malley, M.J. "Market Designs for the Primary Frequency Response Ancillary Service— Part I: Motivation and Design", IEEE Transactions on Power Systems, Vol. 29, pp.421- 431, 2014.

Ela, E., Gevorgian, V, Tuohy, A., Kirby, Milligan, M. and O'Malley, M.J. "Market Designs for the Primary Frequency Response Ancillary Service— Part II: Case Studies", IEEE Transactions on Power Systems, Vol. 29, pp. 432- 440, 2014.

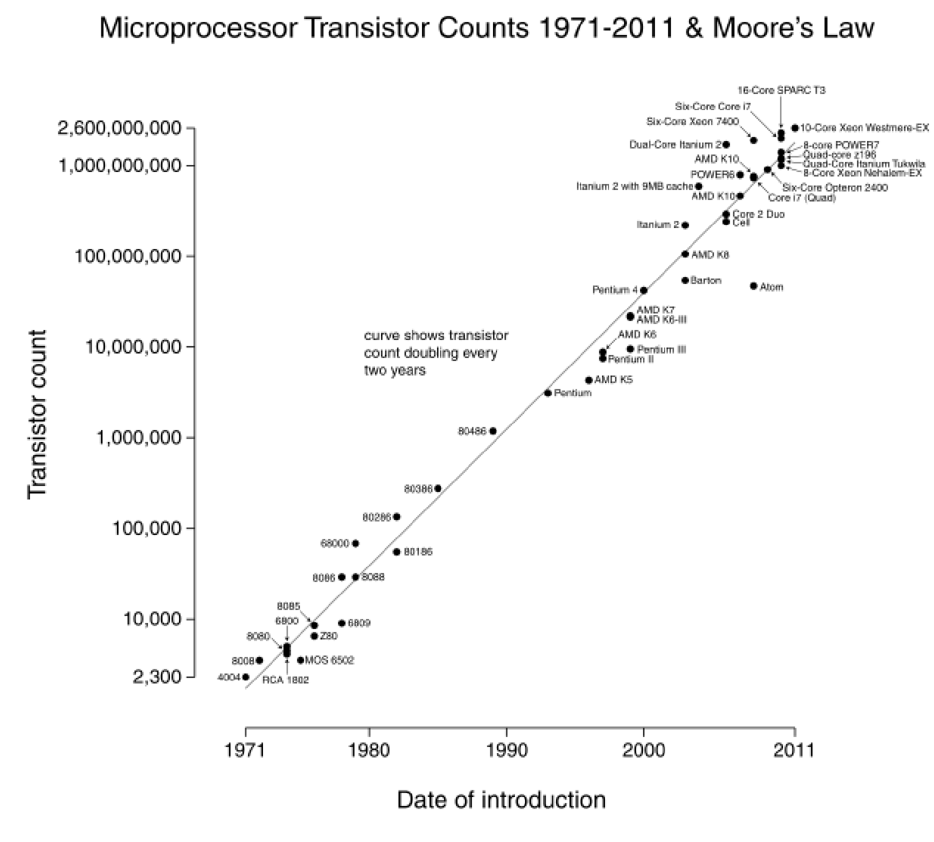
The good, the bad and the ugly

$$\oint \mathbf{E}\cdot d\mathbf{A} = \frac{q_{enc}}{\varepsilon_0}$$
$$\oint \mathbf{B}\cdot d\mathbf{A} = 0$$
$$\oint \mathbf{E}\cdot d\mathbf{s} = -\frac{d\Phi_B}{dt}$$
$$\oint \mathbf{B}\cdot d\mathbf{s} = \mu_0\varepsilon_0\frac{d\Phi_E}{dt} + \mu_0 i_{enc}$$

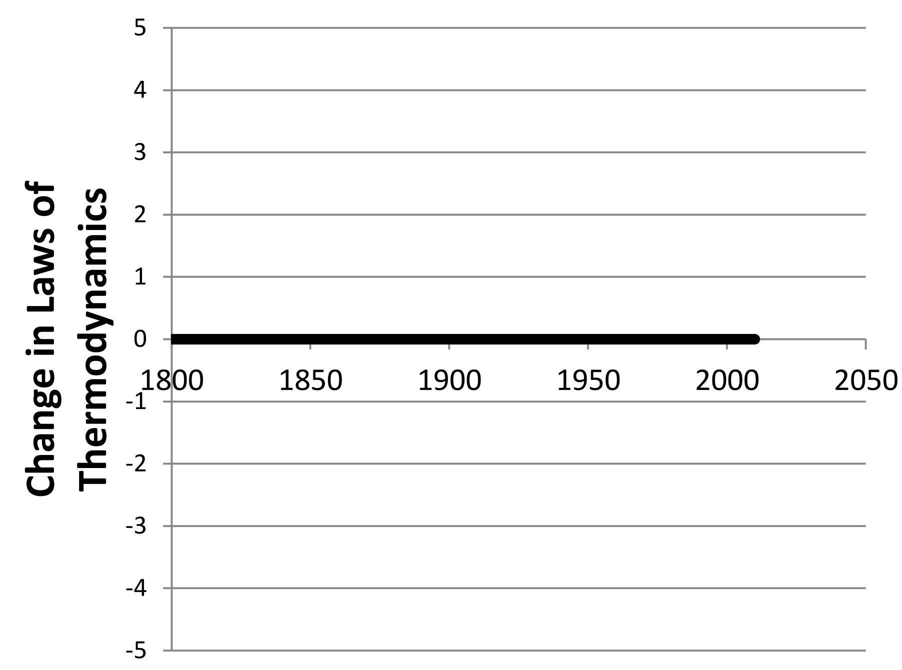


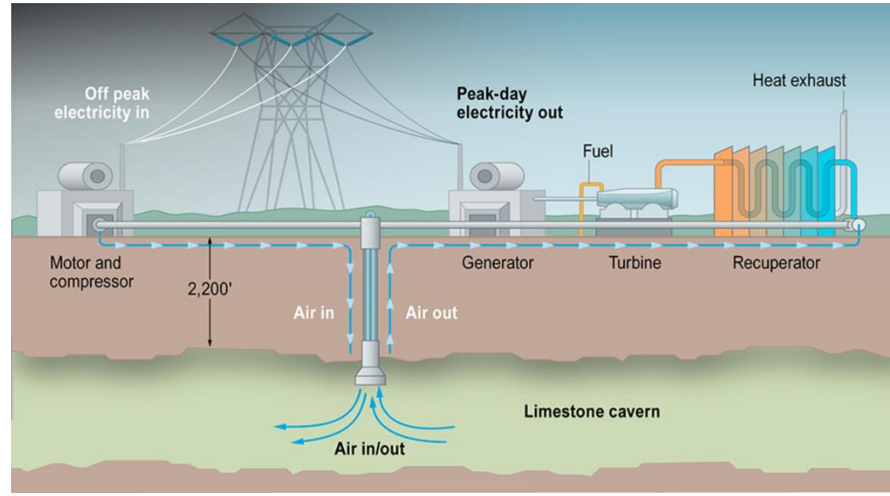
Data and Energy

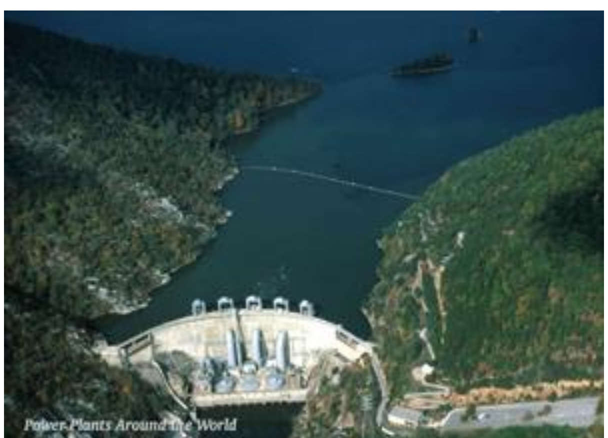
Digital Revolution – Moores Law



Energy Evolution – Laws of Thermodynamics




Off peak
electricity in
Peak-day
electricity out
Heat exhaust
Fuel
Motor and
compressor
2,200'
Air in
Air out
Generator
Turbine
Recuperator
Limestone cavern
Air in/out


Power Plants Around the World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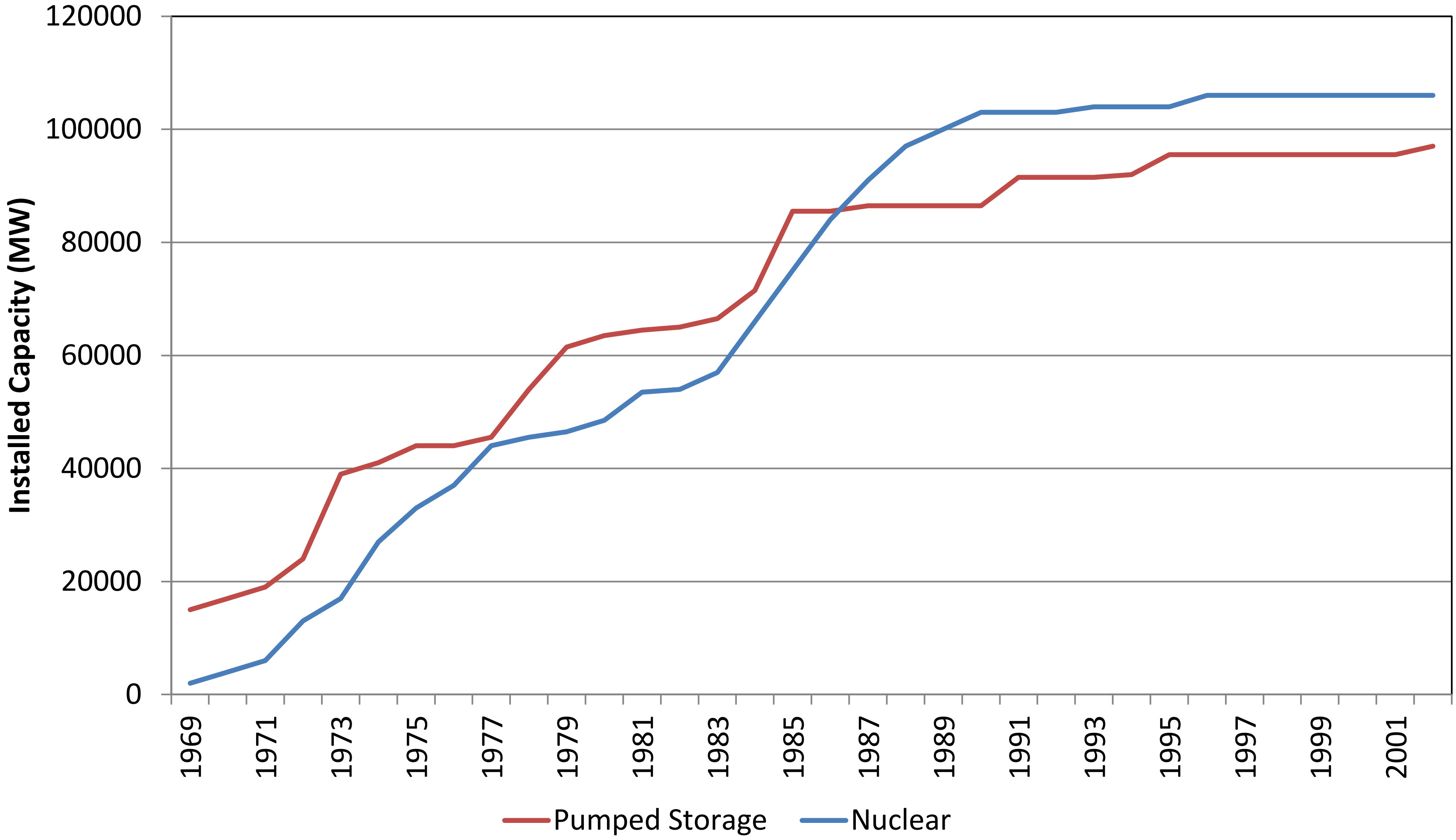
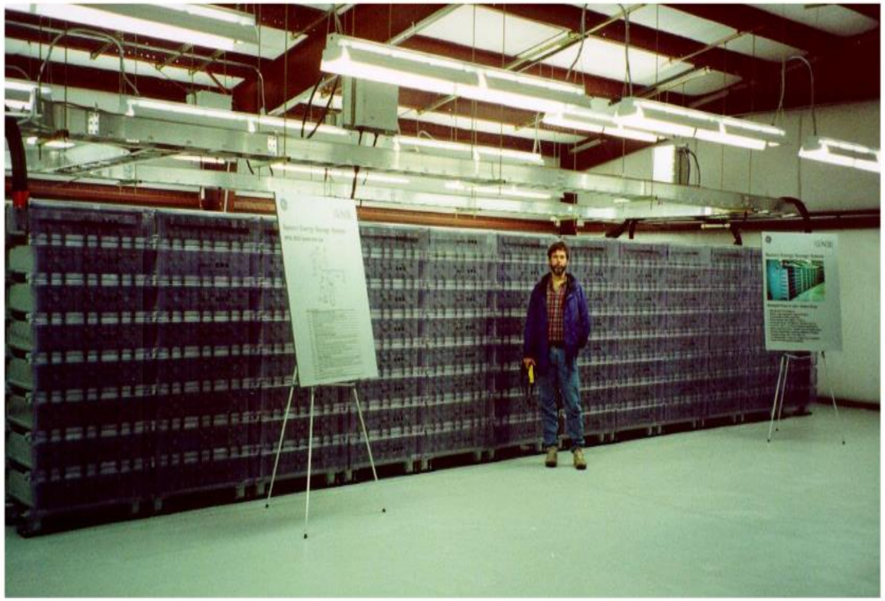
Historical Storage Drivers



Data From OECD Countries only

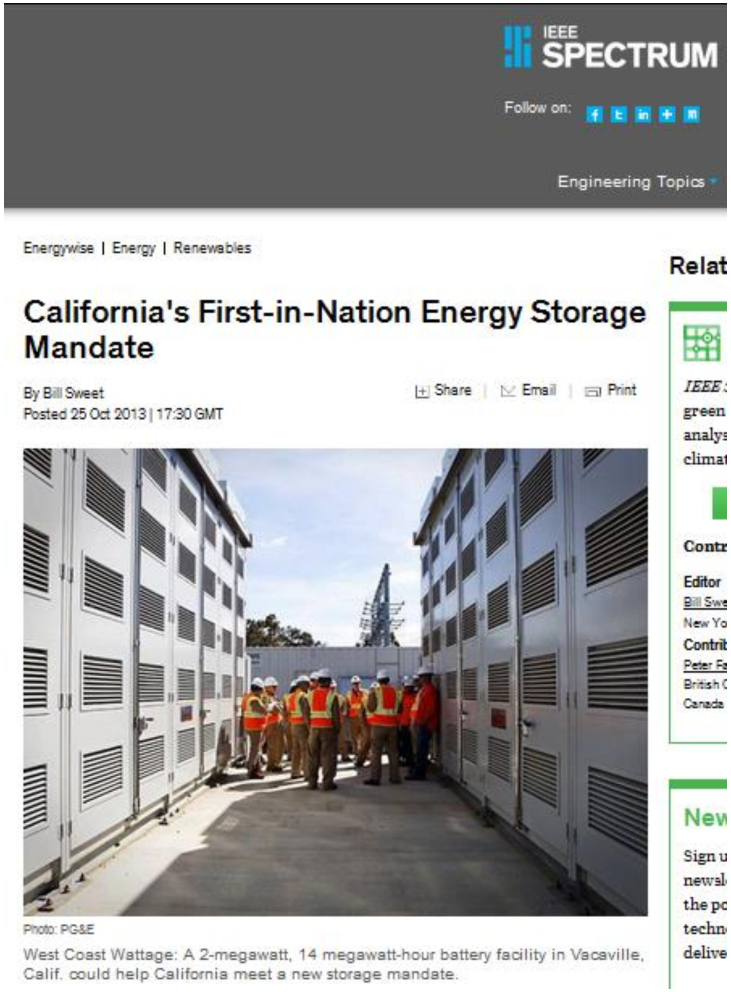
Repeal of fuel use act in US: http://www.eia.gov/oil_gas/natural_gas/analysis_publications/ngmajorleg/repeal.html

GE and Energy Storage



Manz, D.;Piwko, R; Miller, N , “Look Before You Leap: The Role of Energy Storage in the Grid”, IEEE Power and Energy Magazine, pp. 75-84, July/August, 2012.

Miller, N., Providing short term ancillary services: GE Hybrid Wind Turbine programme”, UVIG, Charleston USA, April 2013.



California has adopted the United States' first energy storage mandate, requiring the state's three major power companies to have 1325 MW of electricity storage capacity in place by the end of 2020, and 200 MW by the end of next year. The new rule issued by the California Public Utilities Commission (CPUC) will be key to implementation of the state's ambitious renewable portfolio rules, which calls for 33 percent of delivered electricity to come from renewable sources by 2020 and virtually guarantees that California, along with Germany, will remain in the world vanguard of those aggressively building out wind and solar.

By common expert consent, wind and solar can only reach their full potential if storage is provided for, as otherwise little-used generating capacity must be held in reserve for the times the wind does not blow and the sun does not shine. California's landmark rule was written by Commissioner Carla Peterman, newly appointed to the CPUC late last year by Governor Jerry Brown.

"This is transformative," Chet Lyons, an energy storage consultant based in Boston, told the *San Jose Mercury News*, the state's most tech-savvy newspaper. "It's going to have a huge impact on the development of the storage industry, and other state regulators are looking at this as a precedent."

Though the new rule was adopted by the five CPUC commissioners unanimously, two expressed concerns about the storage mandate's being achieved at reasonable cost to consumers, especially as large pumped storage (hydraulic) facilities do not qualify. There are a wide range of technologies that do qualify, including batteries and flywheels, but costs are generally high. Pike Research has concluded that the United States as a whole could have as much as 14 GW of electrical storage by 2022, but only if storage costs come down to the vicinity of to about $700-$750 kilowatts per hour

http://spectrum.ieee.org/energywise/energy/renewables/californias-firstinnation-energy-storage-mandate

Storage & ancillary services play that went wrong

Mark O'Malley, Chet Lyons, Brendan McGrath, Keith McGrane, NY, July 2011

Flywheel Energy Storage Lives On at Beacon Power

An update on Beacon, emerging from bankruptcy to work the frequency regulation markets

Eric Wesoff
May 31, 2013

The DOE loan program had its obvious big losers (Solyndra), its seemingly big winners (Tesla), and firms like Beacon Power, which are still works in

http://www.greentechmedia.com/articles/read/Flywheel-Energy-Storage-Lives-On-at-Beacon-Power

Demand Response with renewables

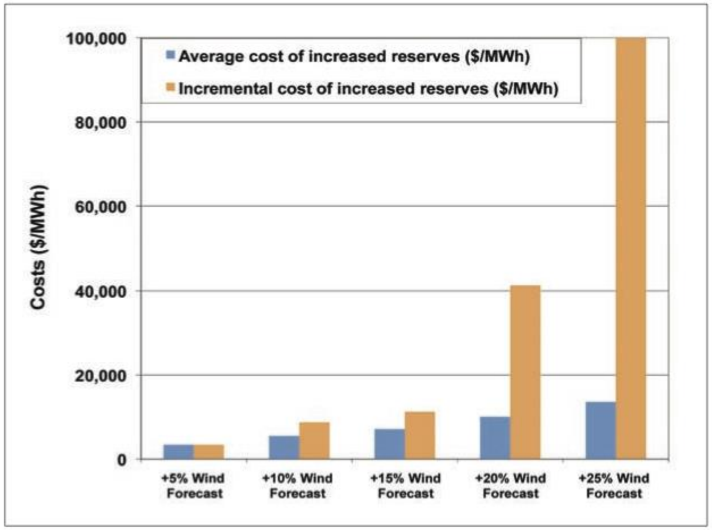


Figure 12 – The cost of increasing spinning reserves increases with higher percentages of spin. The incremental cost increases sharply at higher percentages of spin, indicating that the cost of reducing those final reserve shortfalls is prohibitively high. *The five bars show the effect of increasing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

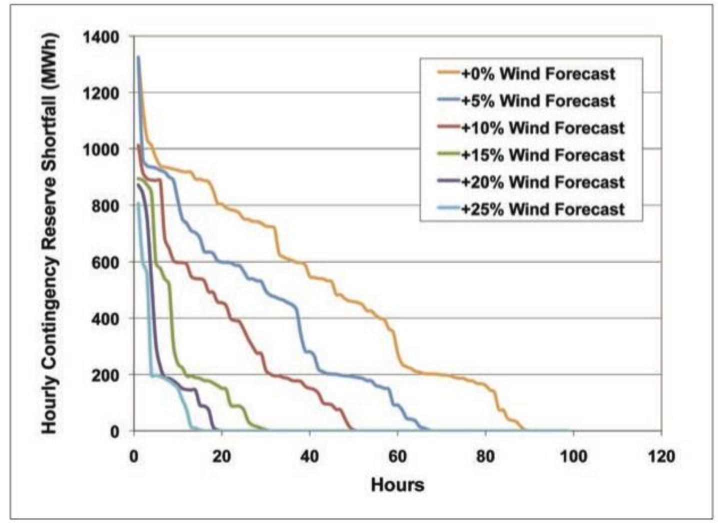
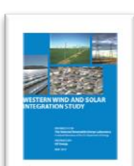


Figure 13 – A demand response program which requires load to participate in the 89 hours of the year that there are contingency reserve shortfalls is more cost-effective than increasing spin for each of the 8760 hours of the year. *Hourly contingency reserve-shortfall duration curves for the In-Area 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

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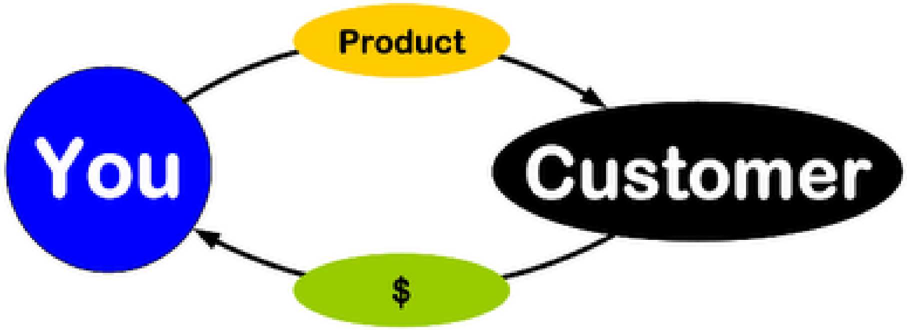
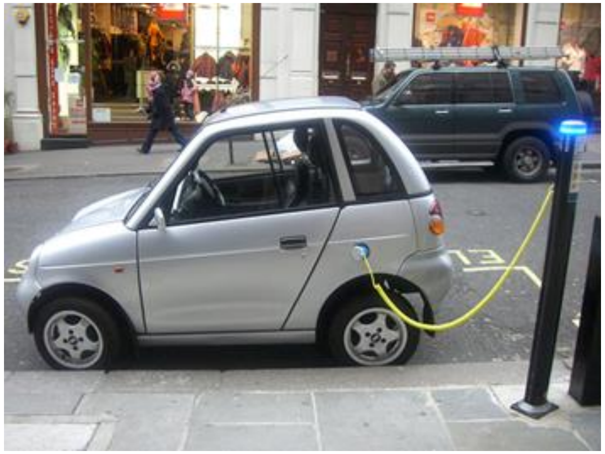
Business model

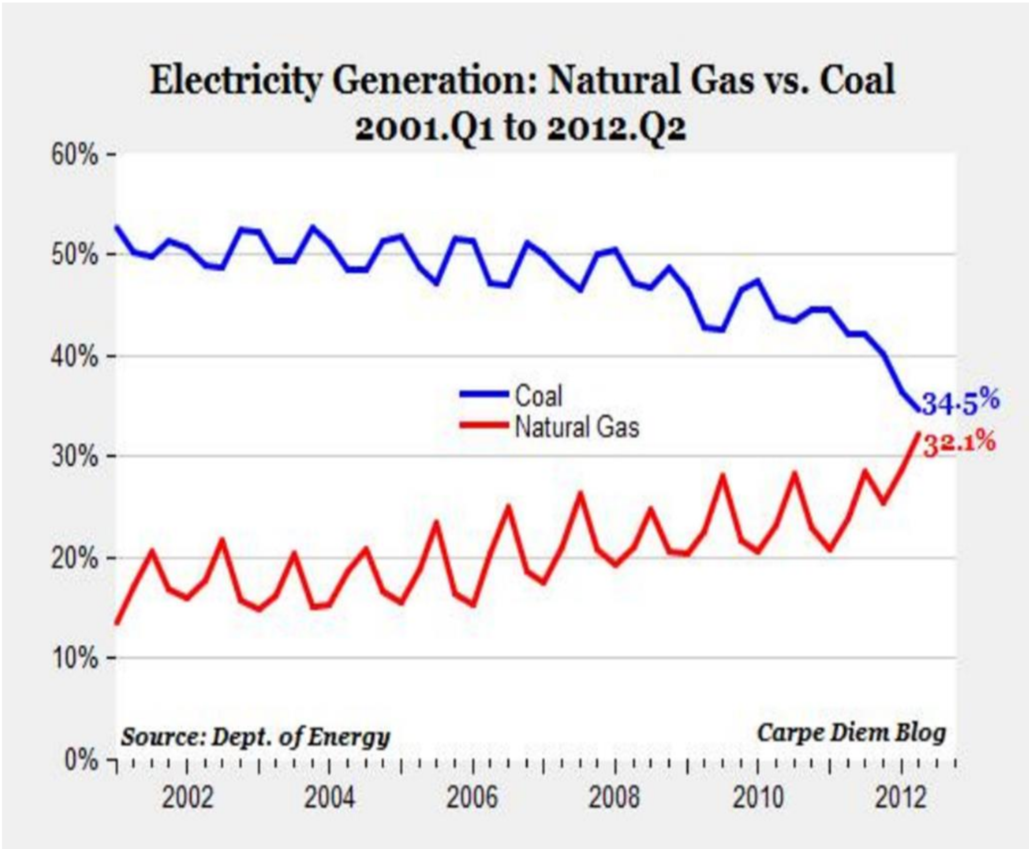


Wider Convergence



Gas/Electricity the Global Situation



" This issue of gas-electric interdependence is not a reason to panic, but it's absolutely a reason to plan, and to do so now"

Cheryl A. LaFleur the acting chairman of the Federal Energy Regulatory Commission


THE WALL STREET JOURNAL.

U.S. EDITION Monday, July 15, 2013 As of 11:49 AM EDT

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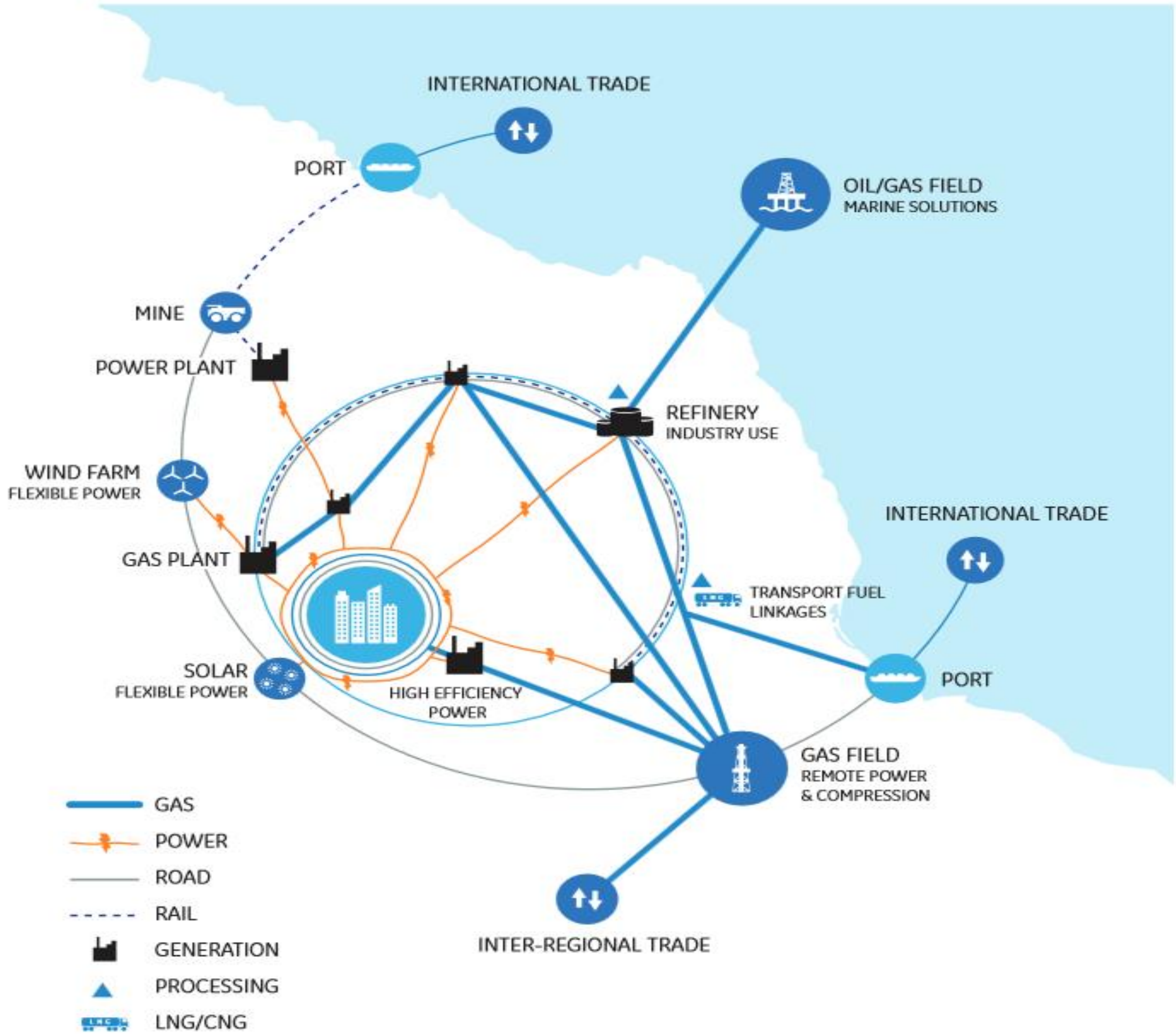
July 15, 2013, 11:49 a.m. ET

E.ON to Mothball Slovak Gas Power Plant Malzenice from October

Figure 12. Multi-Network Integration: Gas, Power, Road and Rail

Source: GE Global Strategy and Analytics, 2013

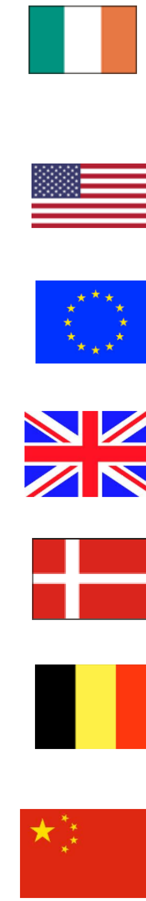


http://www.ge.com/sites/default/files/GE_Age_of_Gas_Whitepaper_20131014v2.pdf

Energy Systems Integration

M. O'Malley and B. Kroposki Guest Editors

- Planning ESI – Jim McCalley *et al.*, Iowa St.
- Hawaii ESI – Dave Corbus, *et al.*, NREL
- EU ESI – John Holms, EASAC & Oxford University
- Danish ESI – Peter Meibom *et al.*, Dansk Energi, DTU
- Tools and modelling for ESI – Juan Van Roy *et al.* KU Leuven
- China ESI – Chongqing Kang *et al.*, Tsinghua University



O'Malley, M.J. and Kroposki B. "Energy comes together the integration of all systems", Editorial, Special issue in Energy Systems Integration, *IEEE Power & Energy Magazine*, Vol. 11, Sept/October, pp. 18 – 23, 2013.

Grid Flexibility, Research and Integrating Variable Renewables

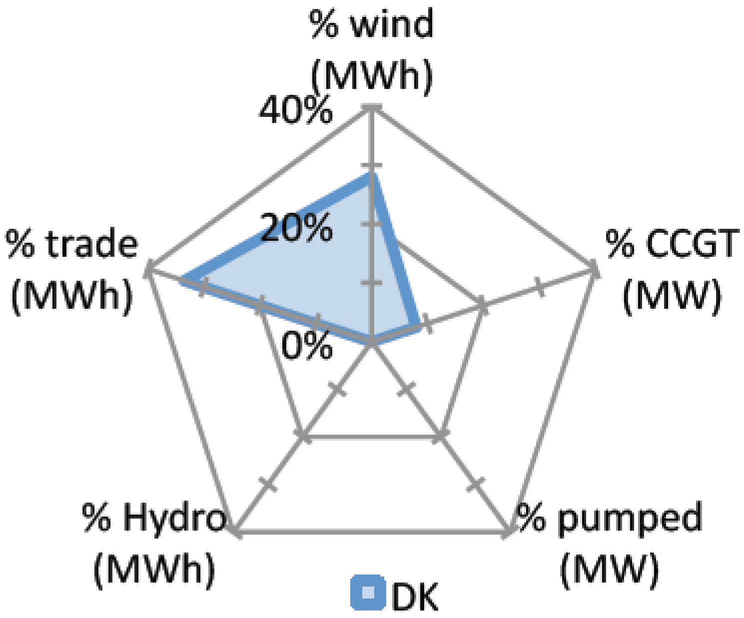
The Vatican Sept 28th 2003


happytoast

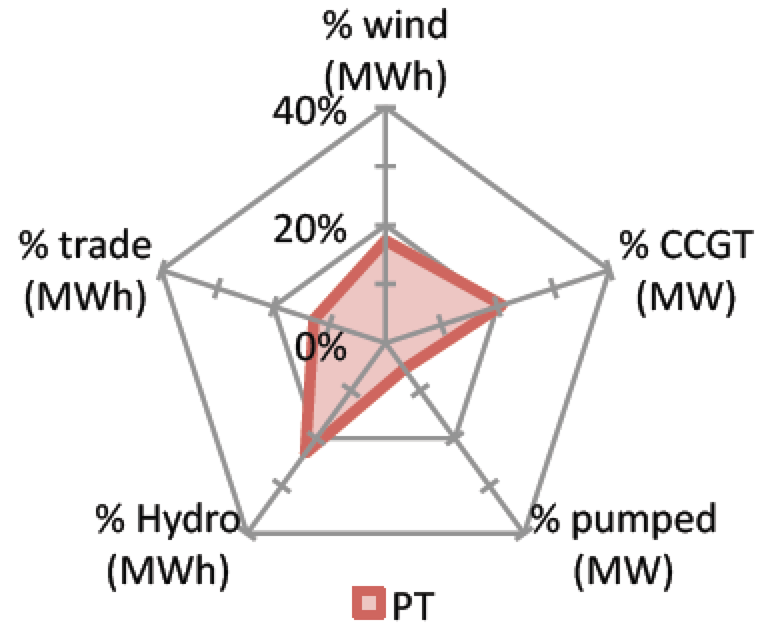
Top wind integration performance (2011)

	% 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 & good market	Curtailment reduced in 2012 to 2.1 %

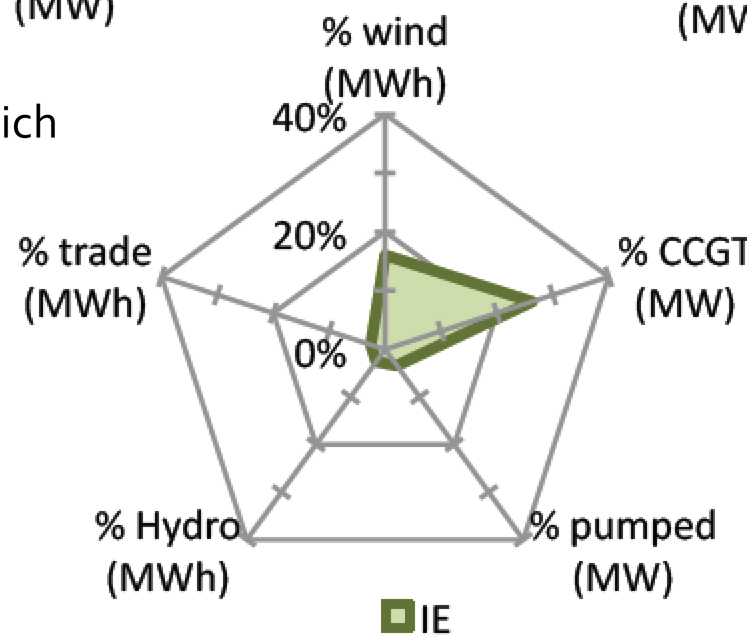
Renewable Integration Solutions; Sources of Flexibility



Denmark: Trading Rich



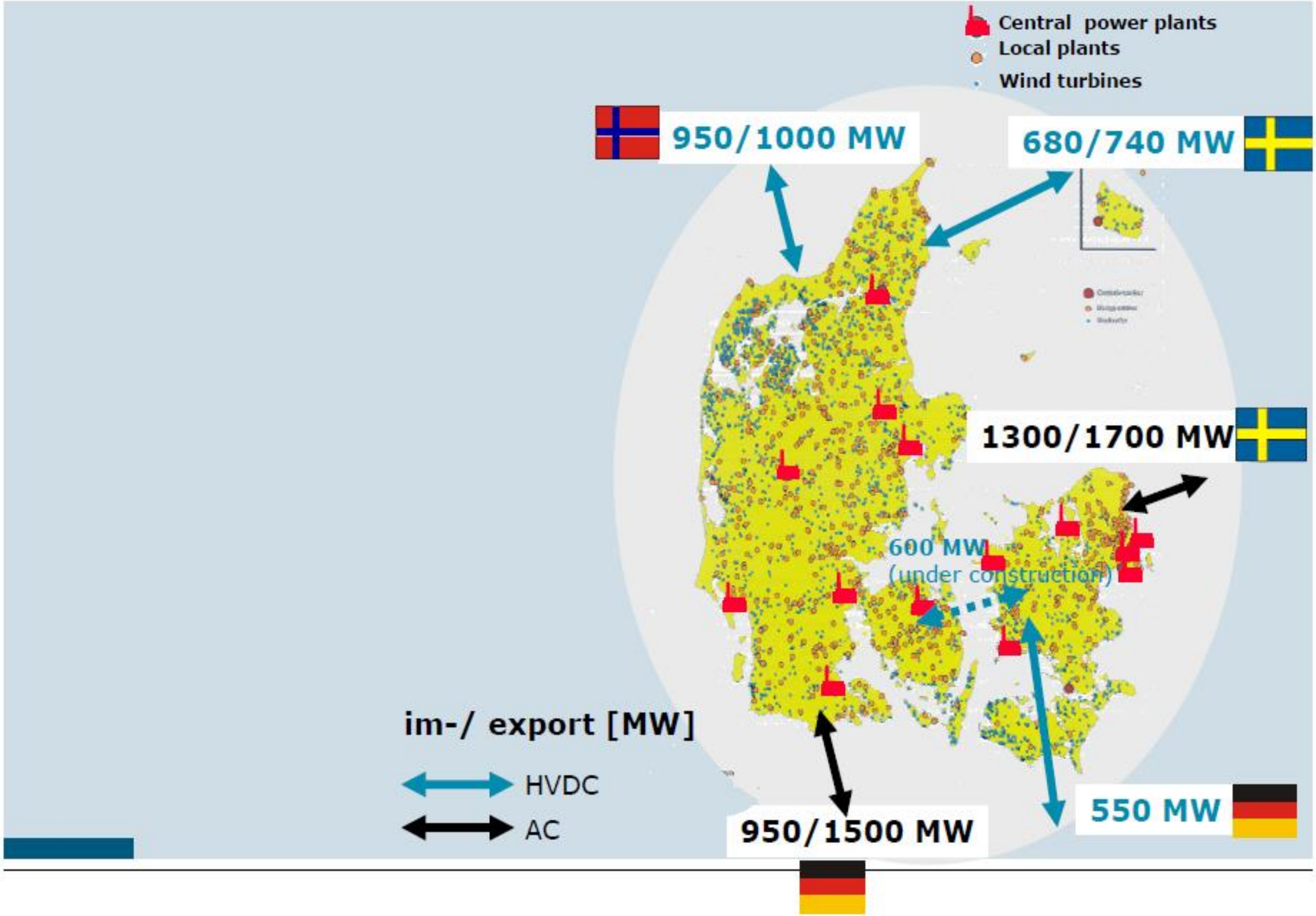
Portugal: Hydro Rich



Ireland: CCGT Rich

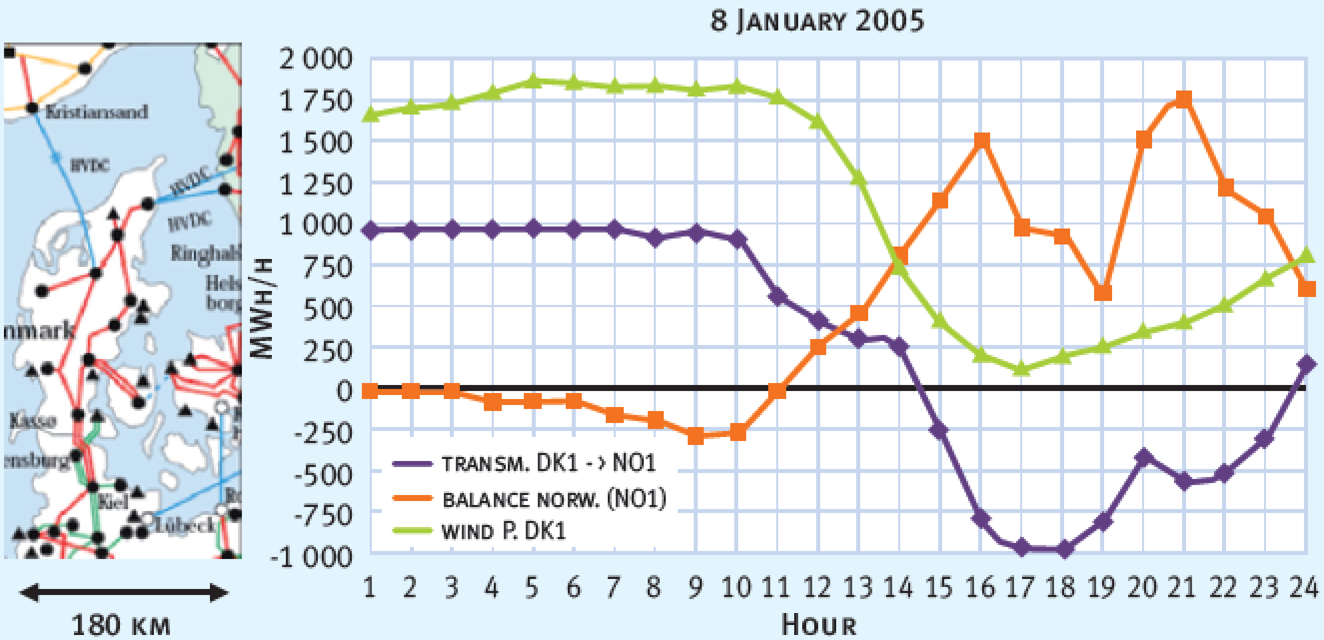
Source: Dr. Yoh Yasuda

Interconnectors 2009



Denmark's Wind is Integrated by the Rest of Europe

FIGURE 25: CORRELATION BETWEEN A STORM HITTING THE DANISH WESTERN COAST, DANISH WIND PRODUCTION AND THE BALANCE OF FLOWS BETWEEN DENMARK AND NORWAY



Source: North European Power Perspectives (http://www.nepp.se/organisation.htm)

Eurelectric 2011 "Flexible Generation: Backing up Renewables" Published as part of EURELECTRIC Renewables Action Plan (RESAP)

Policy Failures Because they are not Holistic

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Windmills Overload East Europe's Grid Risking Blackout: Energy

By Ladka Bauerova and Tino Andresen - Oct 26, 2012 12:01 AM GMT

15 COMMENTS QUEUE

Sean Gallup/Getty Images

Germany is dumping electricity on its unwilling neighbors and by wintertime the feud should come to a head.

Germany is dumping electricity on its unwilling neighbors and by wintertime the feud should come to a head.

Borggrefe, F. and Neuhoff K. "Balancing and Intraday Market Design: Options for Wind Integration" Deutsches Institut für Wirtschaftsforschung October 2011

RES-E-NEXT

Next Generation of RES-E Policy Instruments

4 July 2013

RETD

IEA - RENEWABLE ENERGY TECHNOLOGY DEPLOYMENT

M. Miller, L. Bird, J. Cochran, M. Milligan, M. Bazilian
National Renewable Energy Laboratory

E. Denny, J. Dillon, J. Bialek, M. O'Malley
Ecar Limited

K. Neuhoff
DIW Berlin

Study commissioned by IEA-RETD
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Mackay, M., Bird, L., Cochran, J., Milligan, M., Bazilian, M., Neuhoff, K., Denny, E., Dillon, J., Bialek, J. and O'Malley, M.J., "RES-E-NEXT, Next Generation of RES-E Policy Instruments", IEA RETD, July 2013. http://iea-retd.org/wp-content/uploads/2013/07/RES-E-NEXT_IEA-RETD_2013.pdf

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Windmills Overload East Europe's Grid Risking Blackout: Energy

By Ladka Bauerova and Tino Andresen - Oct 26, 2012 12:01 AM GMT

15 COMMENTS QUEUE

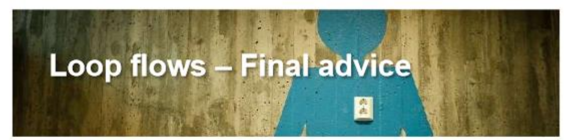
Sean Gallup/Getty Images

Germany is dumping electricity on its unwilling neighbors and by wintertime the feud should come to a head.

Germany is dumping electricity on its unwilling neighbors and by wintertime the feud should come to a head.

- http://ec.europa.eu/energy/gas_electricity/studies/doc/electricity/201310_loop-flows_study.pdf

THEMA CONSULTING GROUP

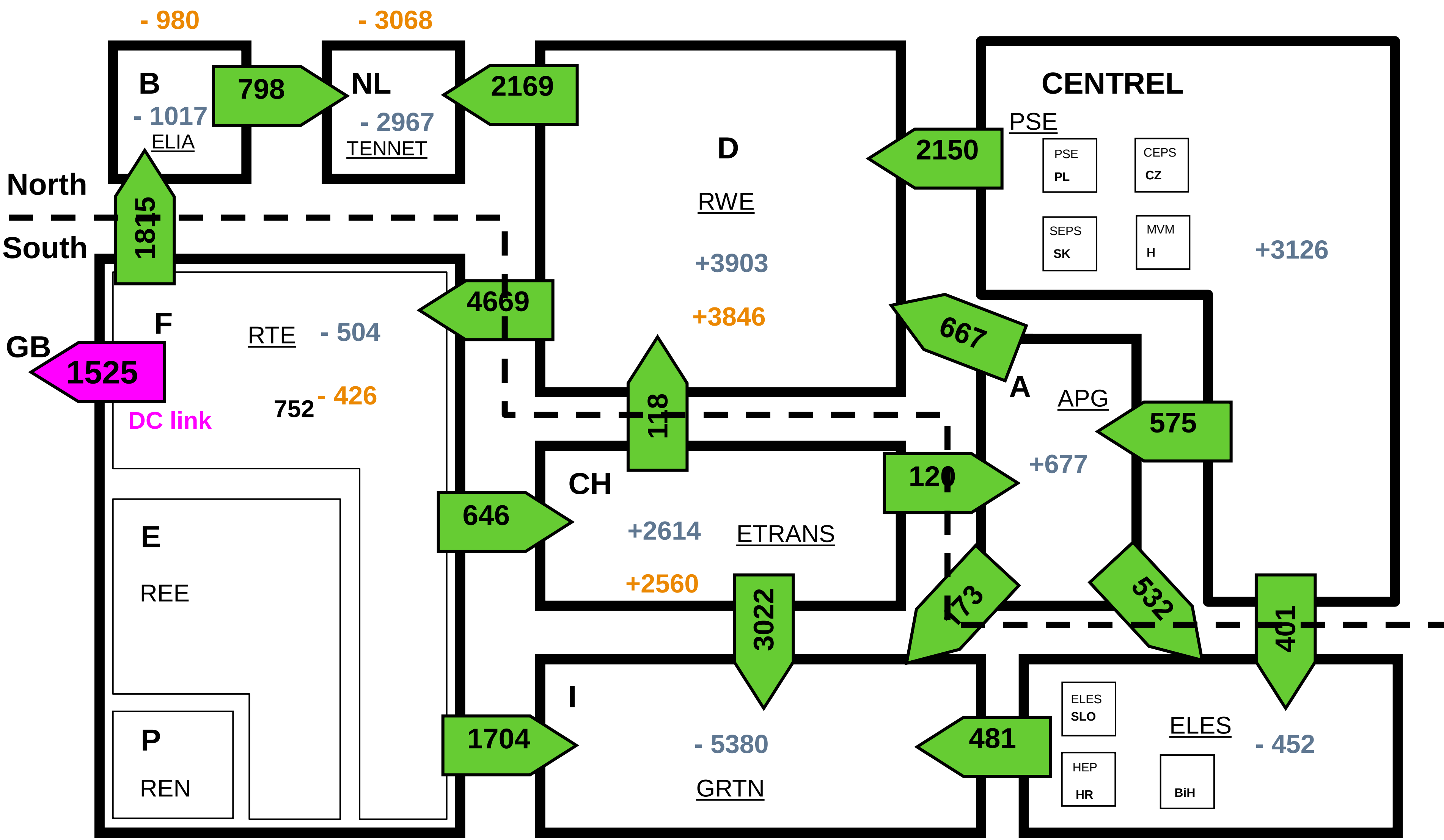


Prepared for The European Commission
October 2013

THEMA Report 2013-36

Unannounced Wind Power in the Northern Germany

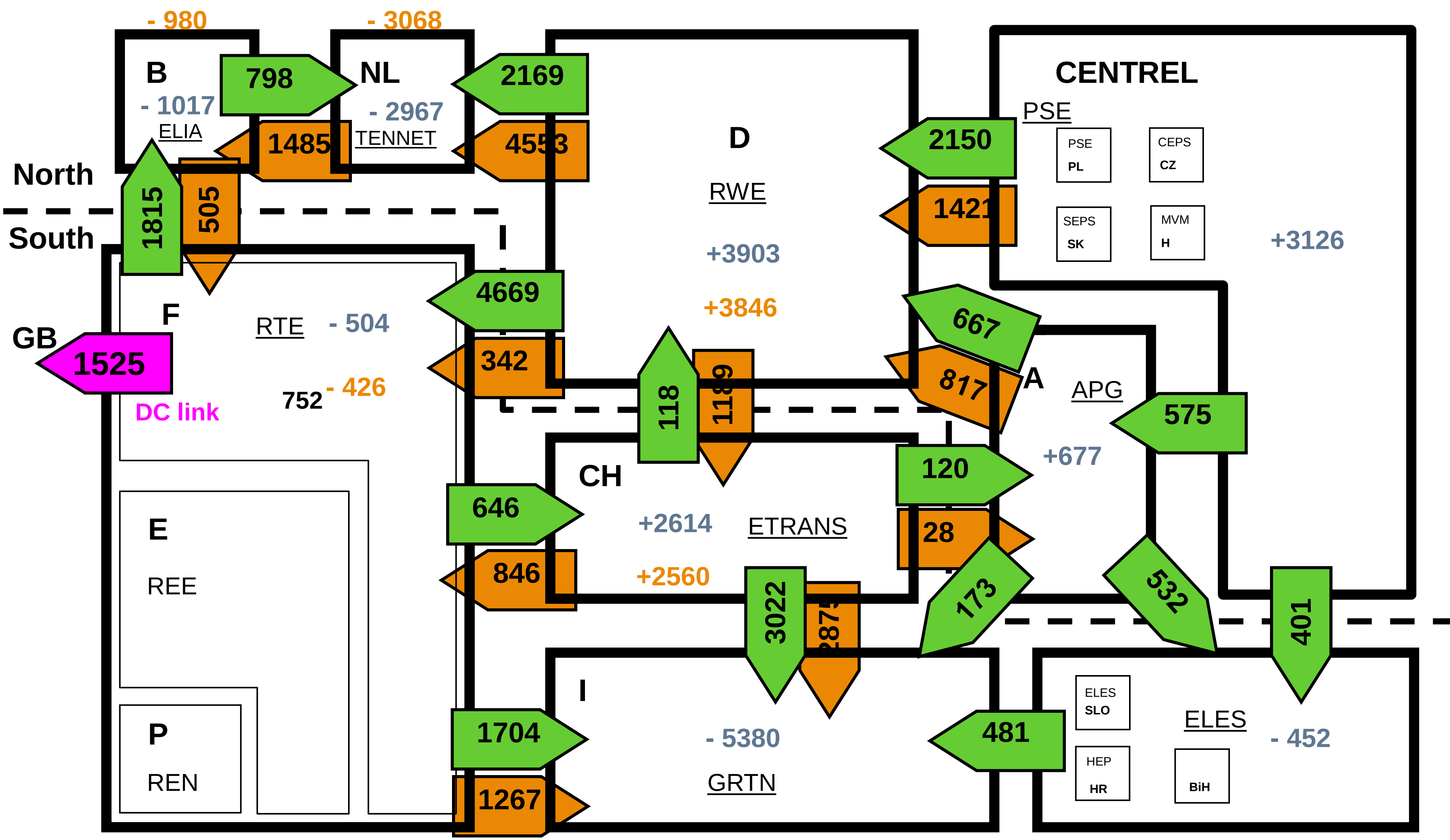
Scheduled Power Exchanges



Source: Ronnie Belmans, ELIA

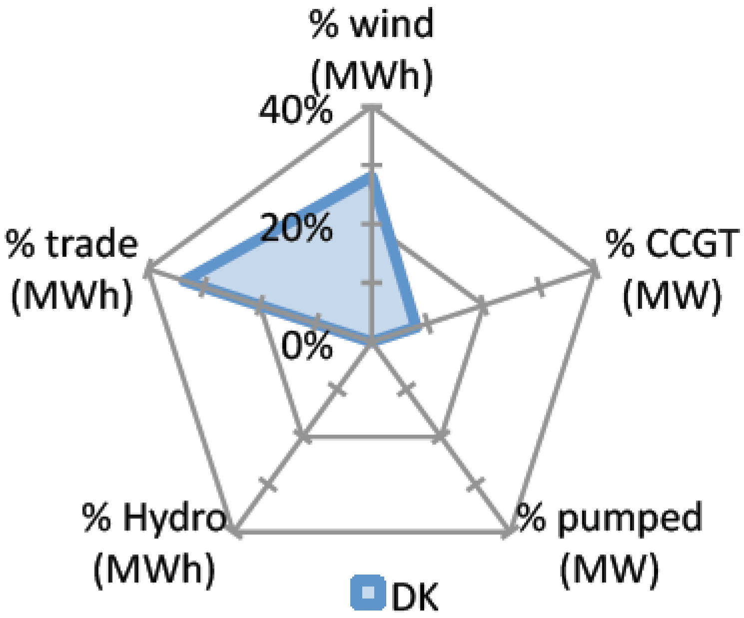
Unannounced Wind Power in the Northern Germany

Scheduled Power Exchanges vs Physical Power Flows

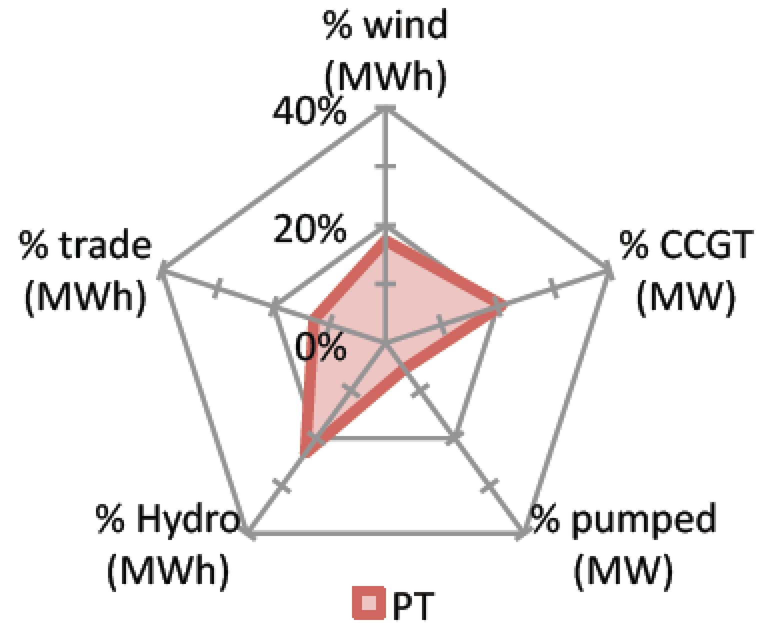


Source: Ronnie Belmans, ELIA

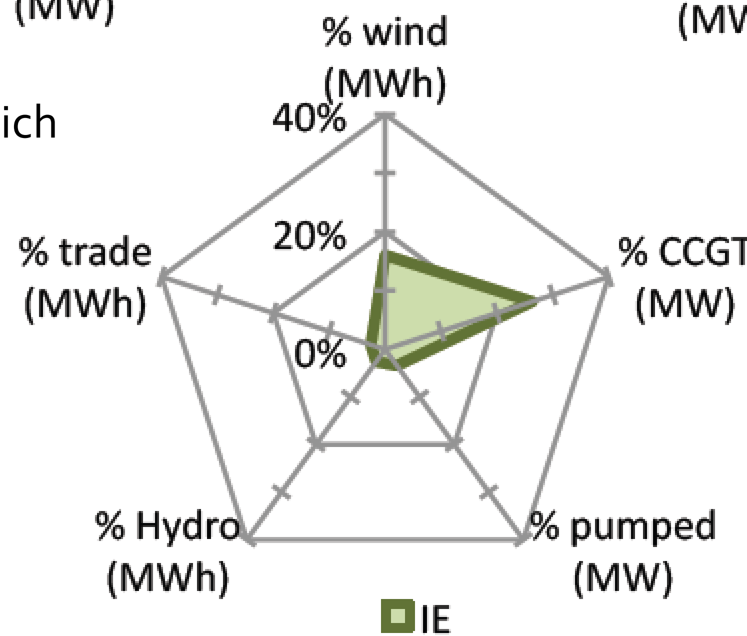
Renewable Integration Solutions; Sources of Flexibility



Denmark: Trading Rich



Portugal: Hydro Rich



Ireland: CCGT Rich

Source: Dr. Yoh Yasuda

Can Thermal Power Plant Skip ?

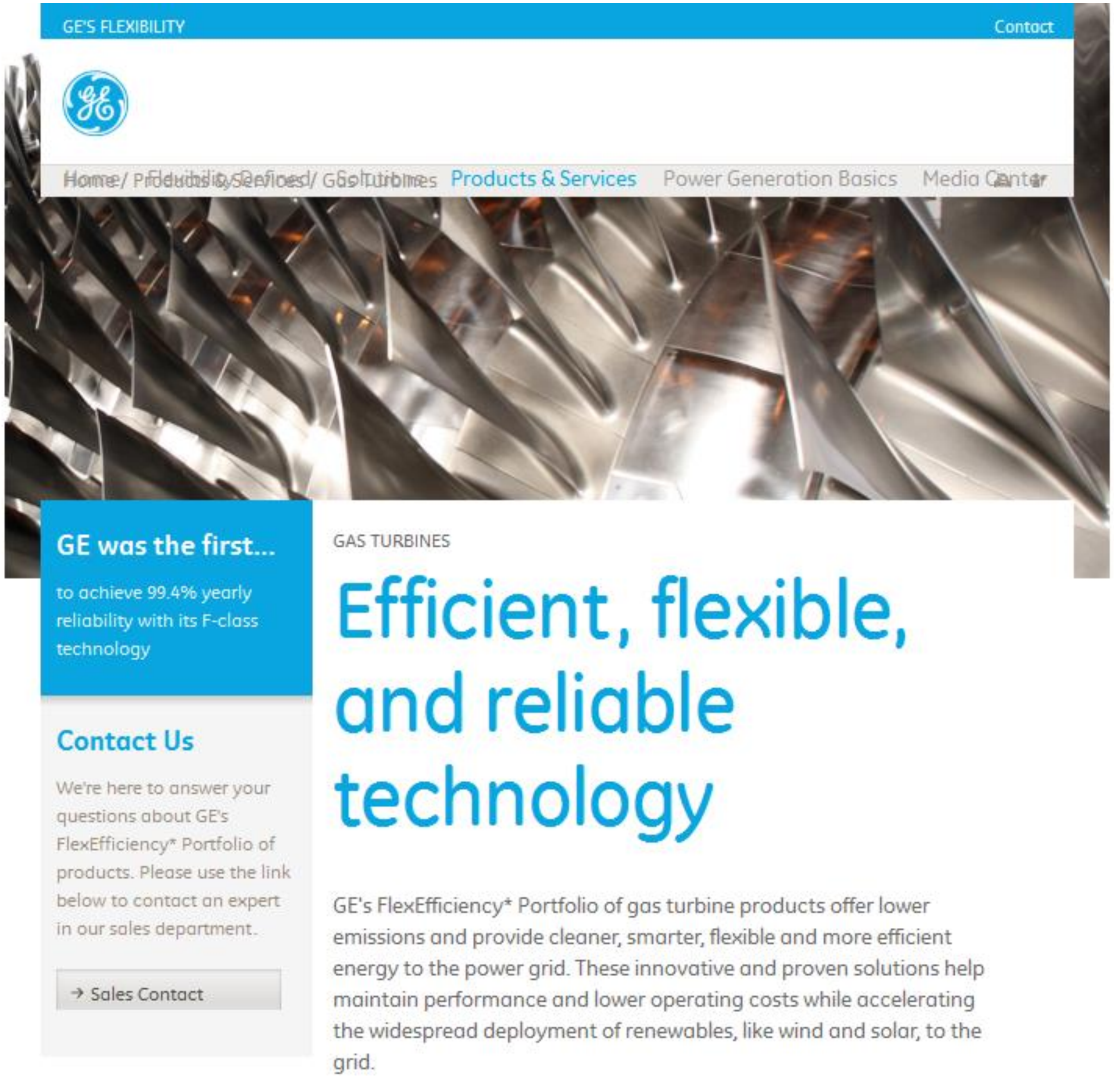
Table 3.2: The load following ability of dispatchable power plants in comparison

	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.

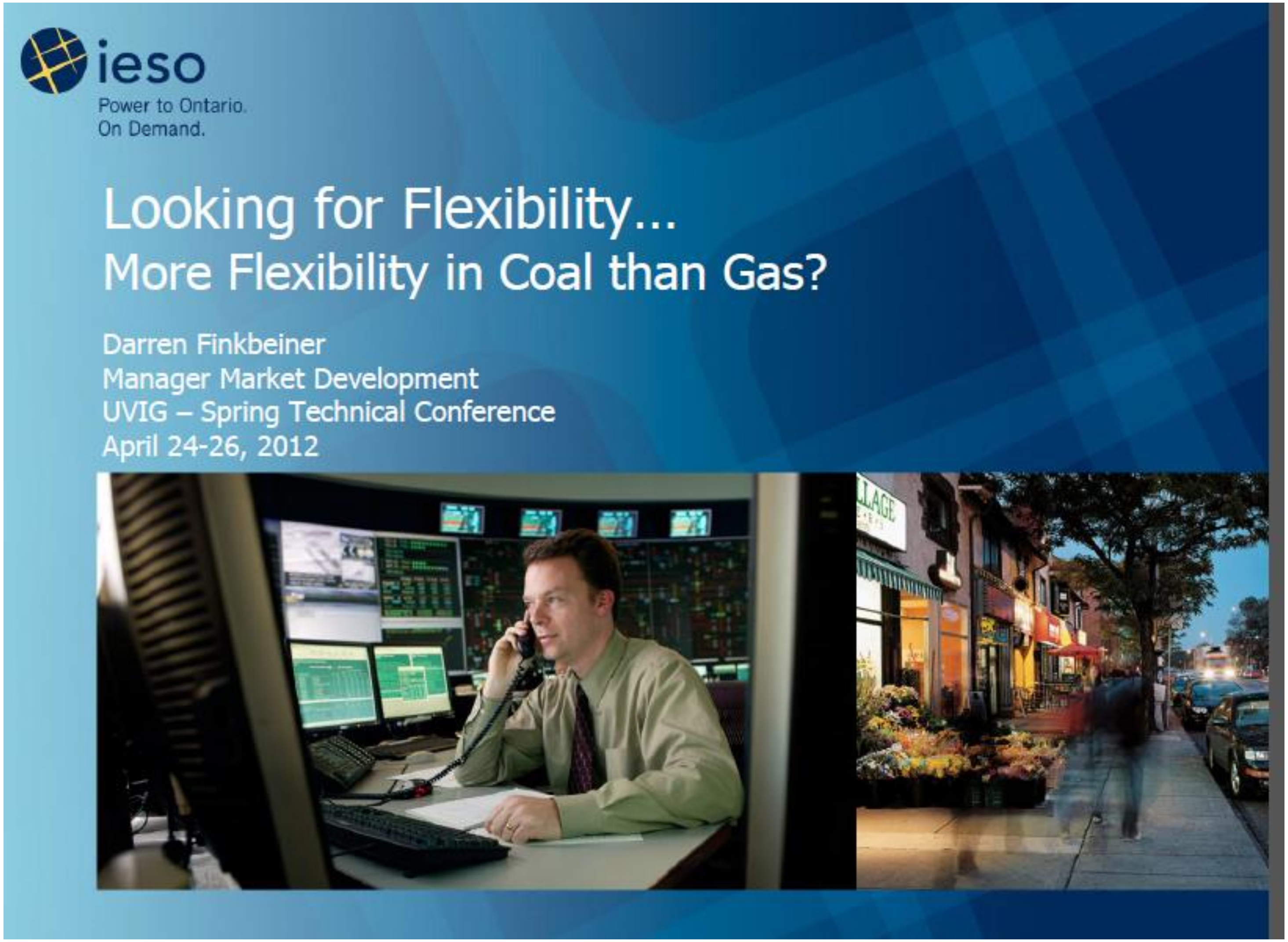
NEA 2012 “Nuclear Energy and Renewables: System Effects in Low-carbon Electricity Systems” Nuclear Energy Agency ISBN 978-92-64-18851-8

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.

Wind Power in Ireland 2011

Some Statistics

103 days in 2011 when wind went over 40 % demand

Nov 26th 2011 – 38 % of demand served by wind

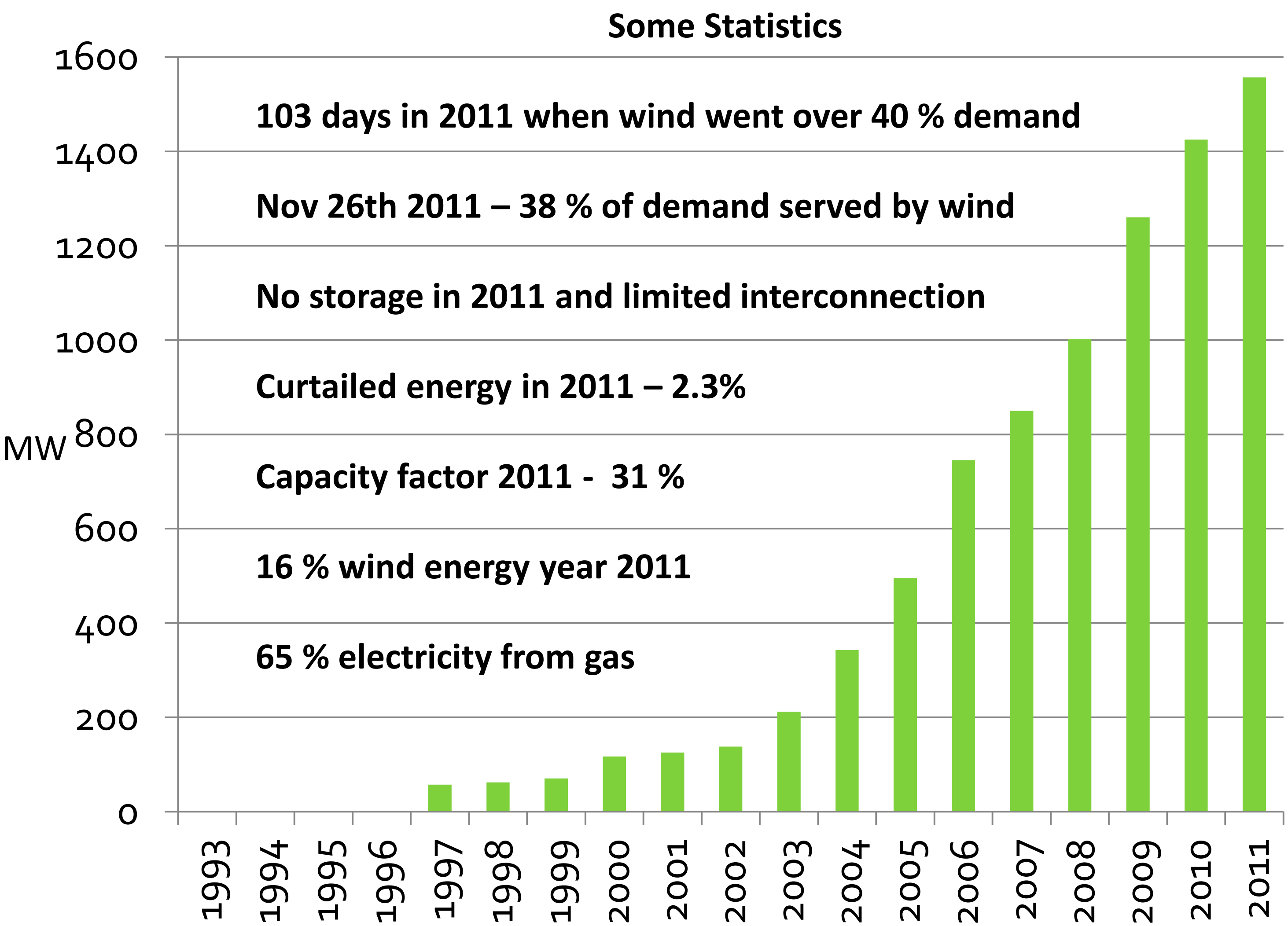
No storage in 2011 and limited interconnection

Curtailed energy in 2011 – 2.3%

Capacity factor 2011 - 31 %

16 % wind energy year 2011

65 % electricity from gas



Source: EirGrid

Wind Curtailment Estimates – US

Curtailment - negative "metric" for flexibility

	2007	2008	2009	2010	2011
Electric Reliability Council of Texas (ERCOT)	109 (1.2%)	1,417 (8.4%)	3,872 (17.1%)	2,067 (7.7%)	2,622 (8.5%)
Southwestern Public Service Company (SPS)	N/A	0 (0.0%)	0 (0.0%)	0.9 (0.0%)	0.5 (0.0%)
Public Service Company of Colorado (PSCo)	N/A	2.5 (0.1%)	19.0 (0.6%)	81.5 (2.2%)	63.9 (1.4%)
Northern States Power Company (NSP)	N/A	25.4 (0.8%)	42.4 (1.2%)	42.6 (1.2%)	54.4 (1.2%)
Midwest Independent System Operator (MISO), less NSP	N/A	N/A	250 (2.2%)	781 (4.4%)	657 (3.0%)
Bonneville Power Administration (BPA)	N/A	N/A	N/A	4.6* (0.1%)	128.7* (1.4%)
Total Across These Six Areas:	**109 (1.2%)**	**1,445 (5.6%)**	**4,183 (9.6%)**	**2,978 (4.8%)**	**3,526 (4.8%)**

Estimated Wind Curtailment in Various Areas, in GWh (and as a % of potential wind generation)

Source: Charlie Smith, UVIG & ERCOT, Xcel Energy, MISO, BPA

Technology

Advances

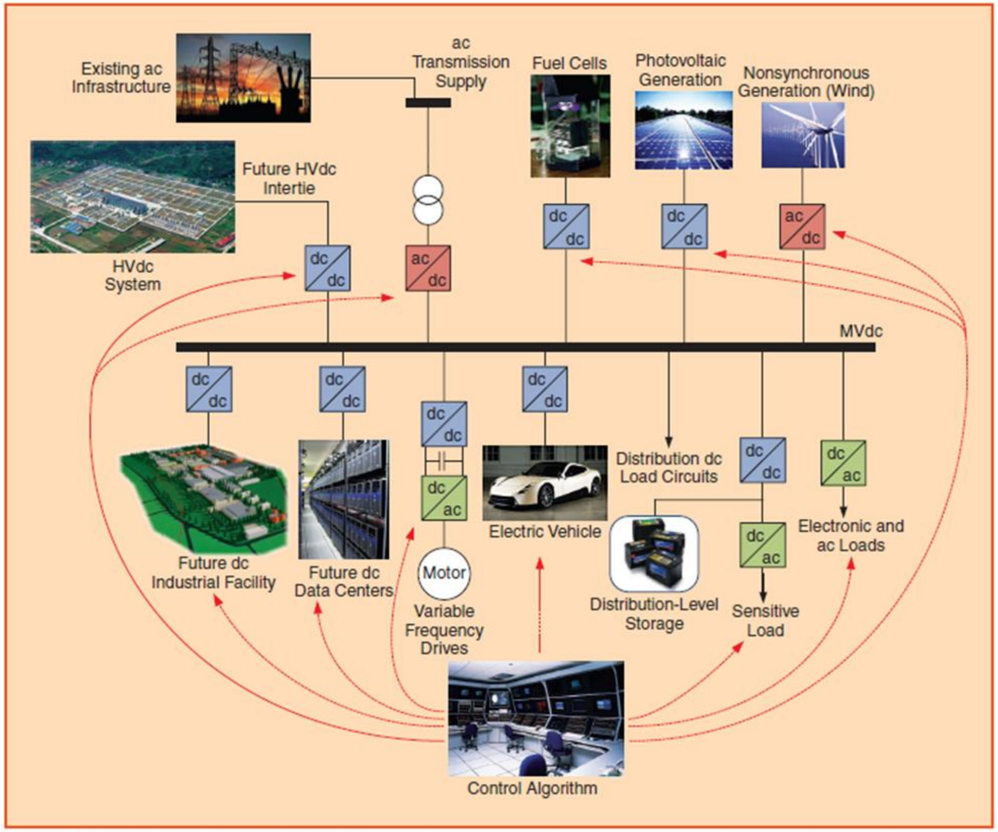
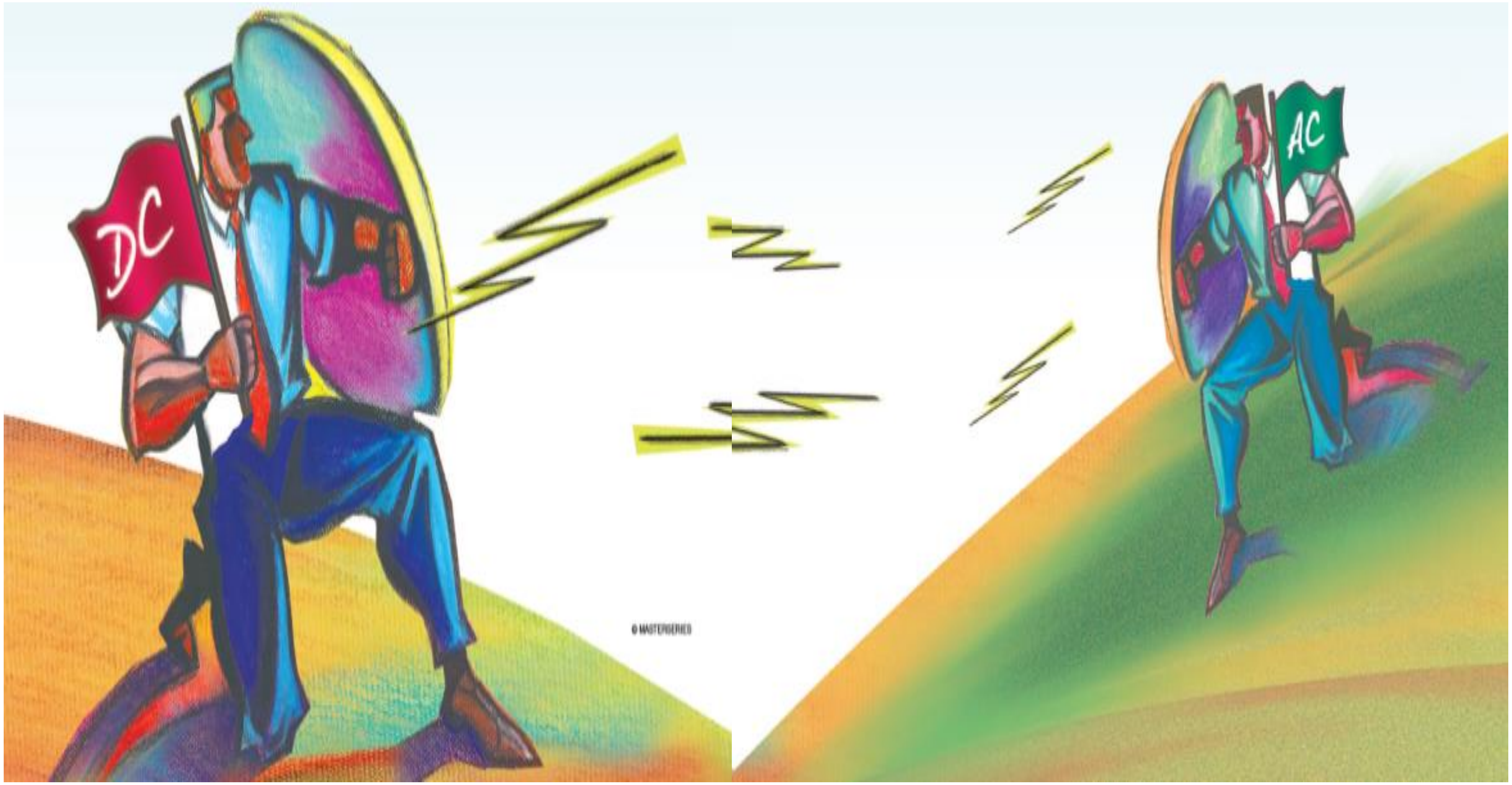
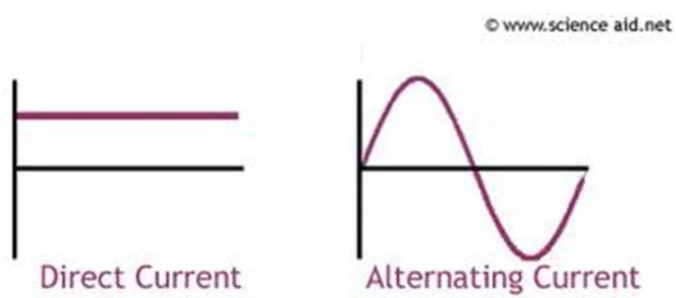
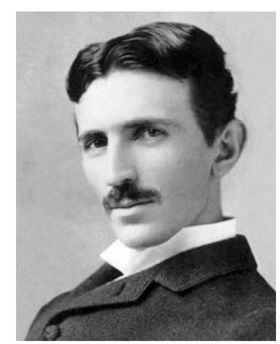


figure 2. General MVdc architecture layout.

Reed, G.F.; Grainger, B.M.; Sparacino, A.R.; Zhi-Hong Mao , "Ship to Grid: Medium-Voltage DC Concepts in Theory and Practice Power and Energy Magazine, Vol. 10 , Issue: 6, pp. 70 – 79, 2013.

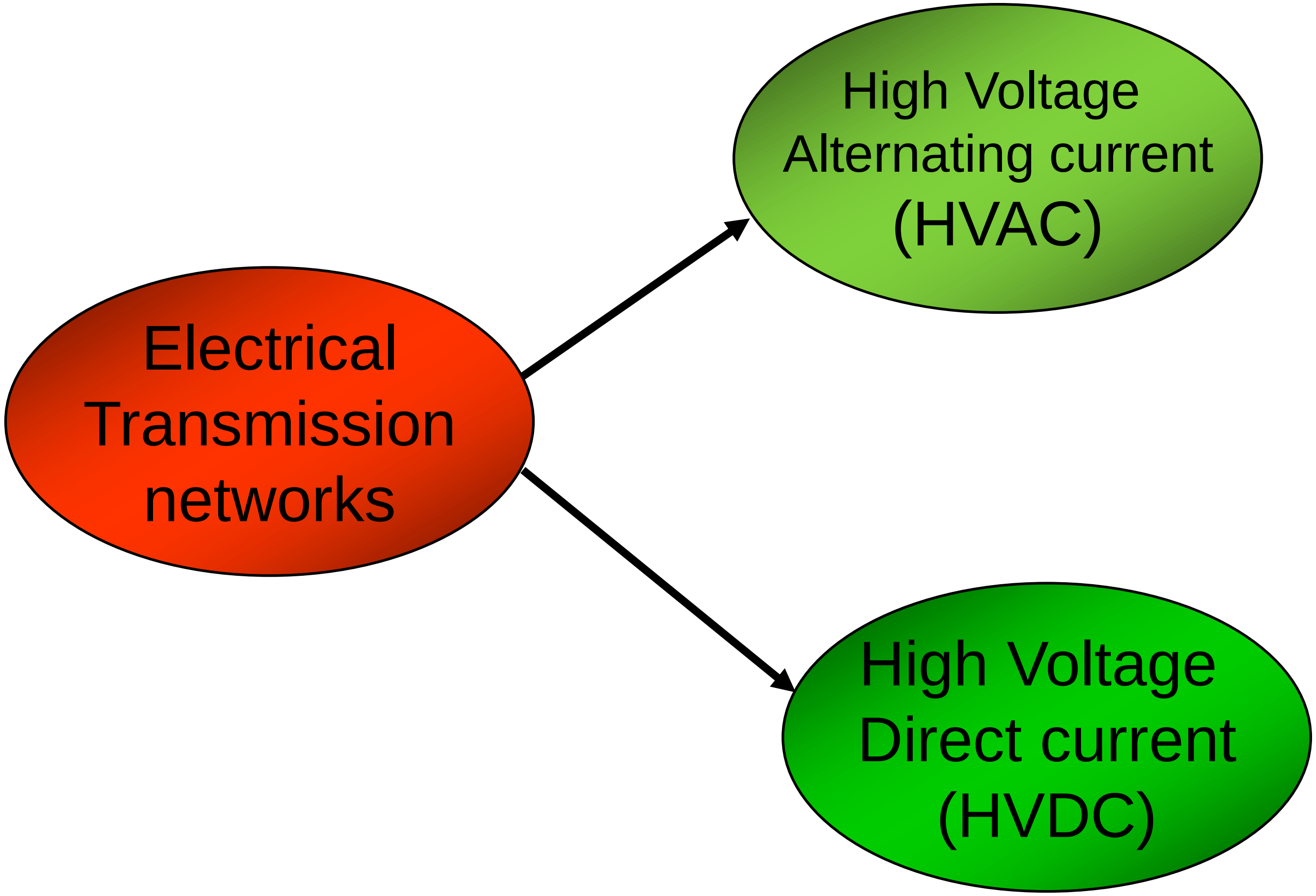






IEEE Power and Energy Magazine, Vol. 10 , Issue: 6, 2012.

Electrical Transmission Systems



HVAC:

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

HVDC:

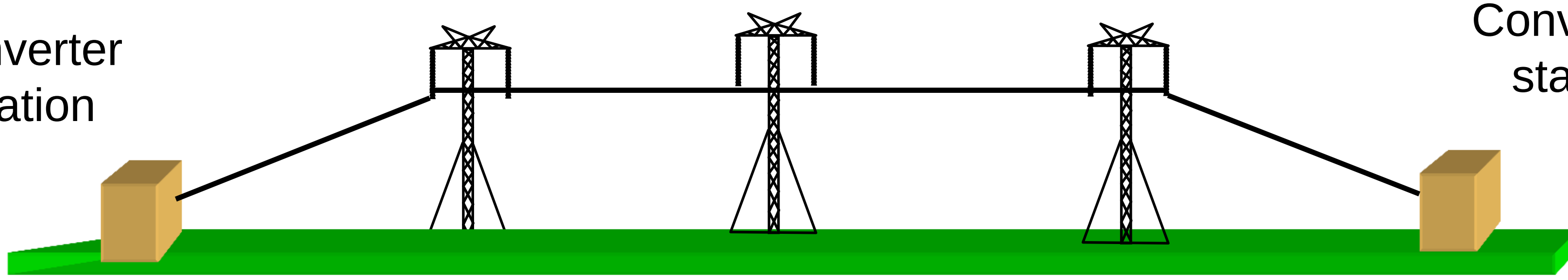
- Overhead lines
- Sea-cables
- Underground cables
- Point to point not meshed

High Voltage Direct Current (HVDC)

Overhead line

Converter station

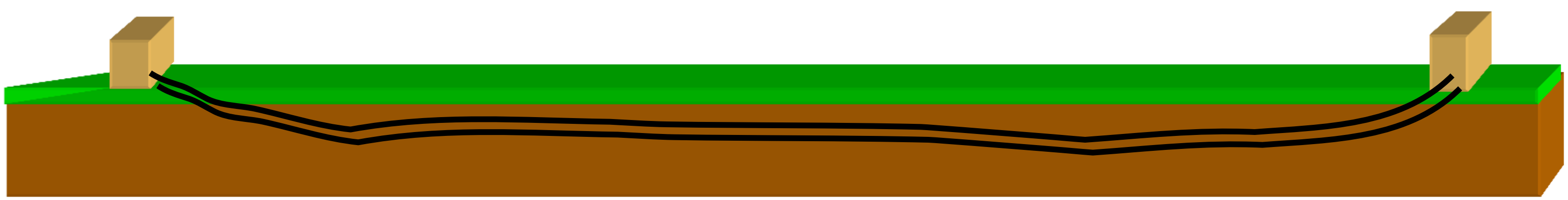
Converter station



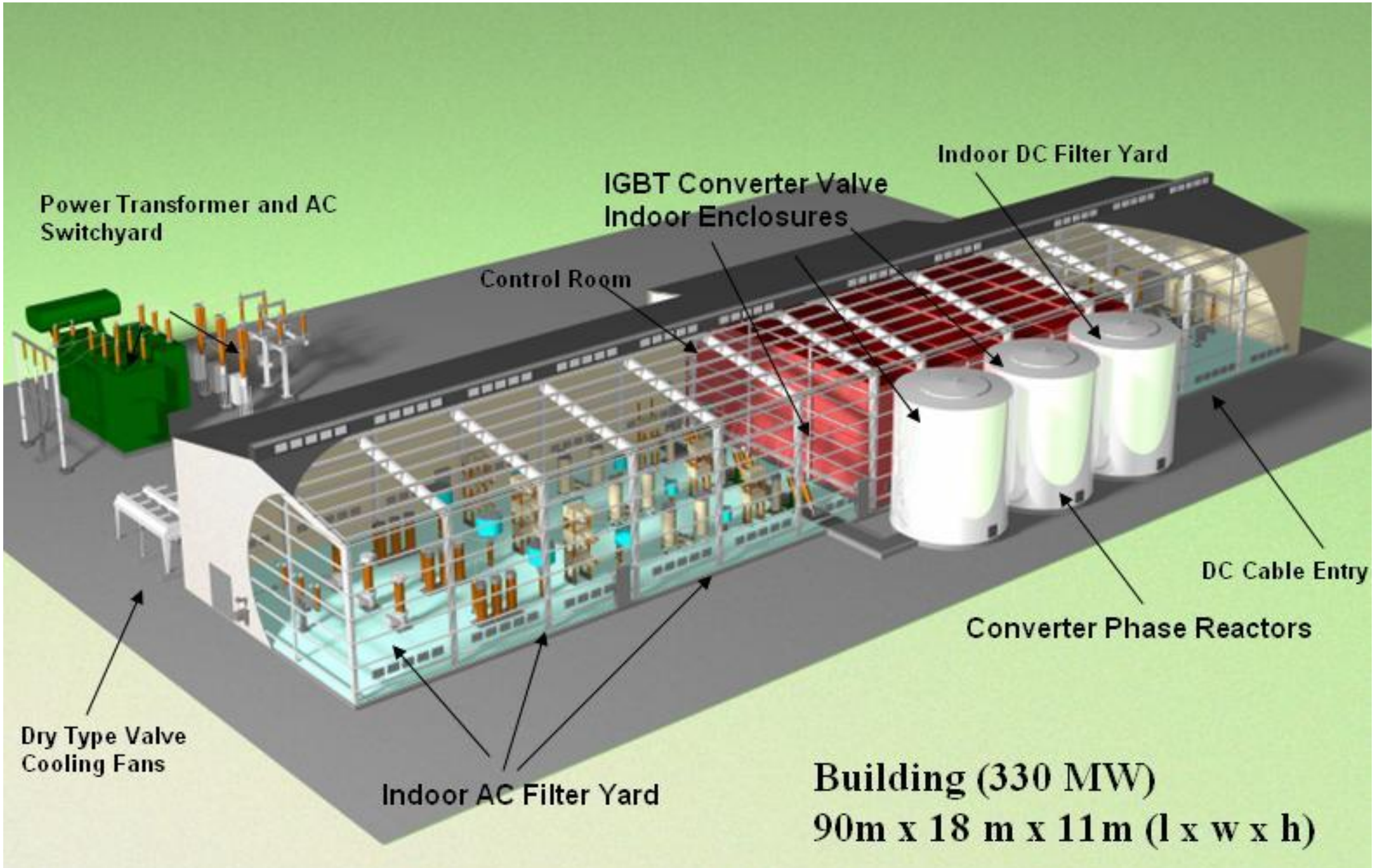
Converter station

Converter station

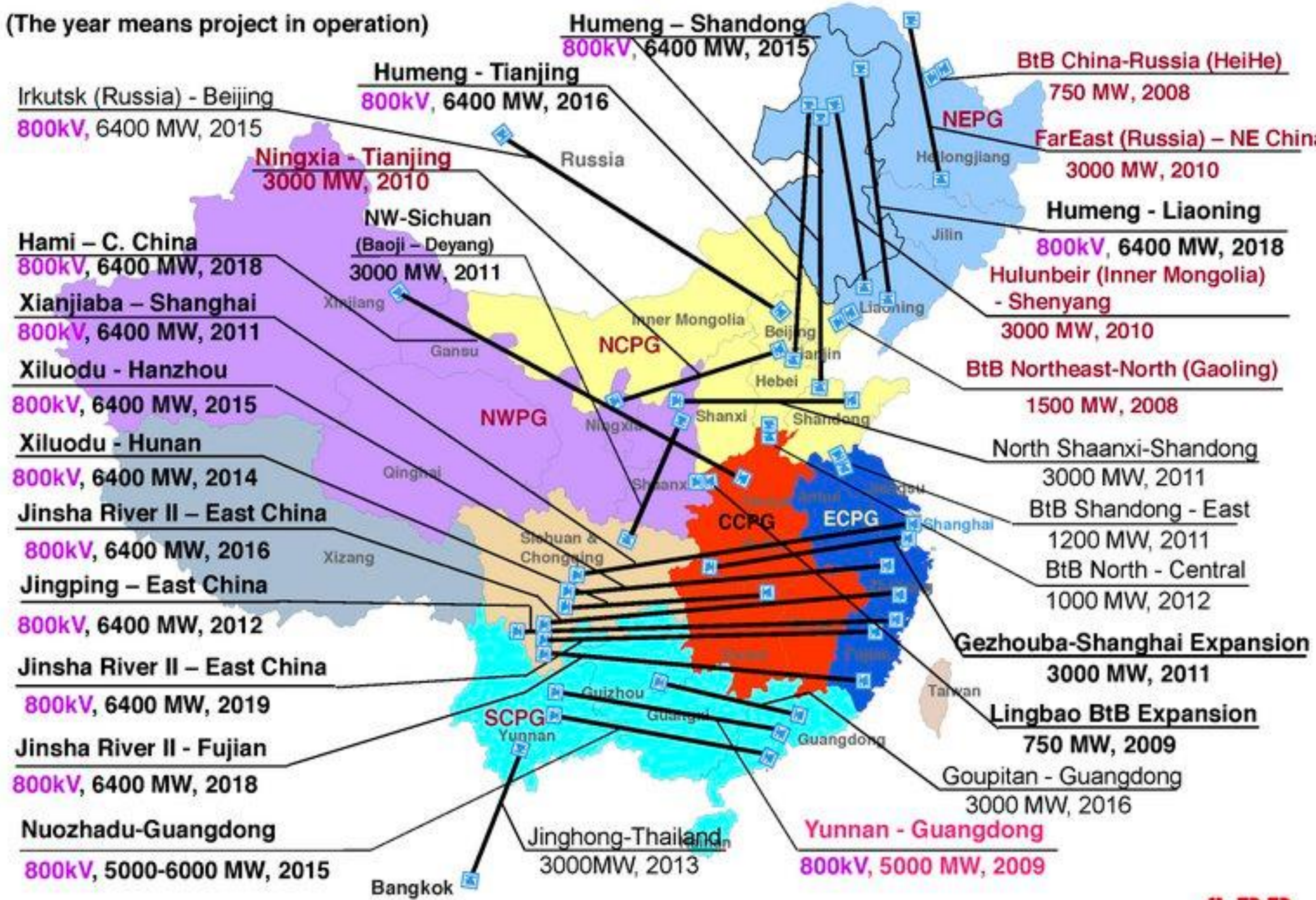
Cables



HVDC Converter Station



Planned Future HVDC Projects by 2020 in China

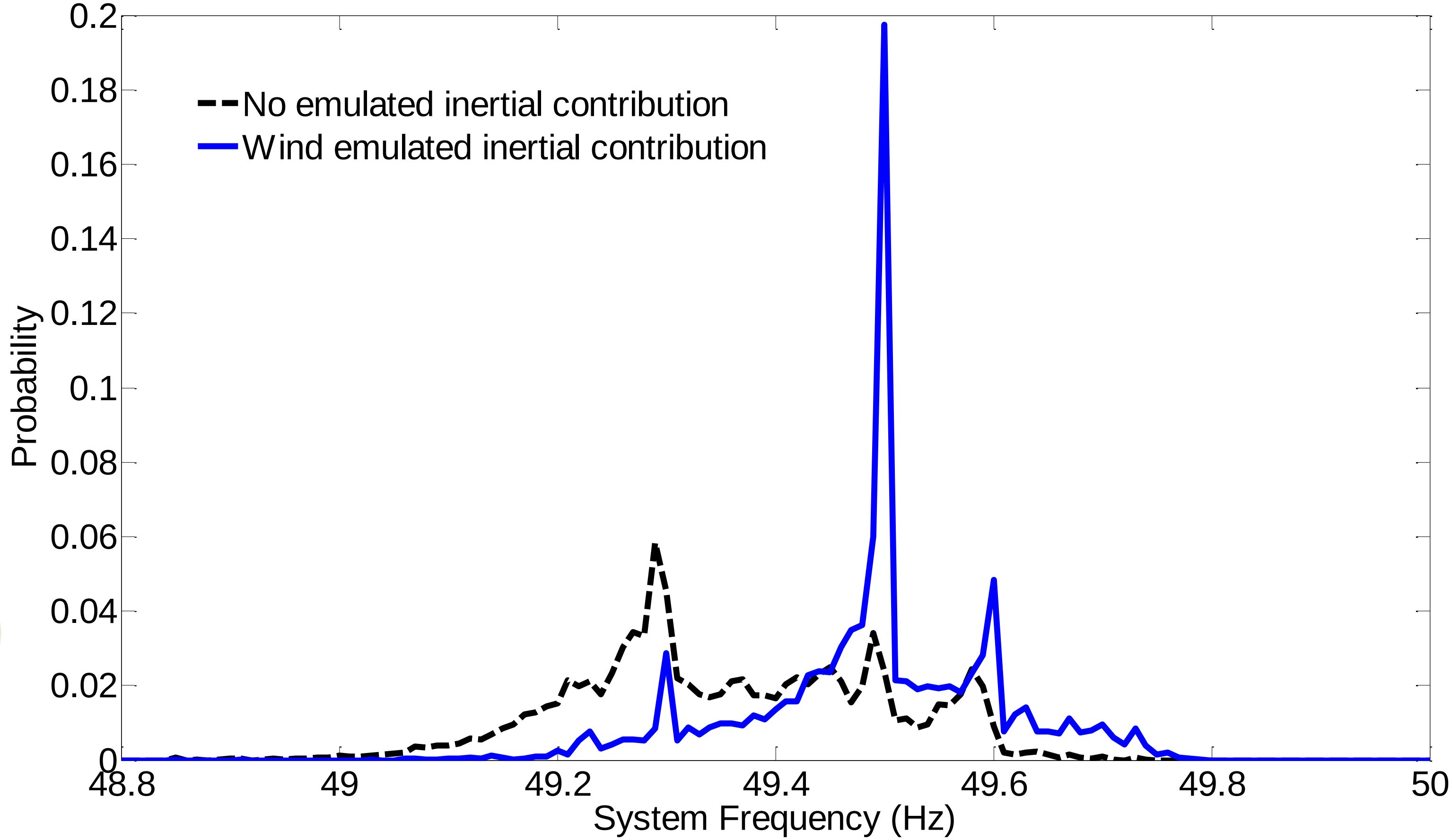


(Indicative map)

Very High Penetrations “Technical” Flexibility is Key

- Frequency nadir (lowest point) can be improved

(DS3)



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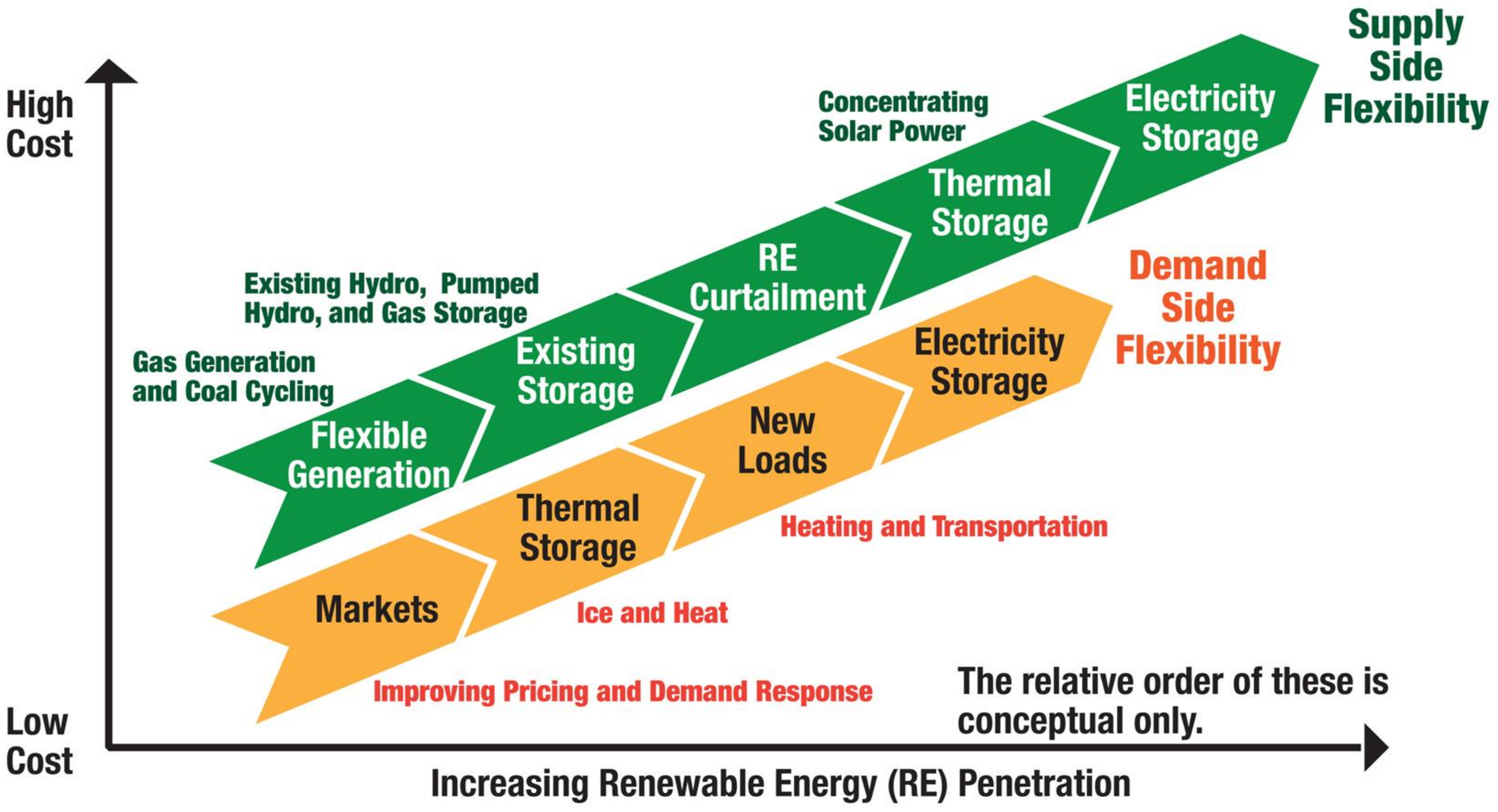
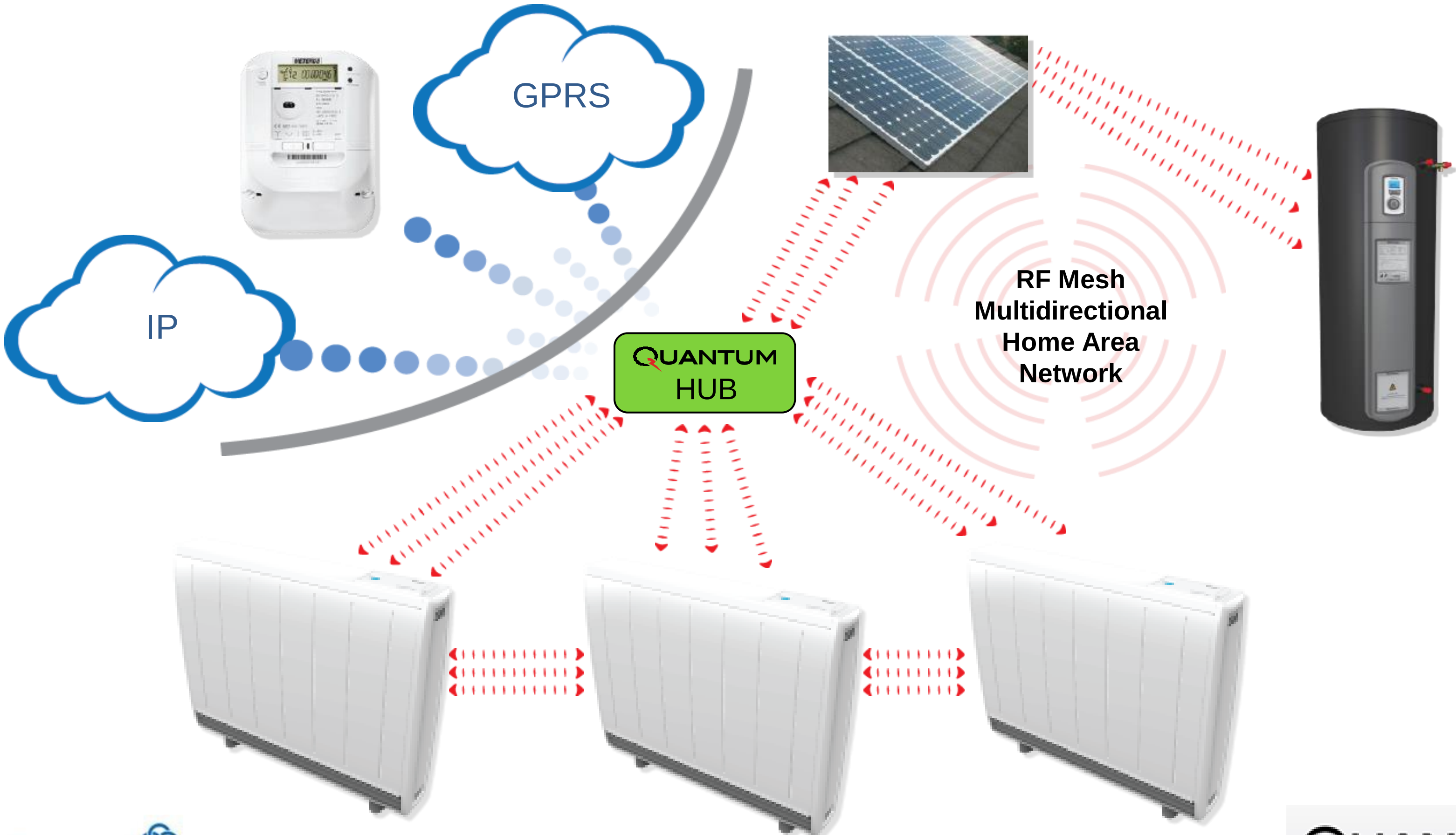
Flexibility Supply Curve



How do we choose the optimum mix of flexibility resources?

Electric Heat Demand is Very Flexible



GlenDimplex

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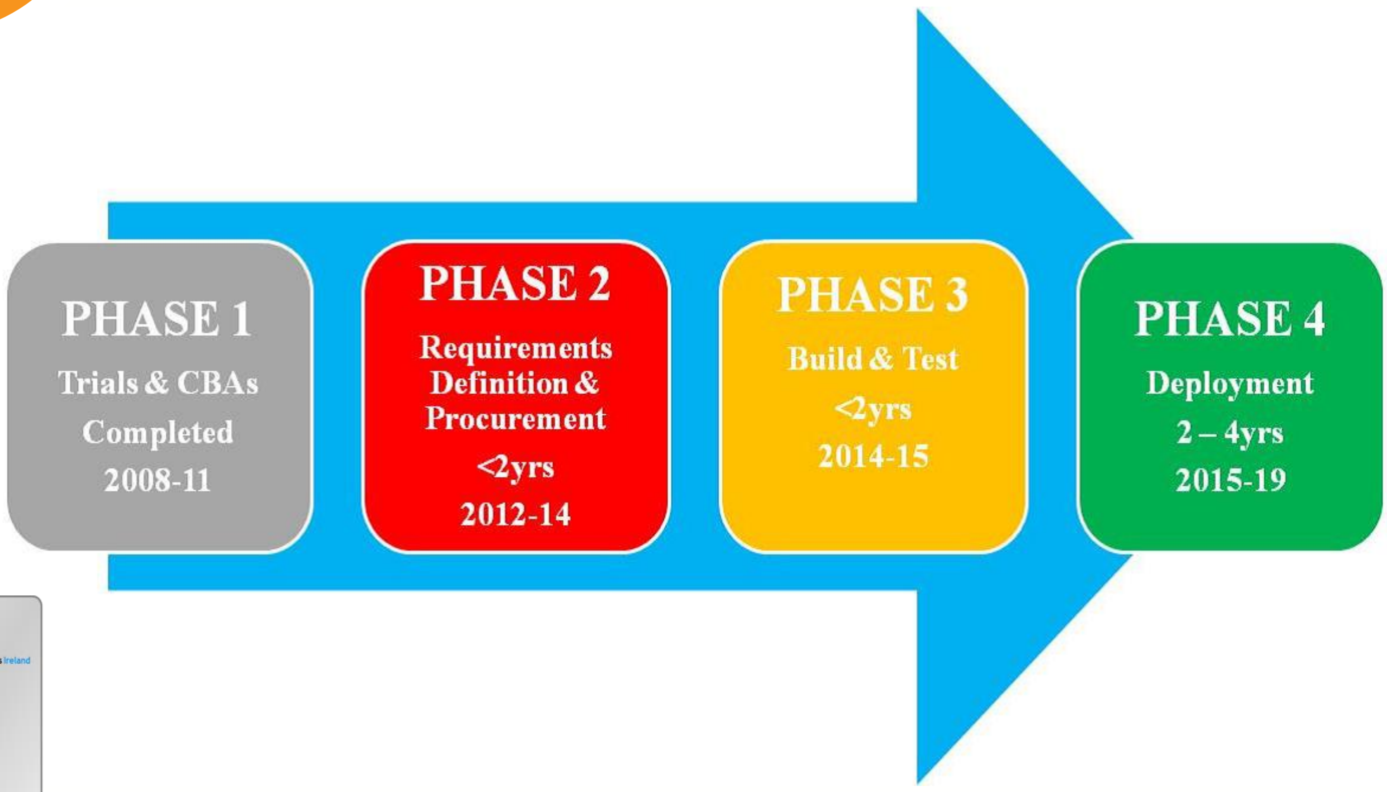
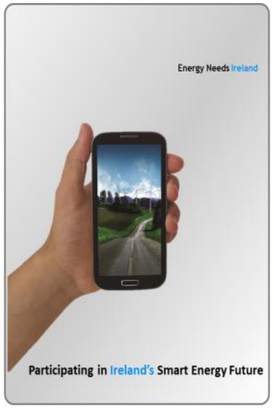
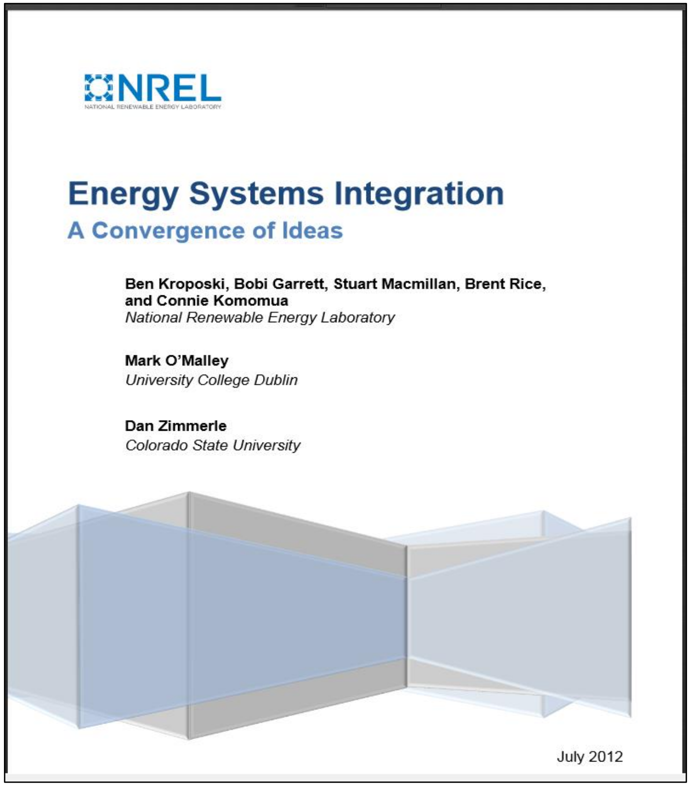
The Consumer and Their Education





http://eni.ucd.ie/2013/ENI_2013_White_Paper.pdf

Some Reading Material


NREL
National Renewable Energy Laboratory

Energy Systems Integration
A Convergence of Ideas

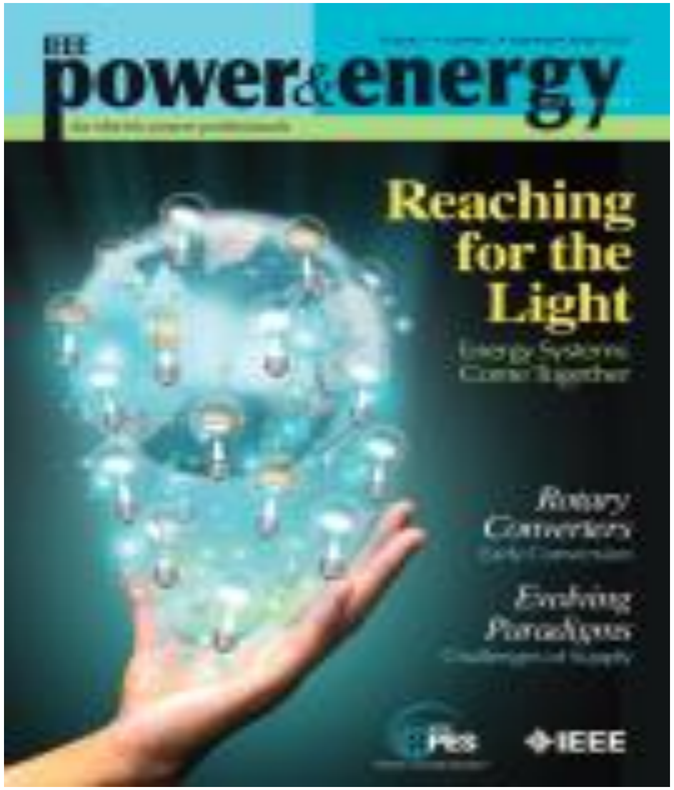
Ben Kroposki, Bobi Garrett, Stuart Macmillan, Brent Rice, and Connie Komomua
National Renewable Energy Laboratory

Mark O'Malley
University College Dublin

Dan Zimmerle
Colorado State University

July 2012

Kroposki, B., Garrett, B., Macmillan, S., Rice, B., Komomua, C., O'Malley, M.J., Zimmerle, D. "Energy Systems Integration, A Convergence of Ideas, National Renewable Energy Laboratory, Technical Paper NREL/TP-6A00-55649, July 2012.
http://www.nrel.gov/docs/fy12osti/55649.pdf



O'Malley, M.J. and Kroposki B. "Energy comes together the integration of all systems", Editorial, Special issue in Energy Systems Integration, *IEEE Power & Energy Magazine*, Vol. 11, Sept/October, pp. 18 – 23, 2013.
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