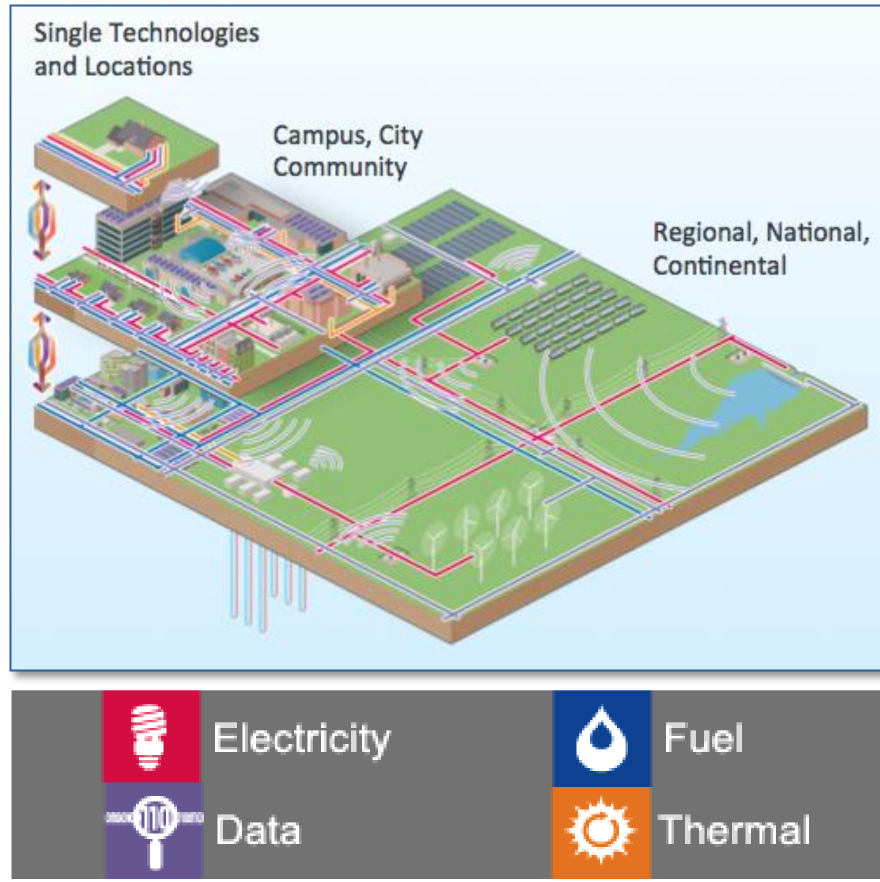
Energy Systems Integration (ESI) 101

Mark O'Malley

mark.omalley@ucd.ie

GCEP Research Symposium, Stanford, USA

8th October 2013



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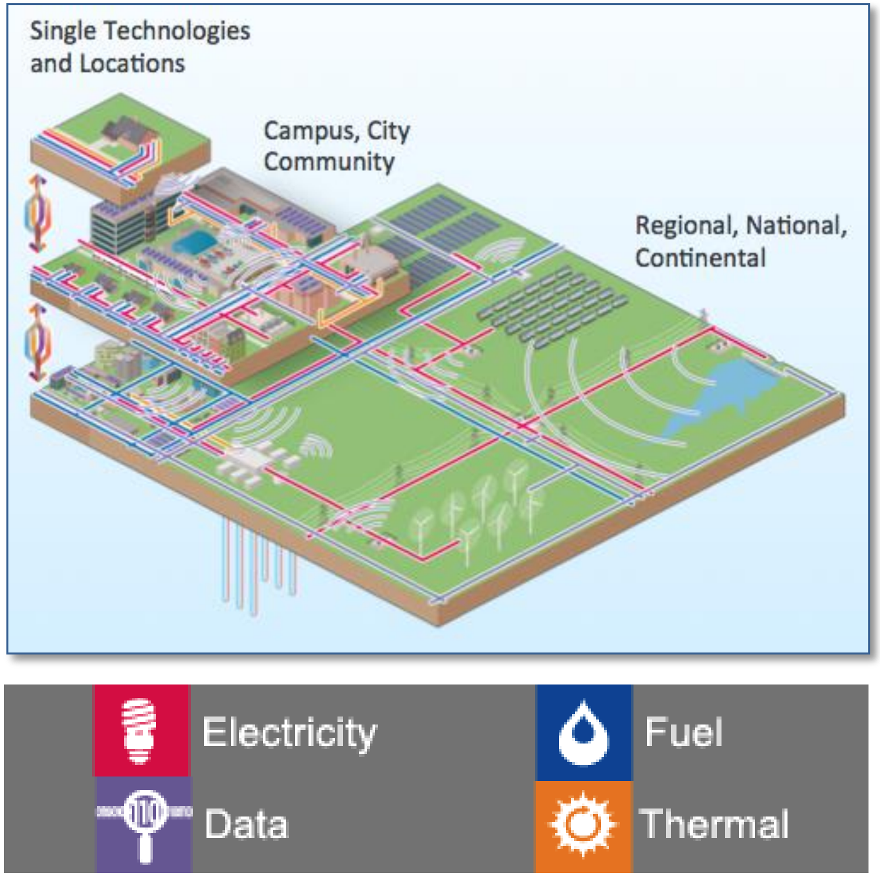

Energy Systems Integration (ESI) 101

NREL, Golden Colorado

Mid July 2014

Contact:
courtney.pailing@nrel.gov

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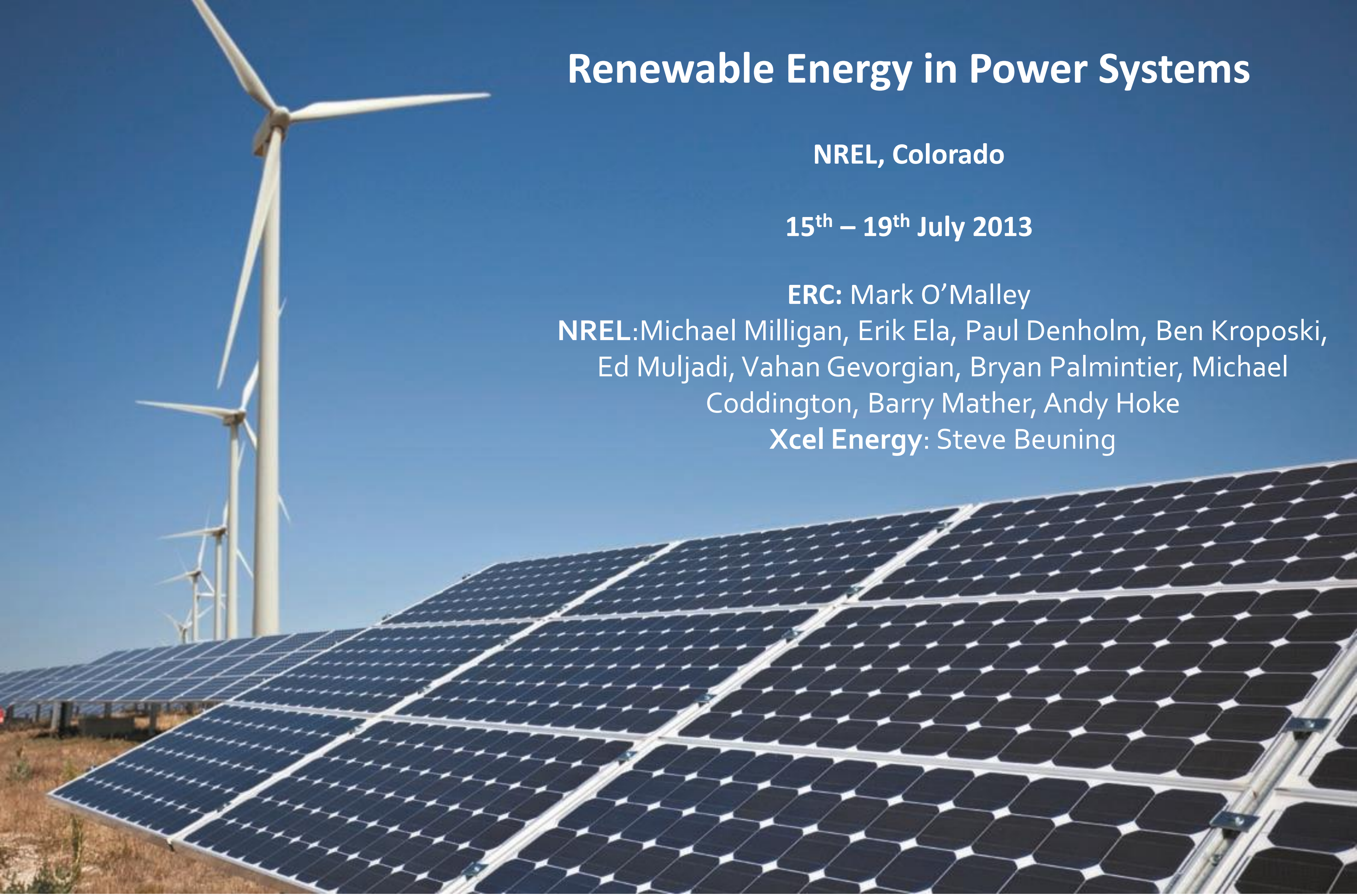
Renewable Energy in Power Systems

NREL, Colorado

15th – 19th July 2013

ERC: Mark O'Malley
NREL:Michael Milligan, Erik Ela, Paul Denholm, Ben Kroposki, Ed Muljadi, Vahan Gevorgian, Bryan Palmintier, Michael Coddington, Barry Mather, Andy Hoke
Xcel Energy: Steve Beuning



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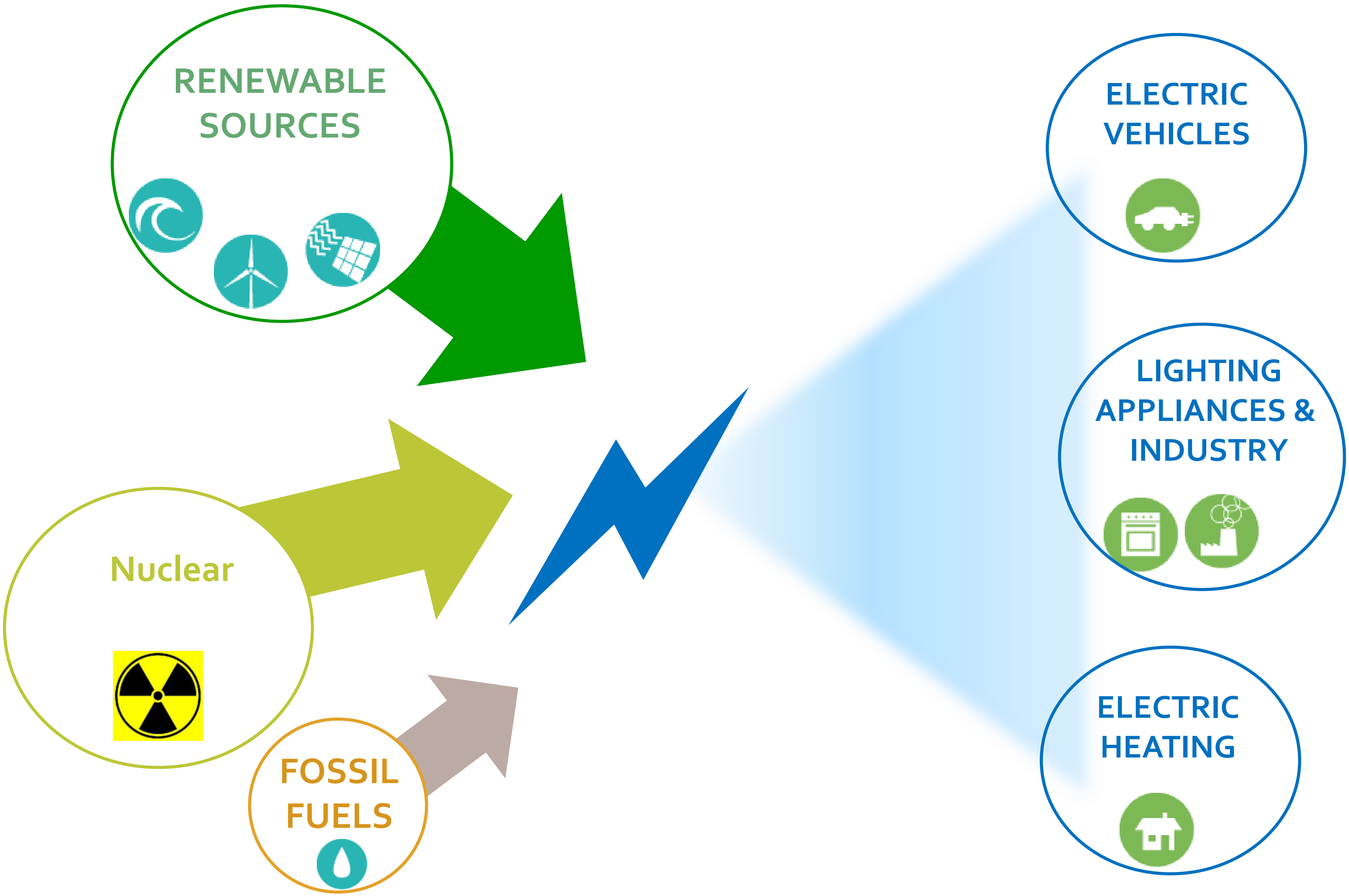
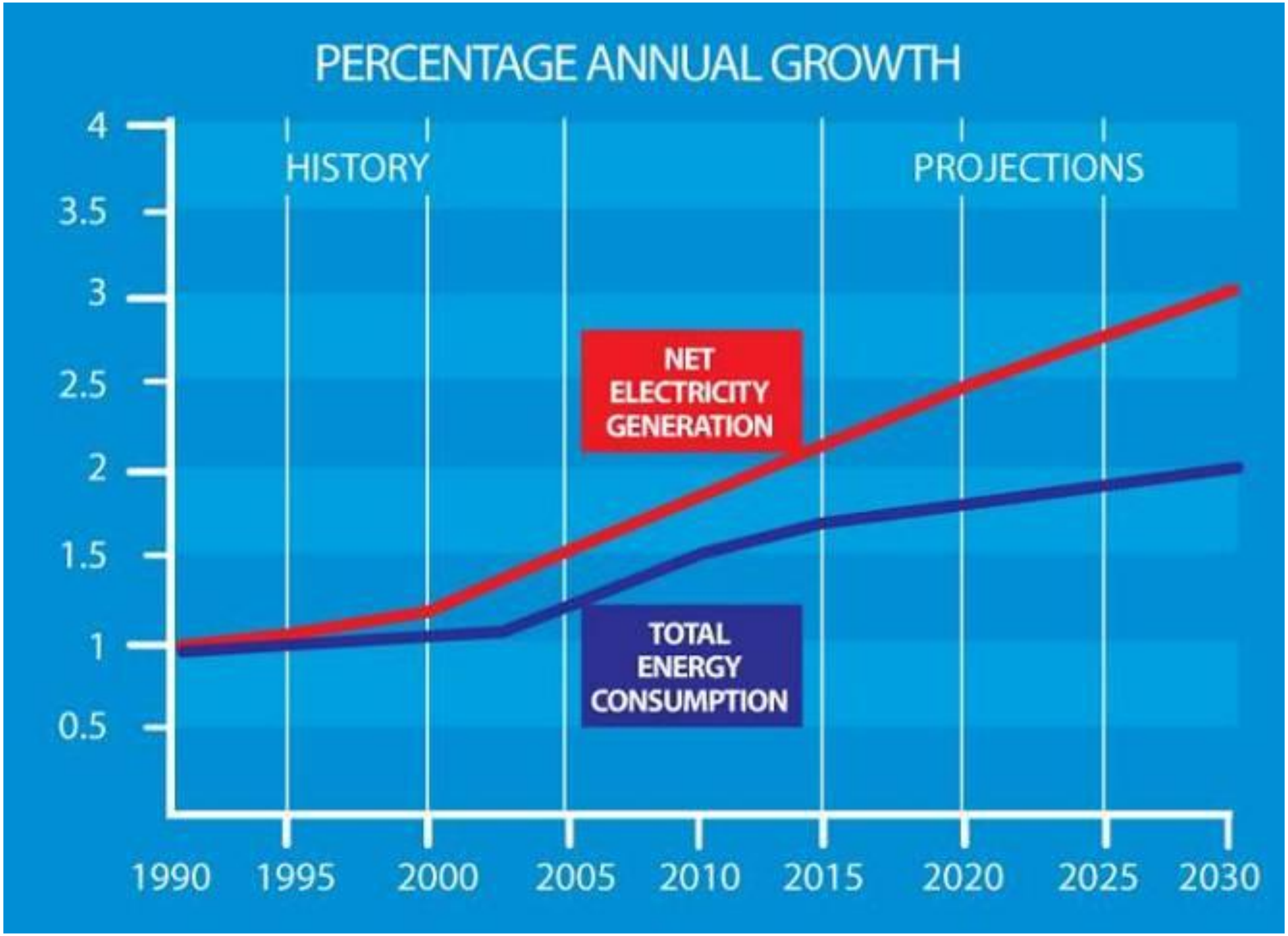
Electric future



The future is electric



Source: Energy Information Administration (EIA), 2008.

Grid Flexibility and Research Challenges to Enhance the Integration of Variable Renewable Energy Sources

Mark O'Malley, Electrical Engineering Dept., University College Dublin

Monday, January 14, 2013 | 04:15 PM - 05:15 PM | NVIDIA Auditorium, Jen-Hsun Huang Engineering Center | Free and Open to All

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Tags in Related themes

asia battery storage behavior bio-fuel carbon sequestration china clean tech climate change coal economics energy and climate policy energy efficiency energy ethics and equity energy for the developing world energy policy environment

Key Take Away # 1

- It is not all about Electricity, and the presenter is out of his comfort zone.

GLOBAL CLIMATE AND ENERGY PROJECT | STANFORD UNIVERSITY

GCEP

Energy Tutorial:
Energy & Earth Systems 101

GCEP RESEARCH SYMPOSIUM 2012 | STANFORD, CA

Pamela Matson

Dean - School of Earth Sciences
Senior Fellow - Woods Institute for Environment

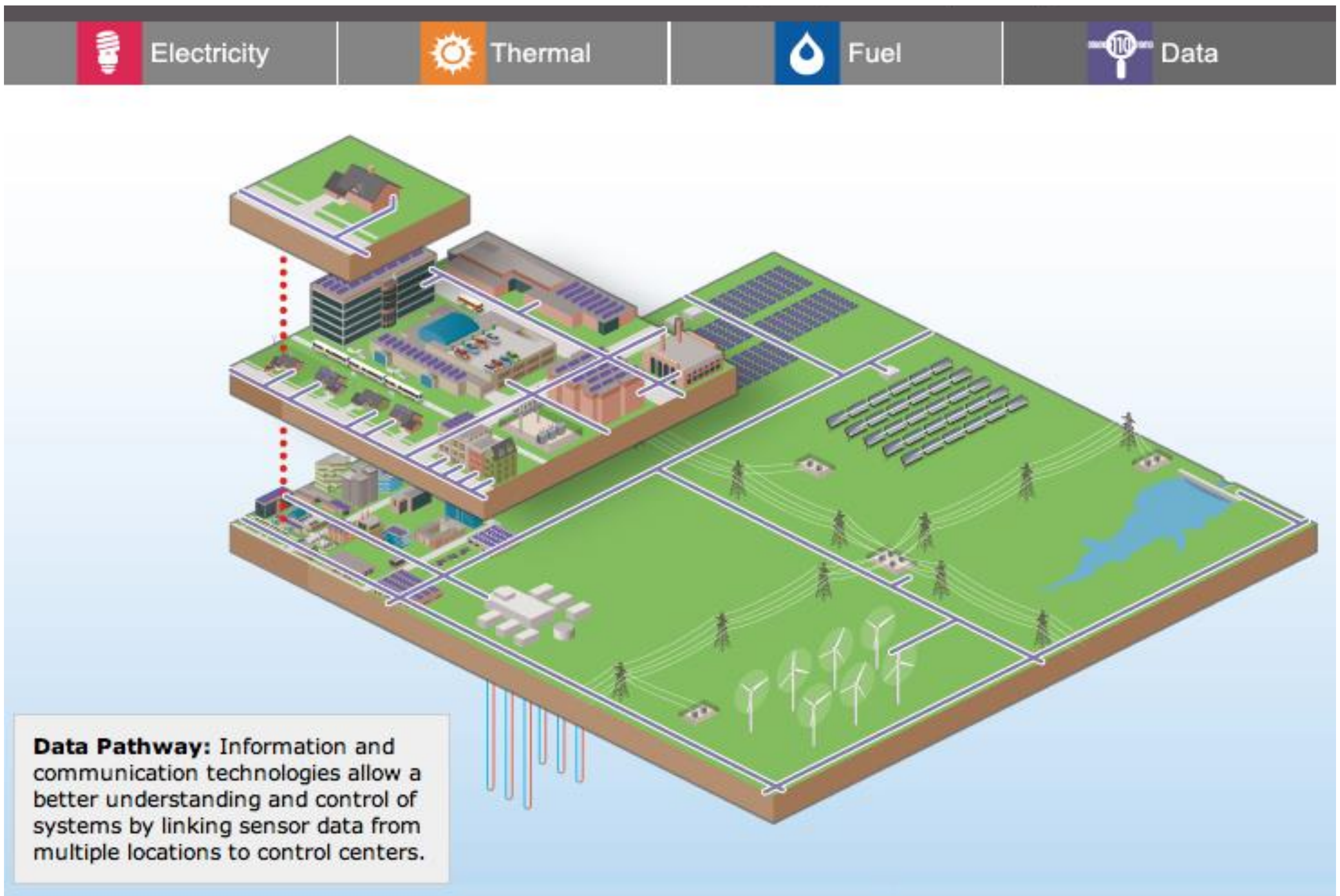
Ian Monroe

Visiting scholar
Stanford University

GLOBAL CHALLENGES – GLOBAL SOLUTIONS – GLOBAL OPPORTUNITIES

What is Energy Systems Integration?

Energy system integration (ESI) = the process of optimizing energy systems across multiple pathways and scales



Electricity

Thermal

Fuel

Data

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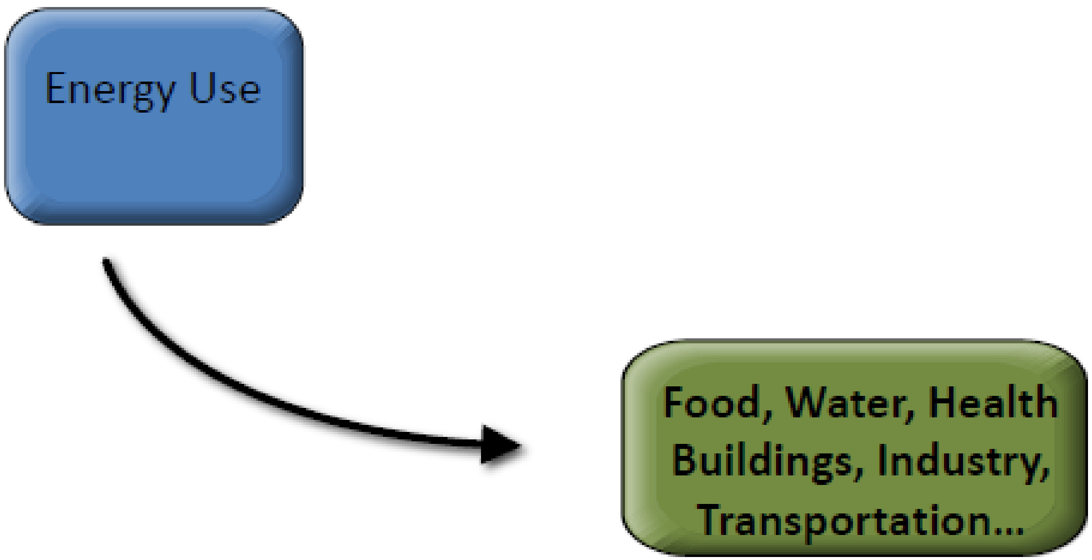
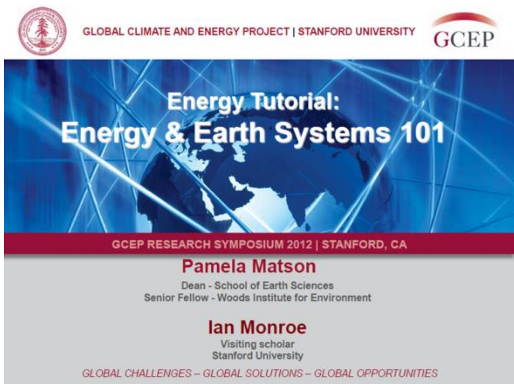
Energy is key to just about everything we do, and provision of energy is a *sustainability* challenge





Wider Convergence

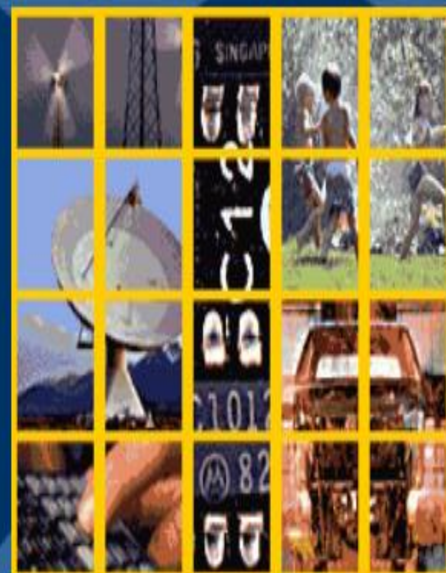
Greatest Engineering Achievements OF THE 20TH CENTURY

◆ 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

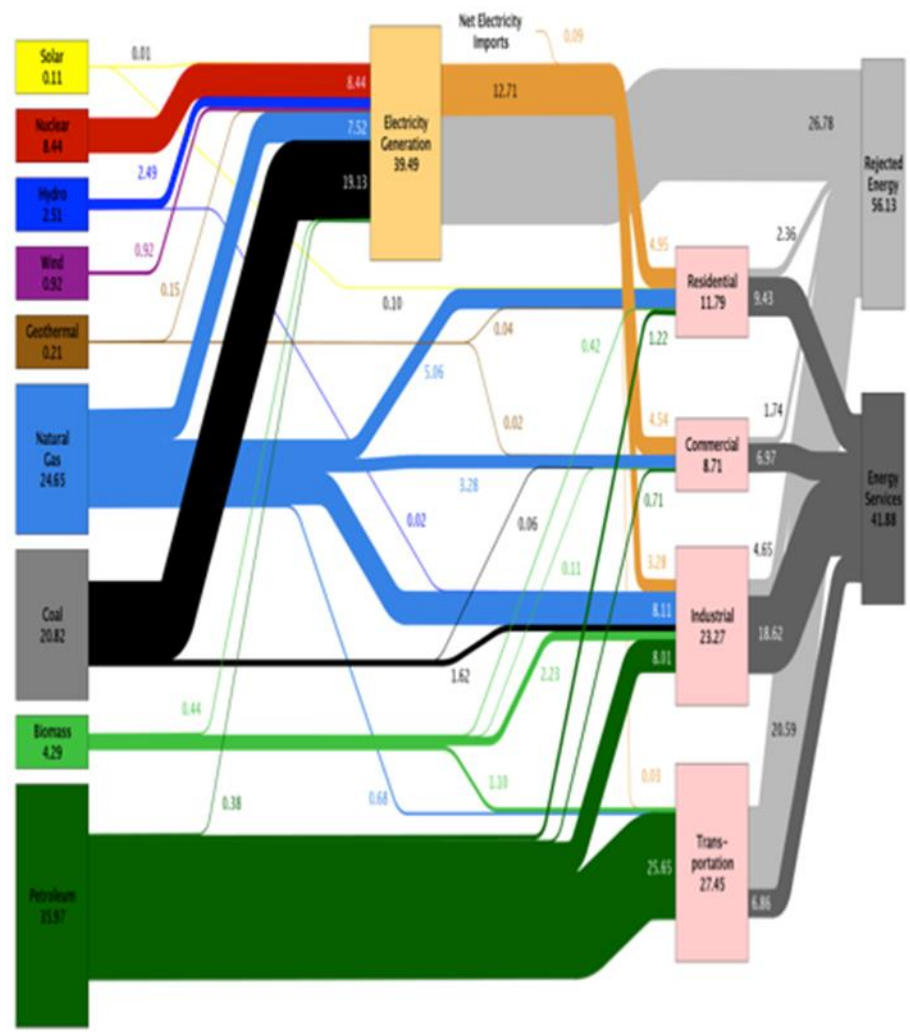
1. Energy conservation
2. Resource protection
3. Food and water production and distribution
4. Waste management
5. Education and learning
6. Medicine and prolonging life
7. Security and counter-terrorism
8. New technology
9. Genetics and cloning
10. Global communication
11. Traffic and population logistics
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.

Energy Systems Integration

- **Major opportunities**
  - Digital revolution and new integration technologies allow for synergistic operation of interdependent infrastructures
  - Greatly increase overall system efficiency through synergistic use of energy sources
  - Increase utilization of existing assets
  - Develop an energy system that provides 80% electricity from clean sources by 2035
- **Major challenges**
  - Need to create and energy infrastructure that empowers flexibility to accommodate clean energy
  - Energy domains (electricity, thermal, fuels, communications, water) not historically planned and operated in an integrated fashion



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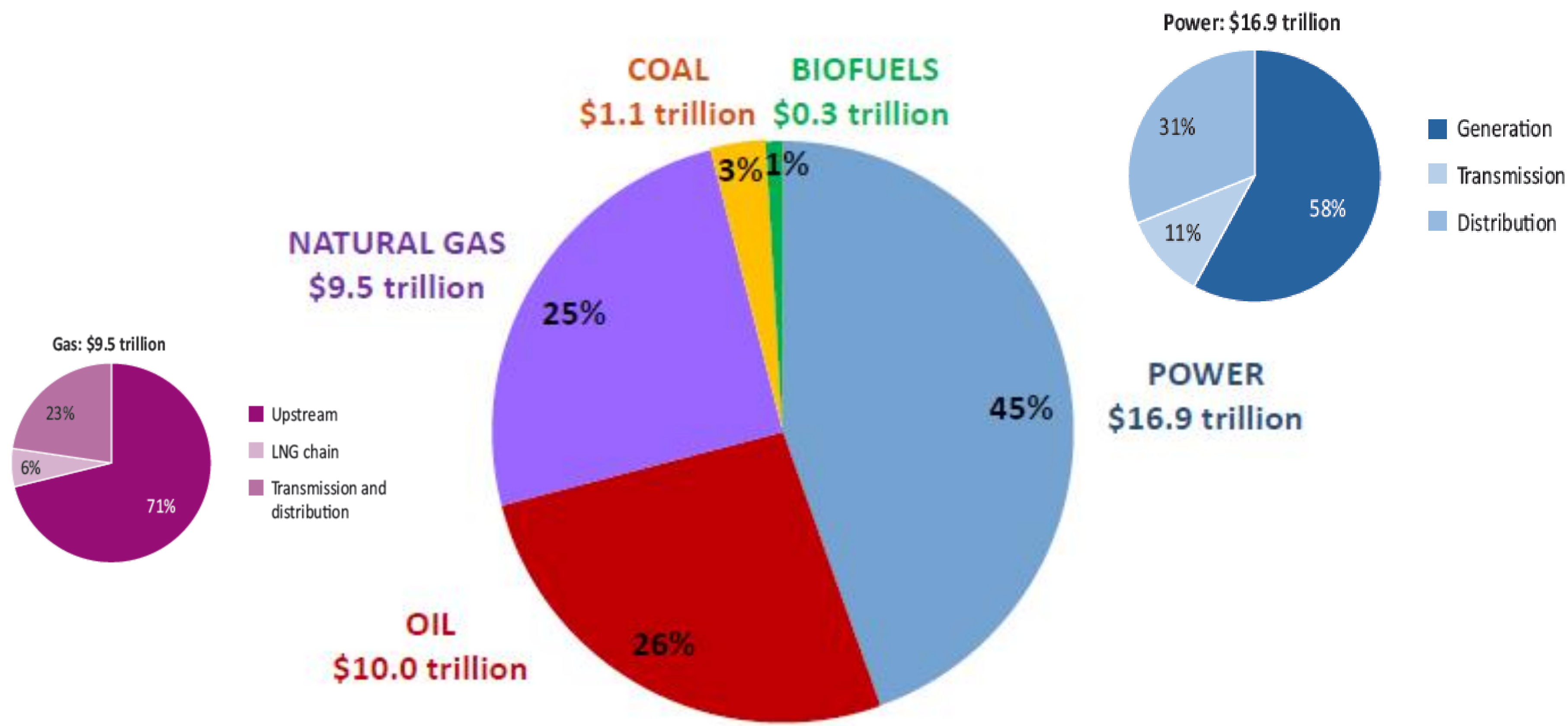
Investment: the essence of energy

WORLD ENERGY OUTLOOK 2011

Cumulative investment in energy infrastructure, *2011-2035*



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

…**renewable energy integration** as well as roll-out solutions for integration into intelligent electricity_grids

…. and **integration of heating/cooling**

… integration of CHP and micro-CHP into smart grids

…. integration of other types of **microgeneration, demand response and storage into the grid**

…innovation is needed in system **integration, interoperable technologies, services, tools, co-ordination schemes, business processes, market architectures and regulatory regimes to plan, build, monitor, control and safely operate end-to-end networks in** an open, competitive, decarbonised, sustainable and climate-change resilient market, under normal and emergency conditions

…integration of **ICT in electricity grid systems**

Key Take Away # 2

- It is very important, evolving & new

electricity research centre

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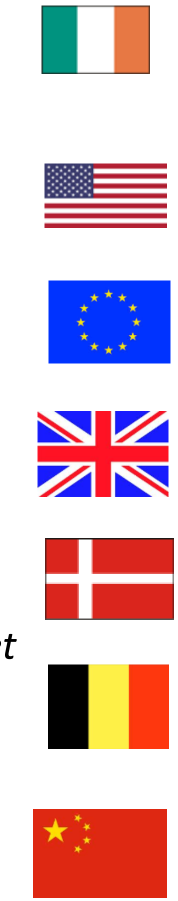
What have we done about this ?

IEEE Power & Energy Magazine, Sept./Oct. 2013

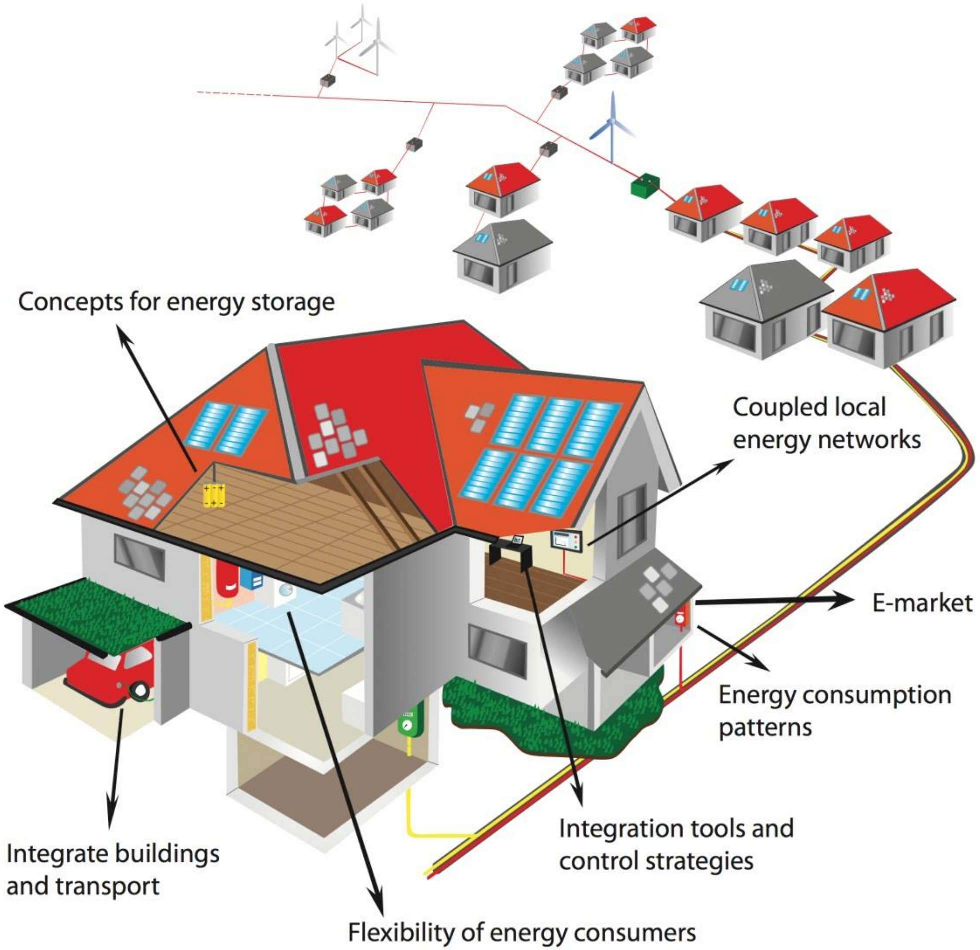
M. O'Malley and B. Kroposki Guest Editors

- 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 modeling for ESI – Juan Van Roy *et al.* KU Leuven
- China ESI – Chongqing Kang *et al.*, Tsinghua University

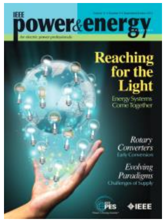


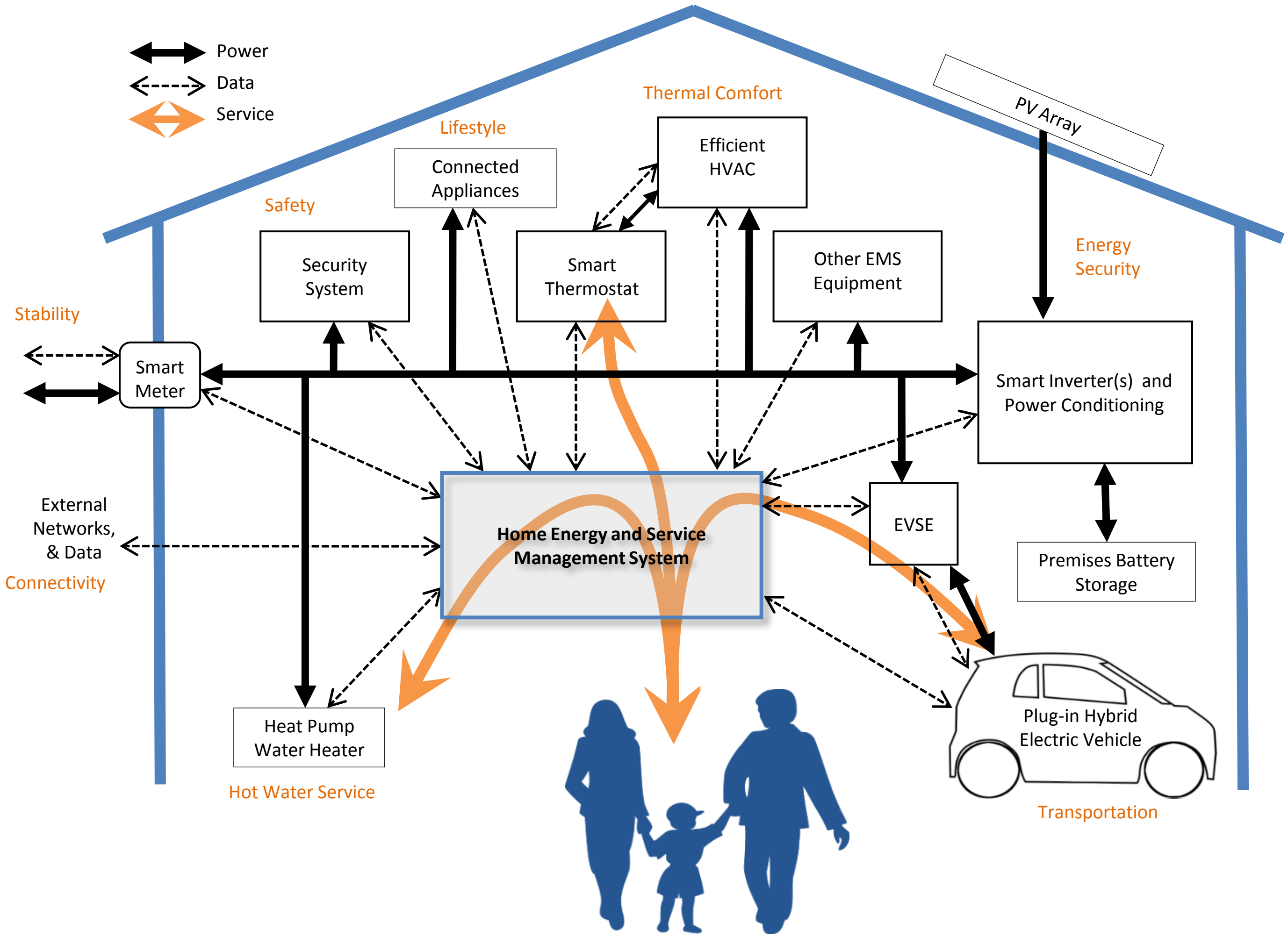
O'Malley, M.J. and Kroposki B. "Energy comes together the integration of all systems", Editorial, Special issue in Energy Systems Integration, *IEEE Power & Energy Magazine*, Vol. 11, Sept/October, pp. 18 – 23, 2013.

Smart Homes



Van Roy, J.; Verbruggen, B.; Driesen, J., "Ideas for Tomorrow: New Tools for Integrated Building and District Modeling," *Power and Energy Magazine, IEEE* , vol.11, no.5, pp.75,81, Sept. 2013. doi: 10.1109/MPE.2013.2268815





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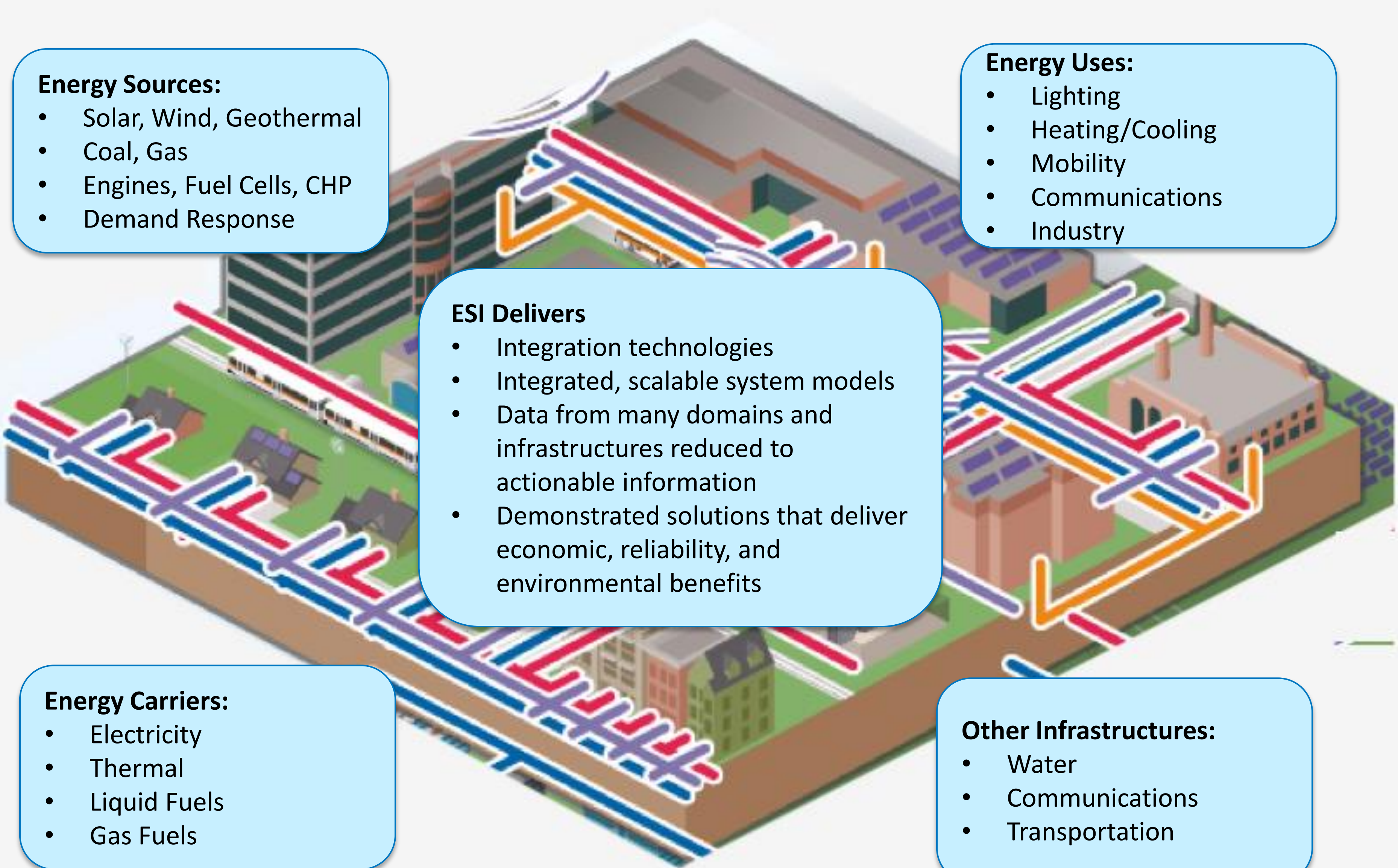
The Smart City



Energy Sources:
- Solar, Wind, Geothermal
- Coal, Gas
- Engines, Fuel Cells, CHP
- Demand Response

Energy Uses:
- Lighting
- Heating/Cooling
- Mobility
- Communications
- Industry

ESI Delivers
- Integration technologies
- Integrated, scalable system models
- Data from many domains and infrastructures reduced to actionable information
- Demonstrated solutions that deliver economic, reliability, and environmental benefits

Energy Carriers:
- Electricity
- Thermal
- Liquid Fuels
- Gas Fuels

Other Infrastructures:
- Water
- Communications
- Transportation

http://www.nrel.gov/esi/esif.html

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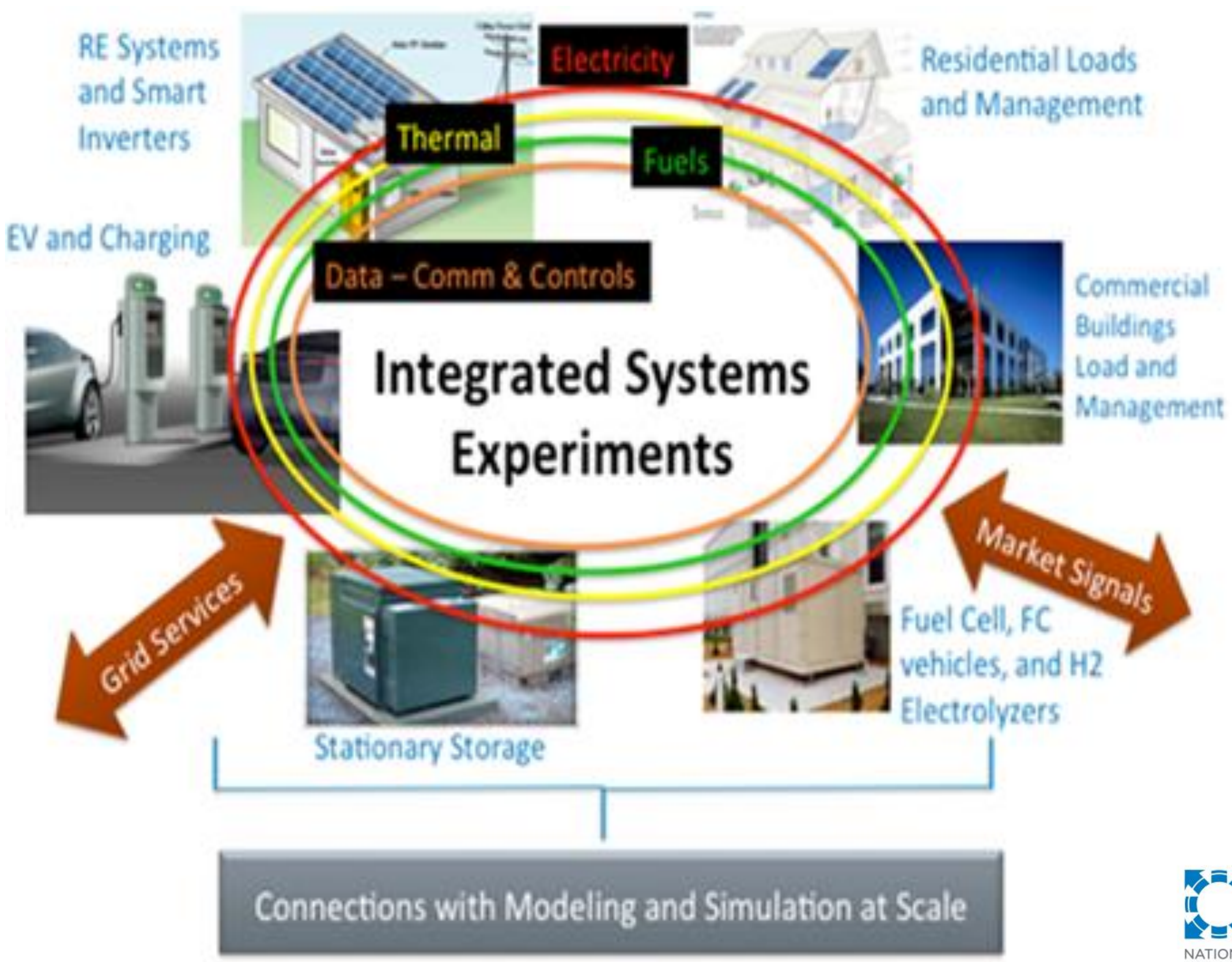
We need to move beyond paper studies and demonstrate solutions at scale



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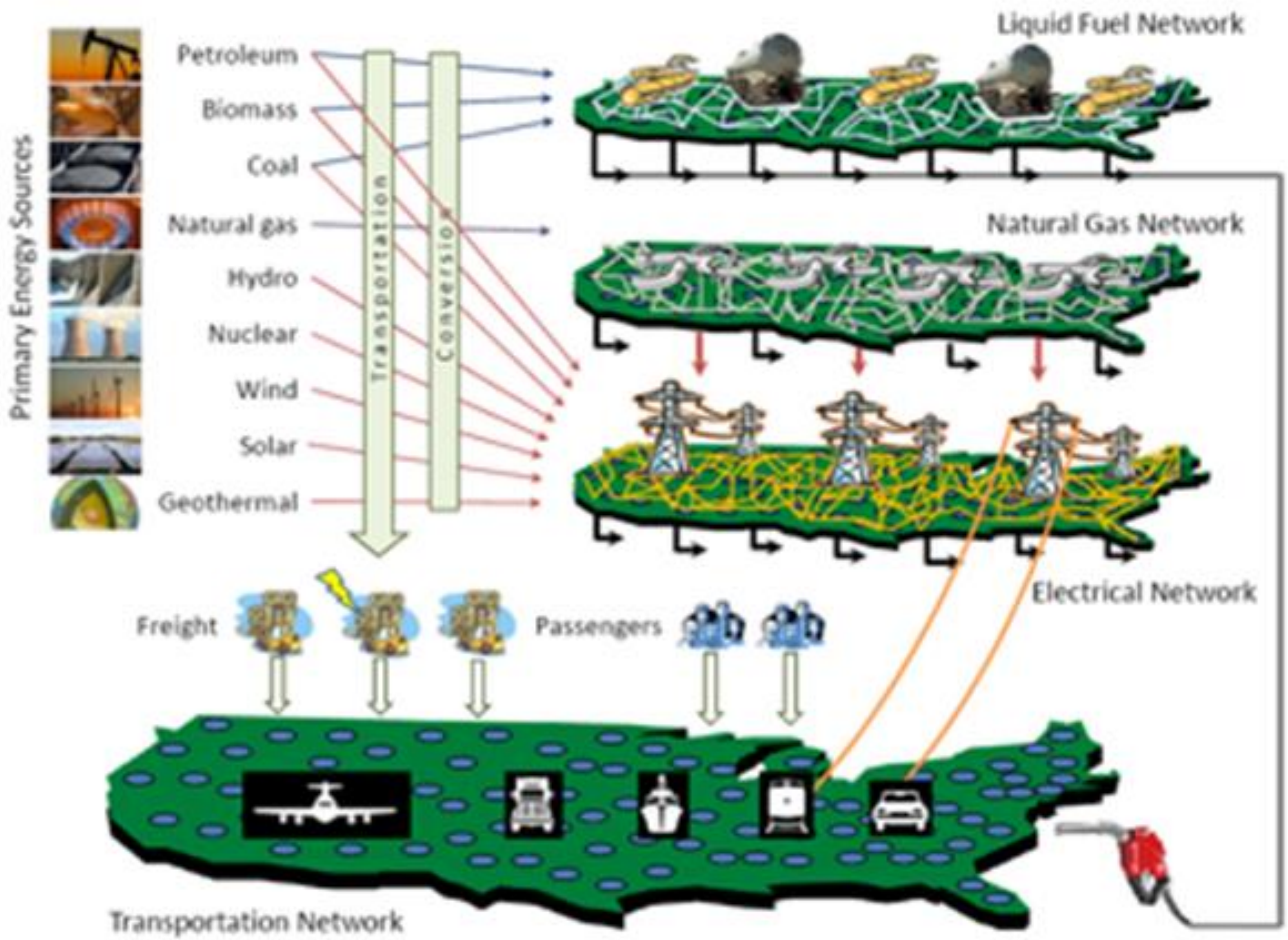
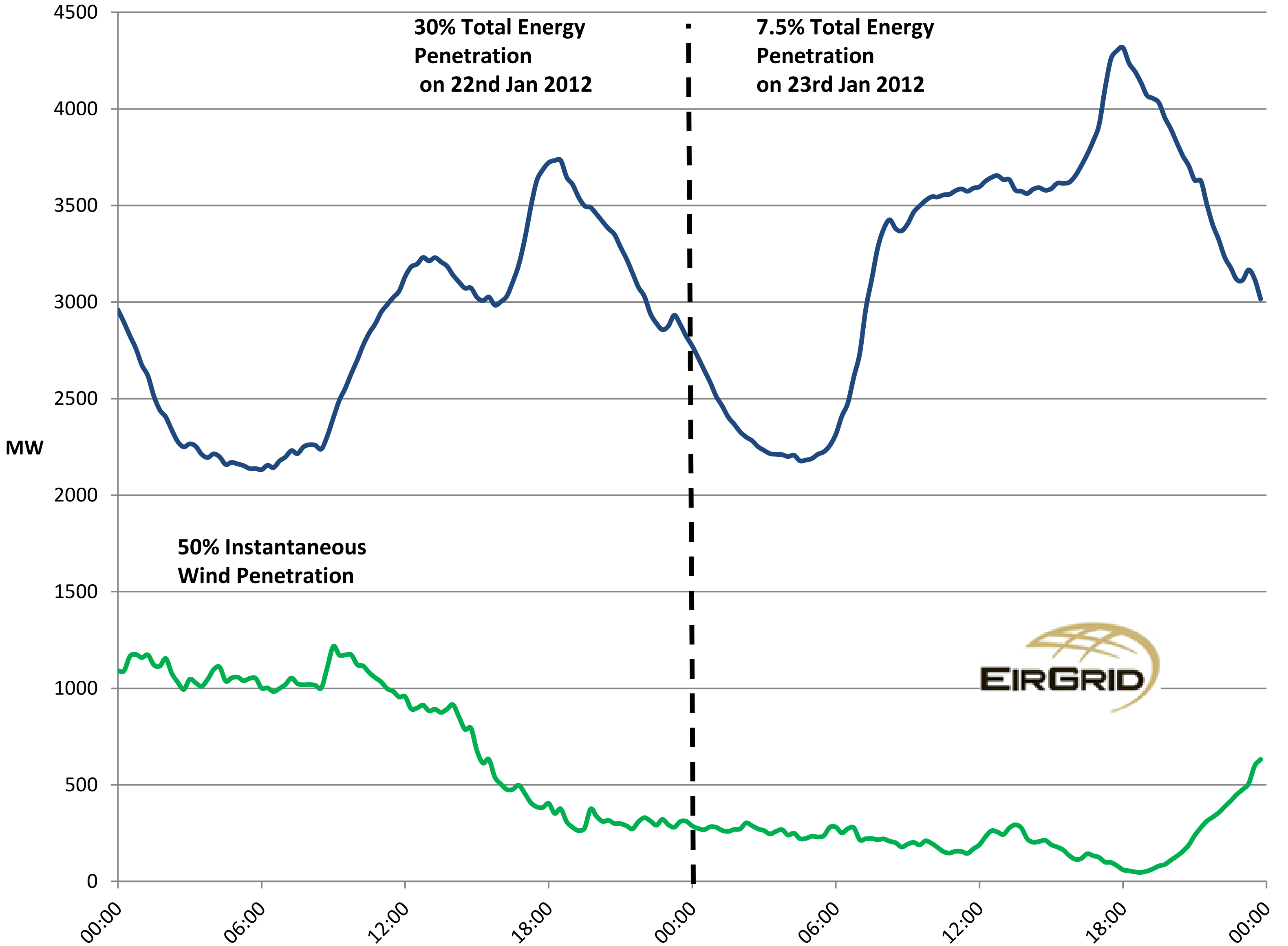
Planning at scale



McCalley, J.; Jewell, W.; Mount, T.; Osborn, D.; Fleeman, J. , *"A Wider Horizon"*, IEEE Power and Energy Magazine, Vol. 9, Issue: 3, 2011

McCalley, J.; Krishnan, V.; Gkritza, K.; Brown, R.; Mejia-Giraldo, D., "Planning for the Long Haul: Investment Strategies for National Energy and Transportation Infrastructures," *Power and Energy Magazine, IEEE* , vol.11, no.5, pp.24,35, Sept. 2013. doi: 10.1109/MPE.2013.2268712

Wind Power in Ireland



Future Grid Test Bed

Memorandum of Understanding

**between ESB, EirGrid plc,
ESB Networks Ltd, SONI Ltd, and NIE Ltd**

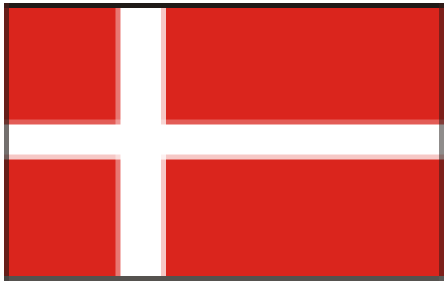
**establishing a collaborative relationship to facilitate
optimal Smart Grid development on the island of Ireland**

Parties

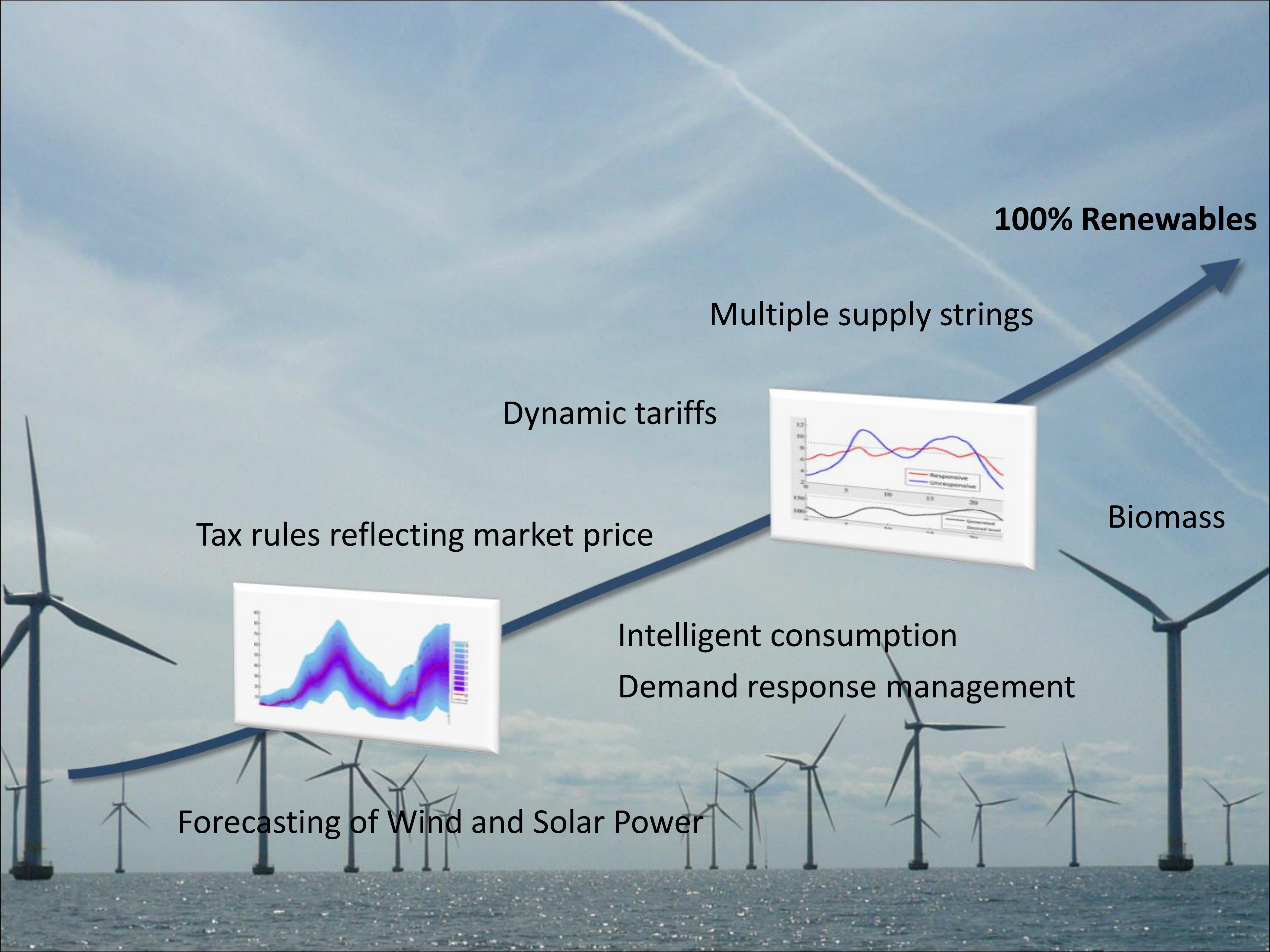
This Memorandum of Understanding is made between the following Parties:

Key Take Away # 3

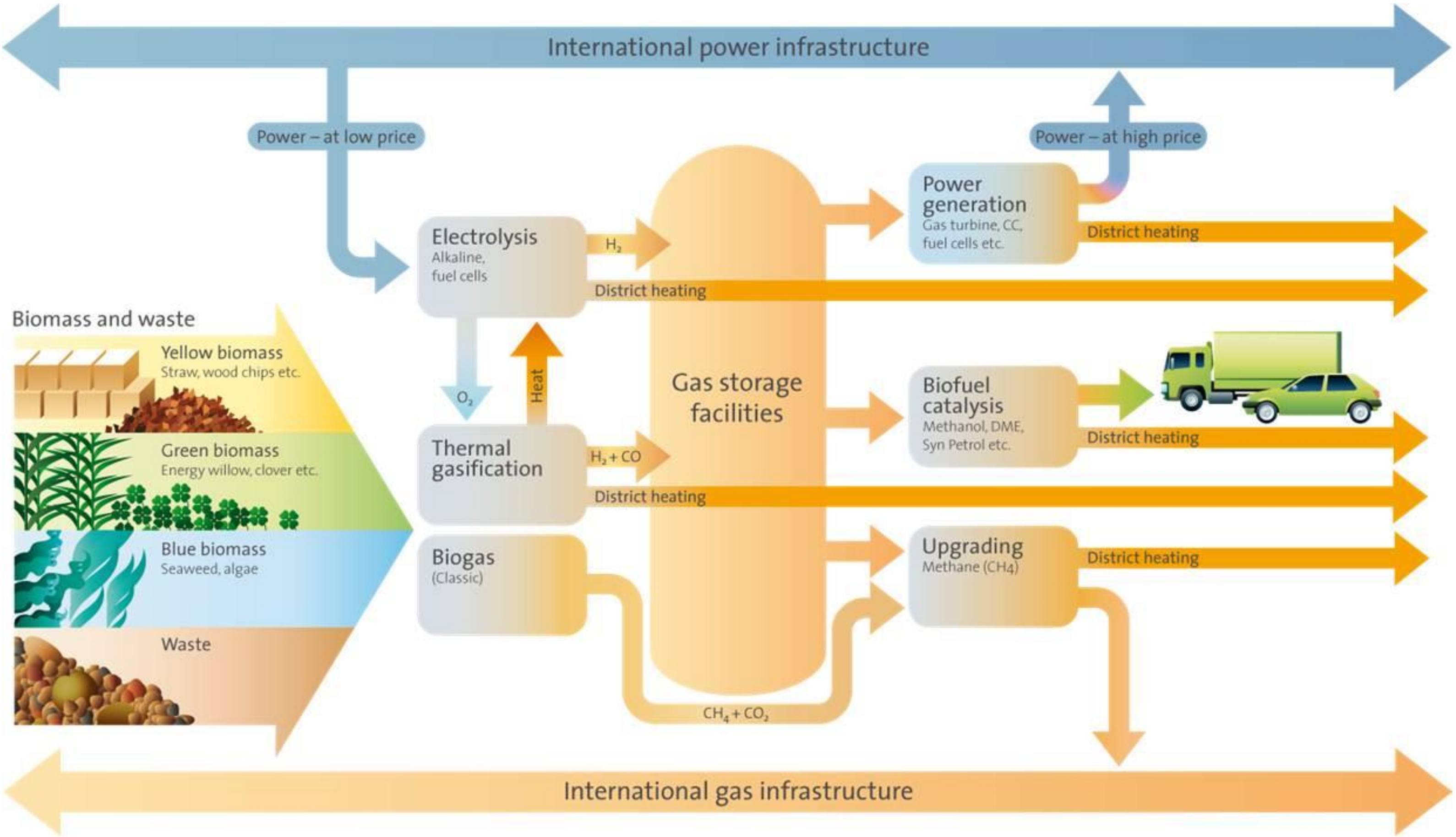
- It is international and at all scales



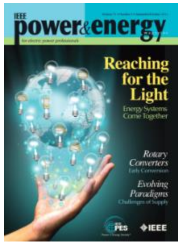
Denmark ahead of the rest


100% Renewables
Multiple supply strings
Dynamic tariffs
Biomass
Tax rules reflecting market price
Intelligent consumption
Demand response management
Forecasting of Wind and Solar Power

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



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 %

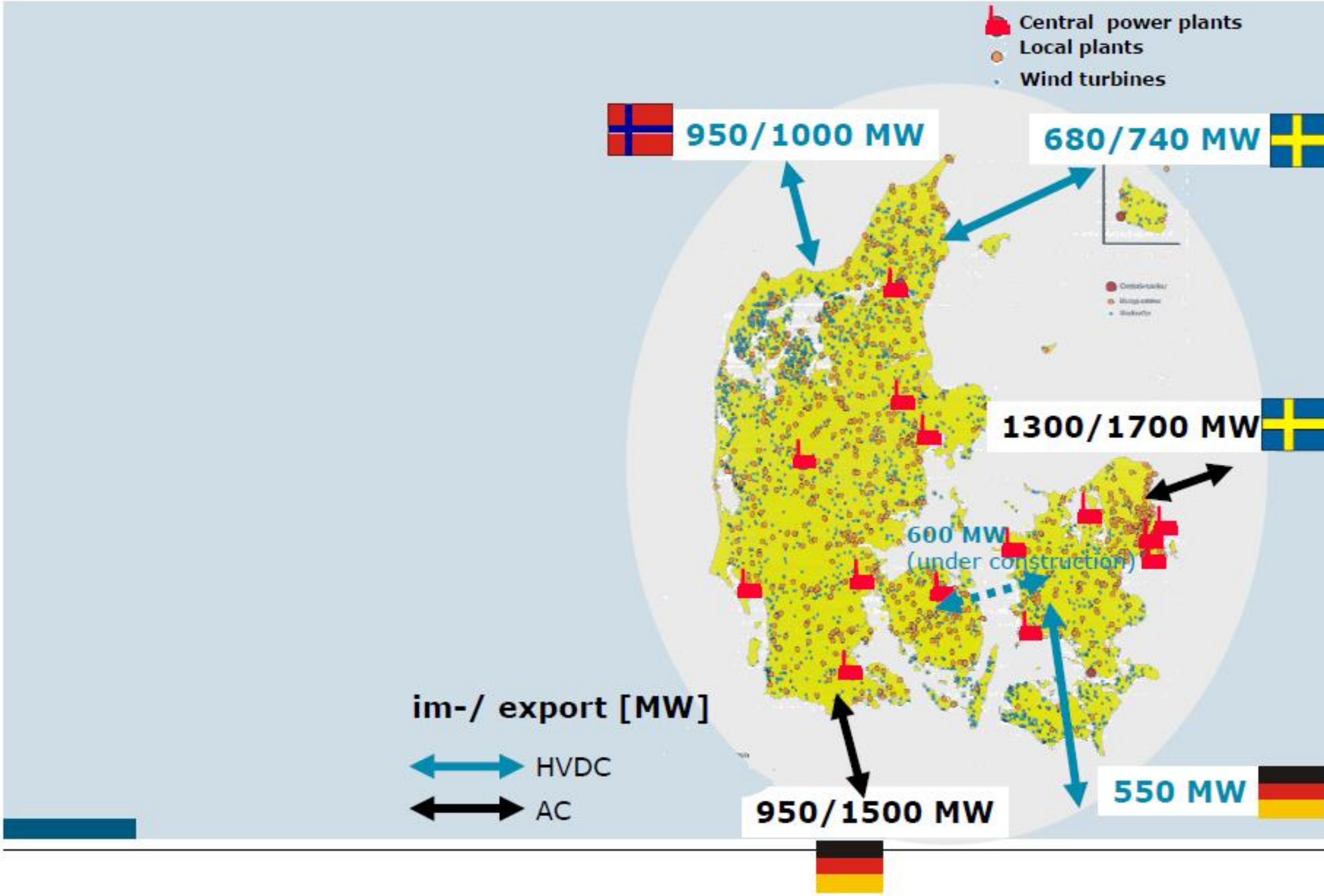
Wind curtailment estimates – US

	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%)**

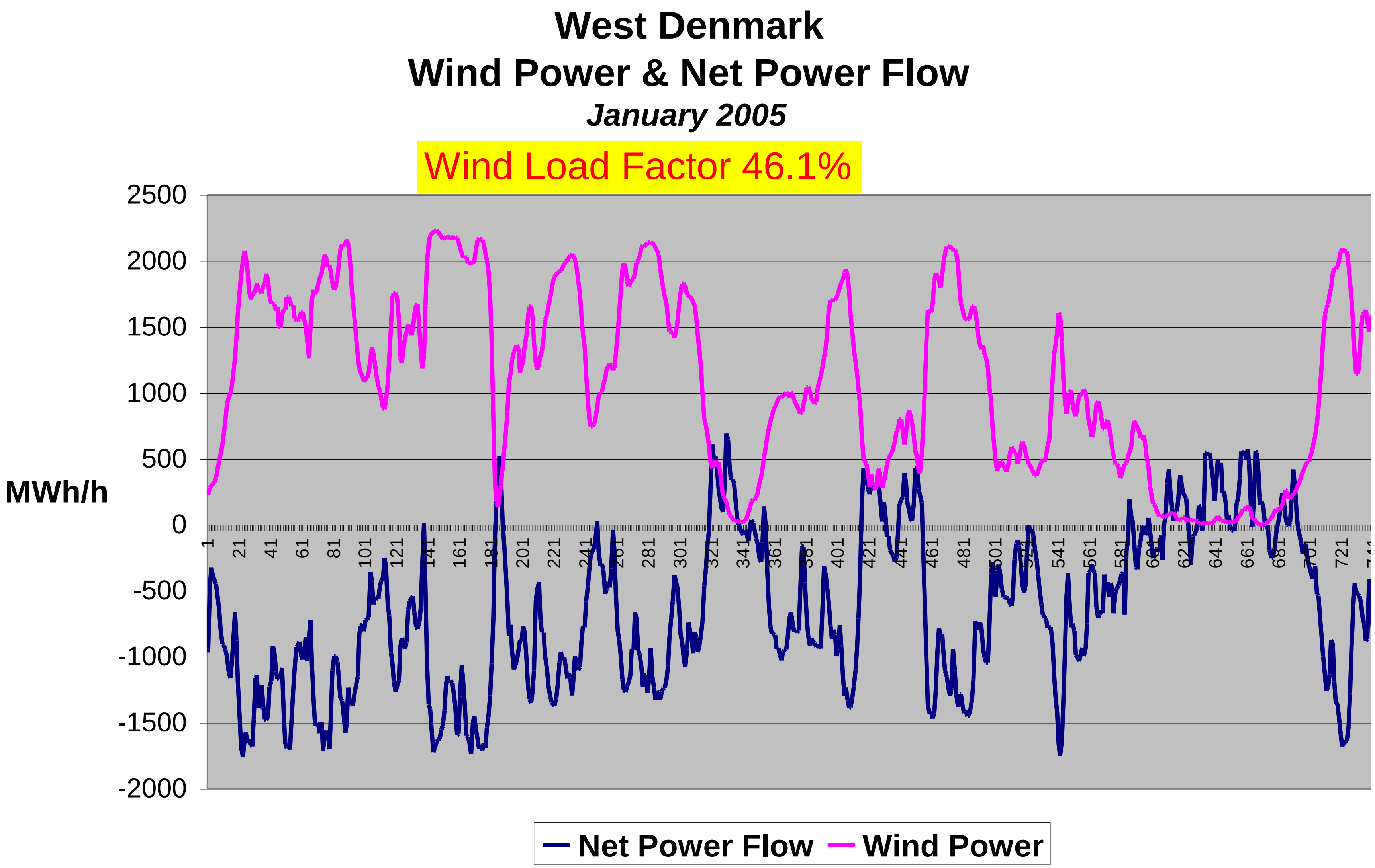
Estimated Wind Curtailment in Various Areas, in GWh (and as a % of potential wind generation)

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

Interconnectors 2009



Rest of Europe integrates West Danish wind



Interconnection

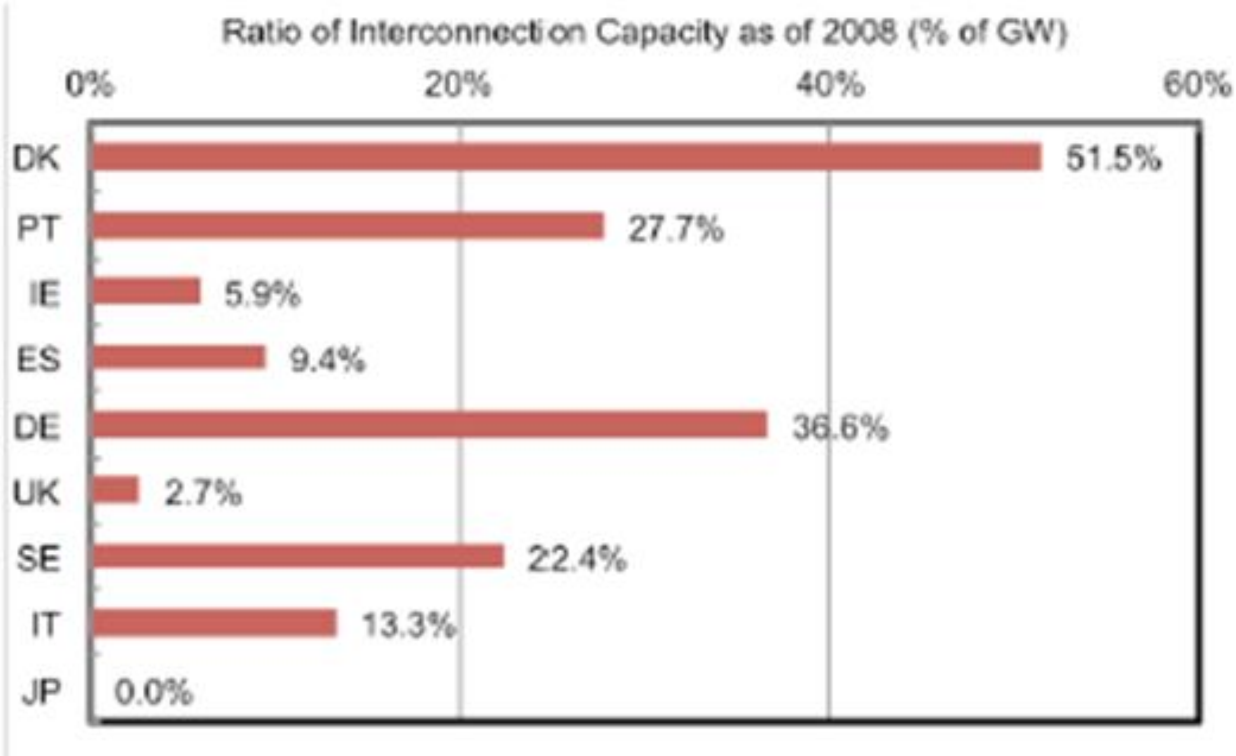
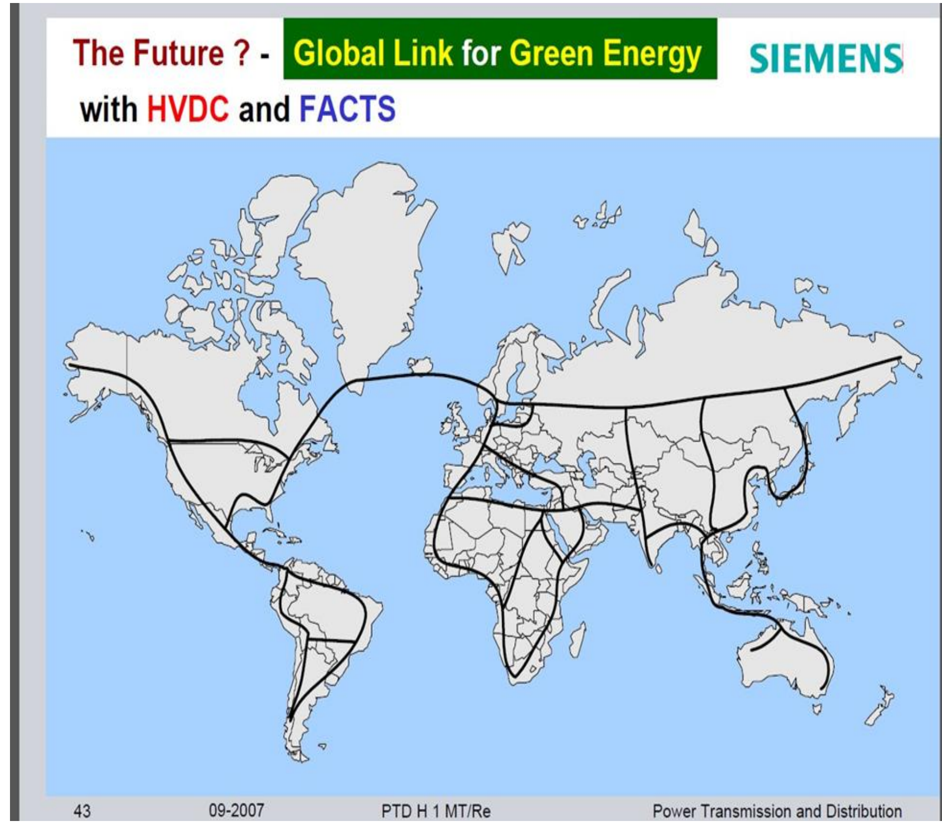


Fig.6 Ratio of Interconnection Capacity against Total Generation Capacity: CR_{IC}

Source: Yasuda Yoh, Kansai University, Japan

Corbus, D.; Kuss, M.; Piwko, D.; Hinkle, G.; Matsuura, M.; McNeff, M.; Roose, L.; Brooks, A., "All Options on the Table: Energy Systems Integration on the Island of Maui," *Power and Energy Magazine, IEEE* , vol.11, no.5, pp.65,74, Sept. 2013 doi: 10.1109/MPE.2013.2268814

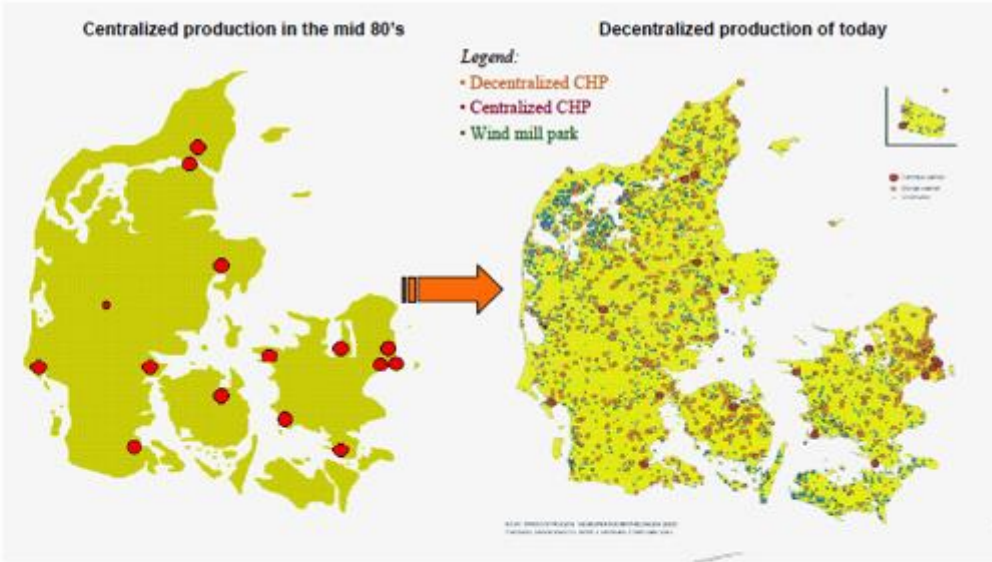
Continental scale integration



Matthias, C. et al. Security and Sustainability of Power Supply – Benefits of HVDC & FACTS for System Interconnection and Power Transmission Enhancement
http://www.ptd.siemens.de/Presentation_Security%20&%20Sustainability_PowerGrid_08-06_V%201.pdf

EASAC, "Transforming Europe's Electricity Supply – An Infrastructure Strategy for a Reliable, Renewable and Secure Power System" European Academy of Sciences Advisory Council, May 2009. http://www.easac.org/document.asp?id=96&pageno=&detail=5&parent

CHP with District Heating in Denmark



- Integrated combined heat and power has:
  - dramatically increased efficiency (30 %)
  - allowed 10 % of electricity from biomass
  - Reduced CO2 emissions by 20 %
  - Increasing the opportunity for natural gas

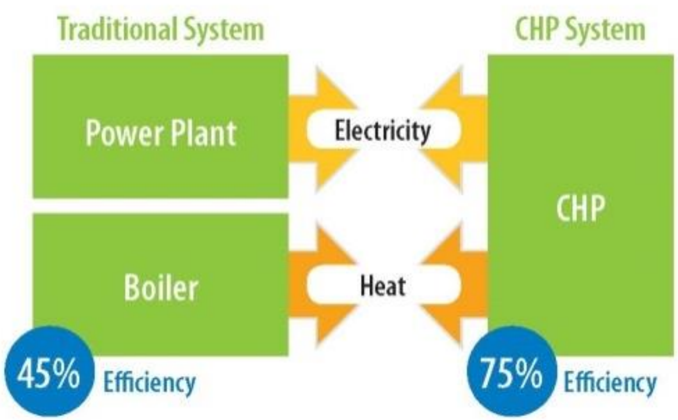
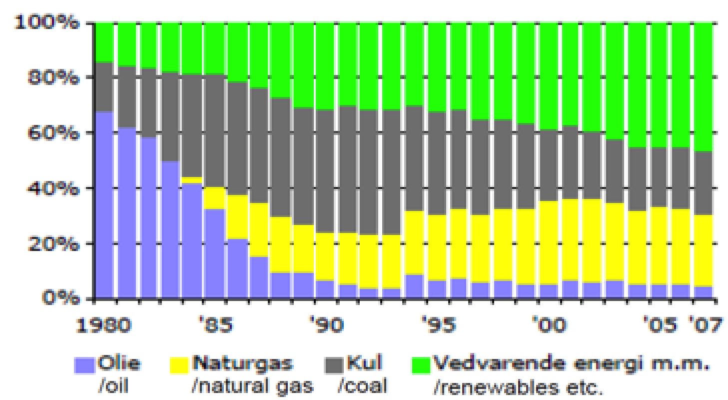
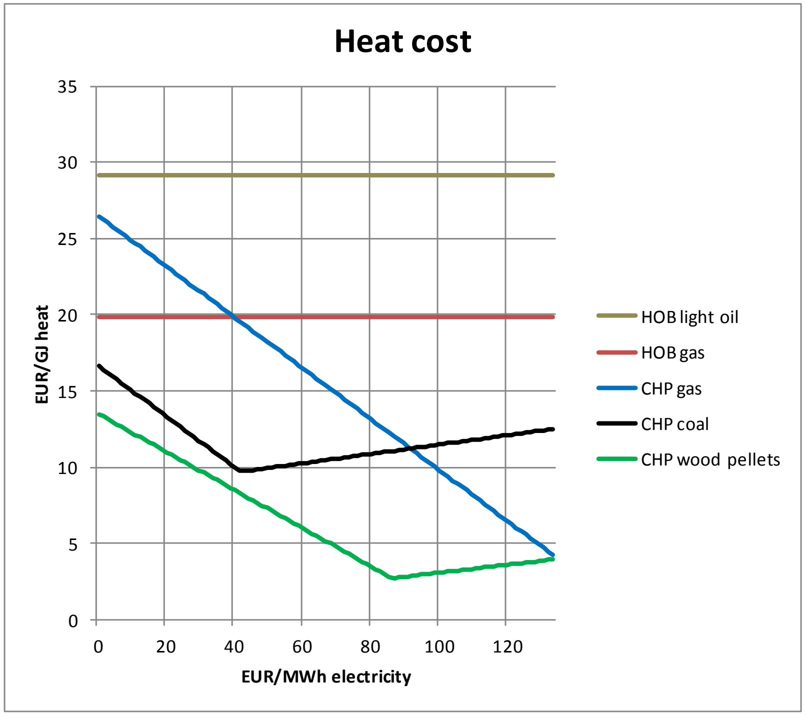
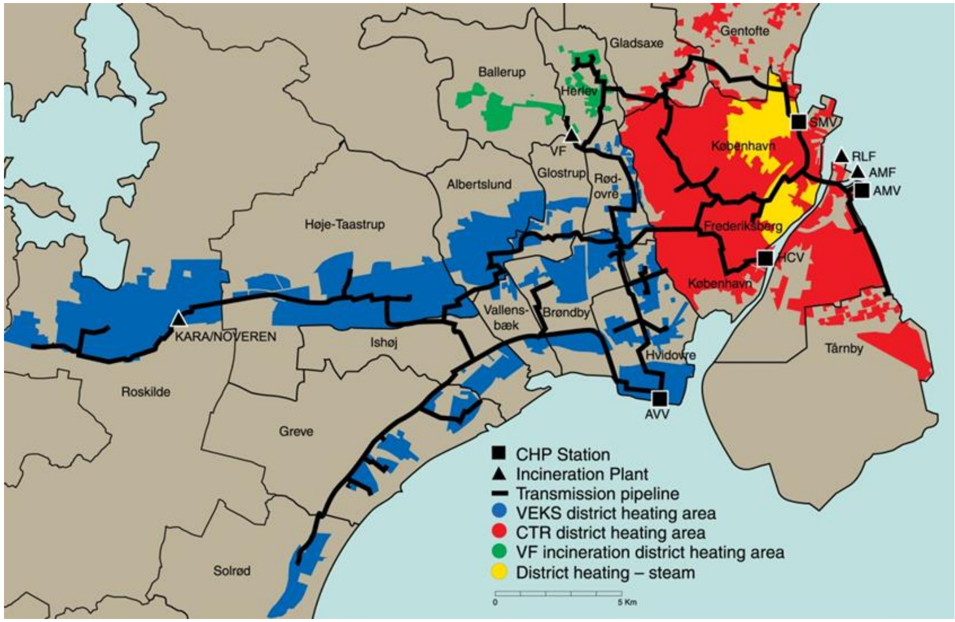


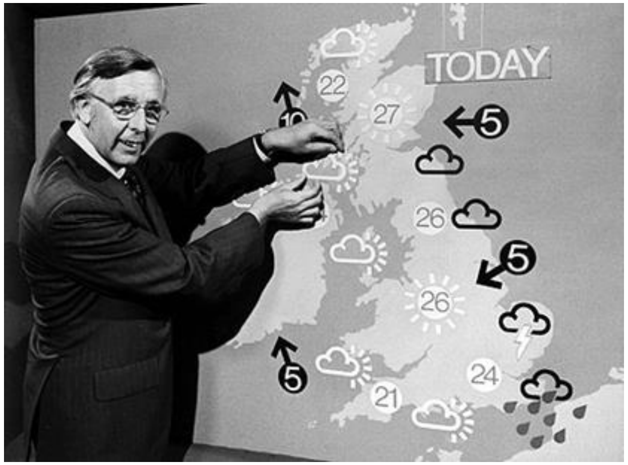
Figure 3: Fuel consumption for district heating production, percentage distribution



Co optimization of heat and electricity at scale

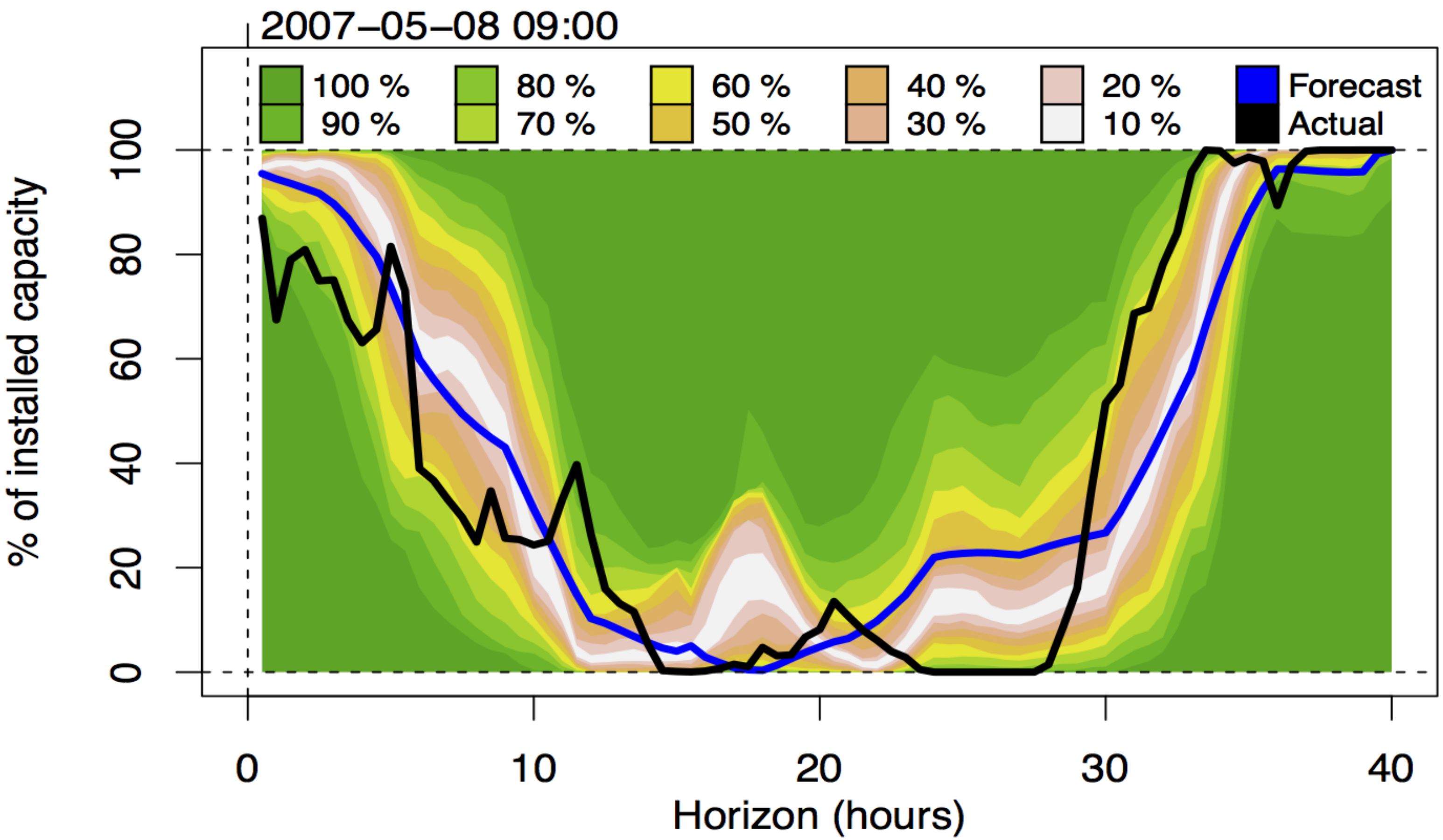




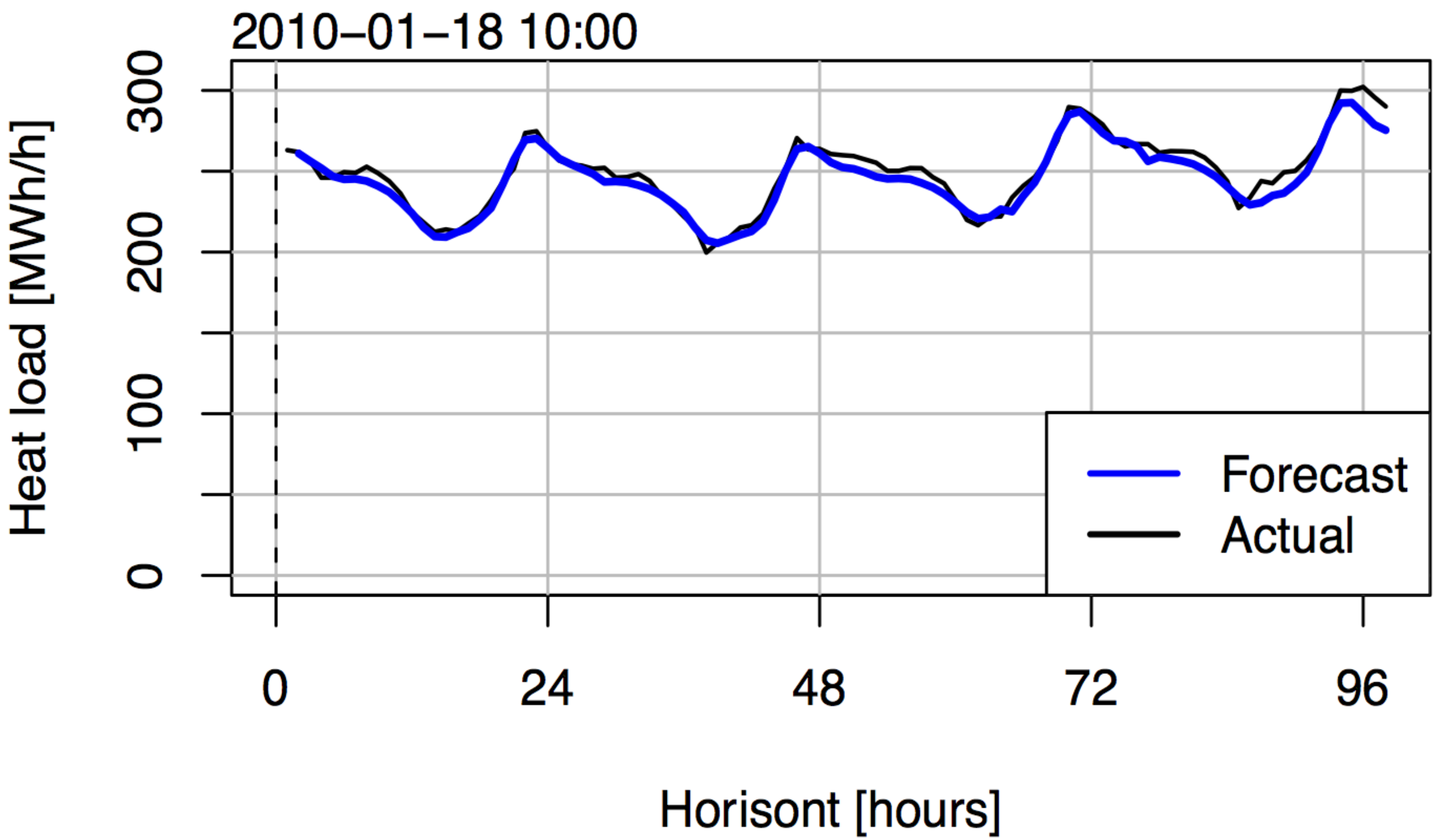


Source: Lars Bregnbæk, EAEA

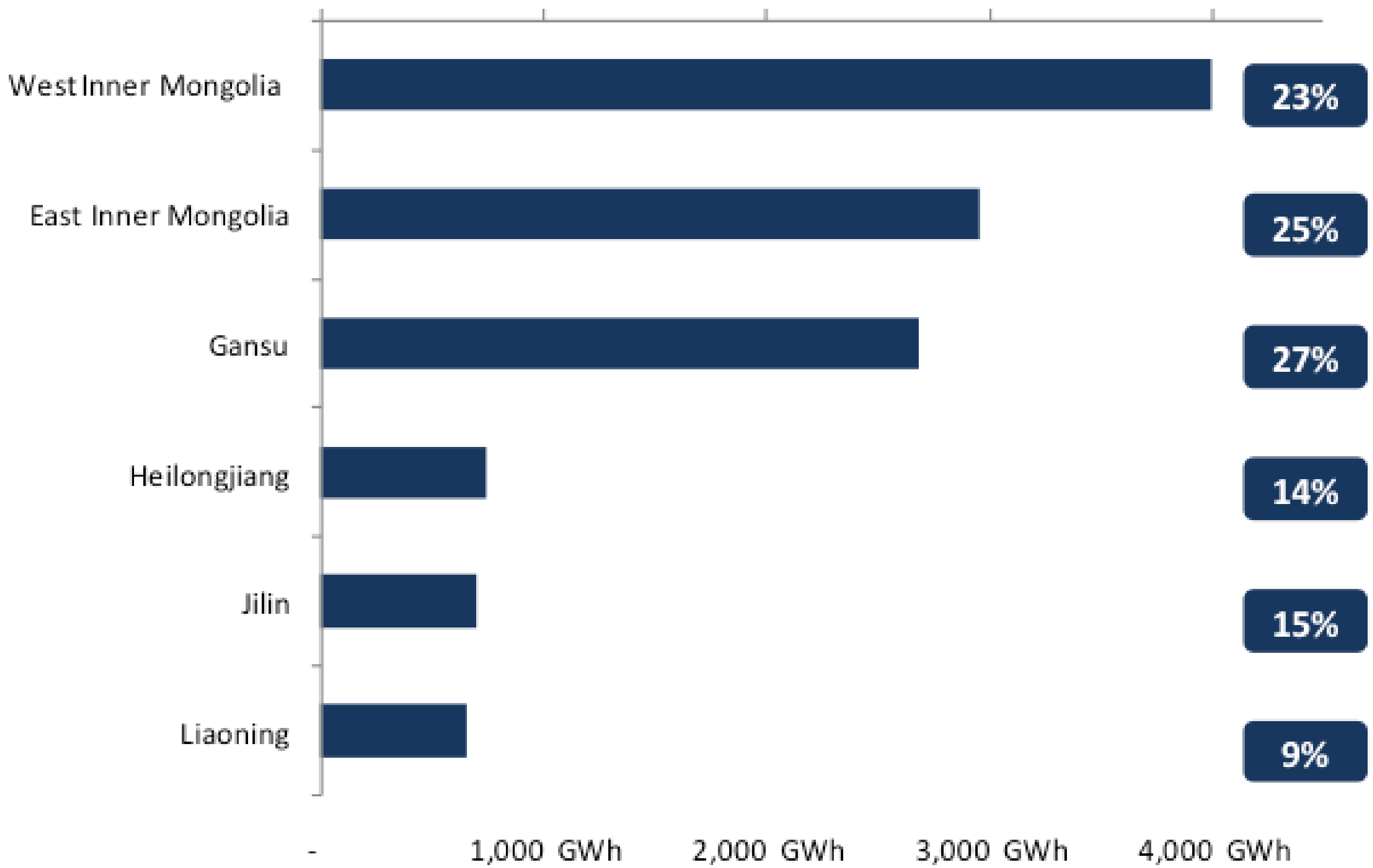
Example of WPPT point and quantile forecasts



Example of PRESS heat load forecast



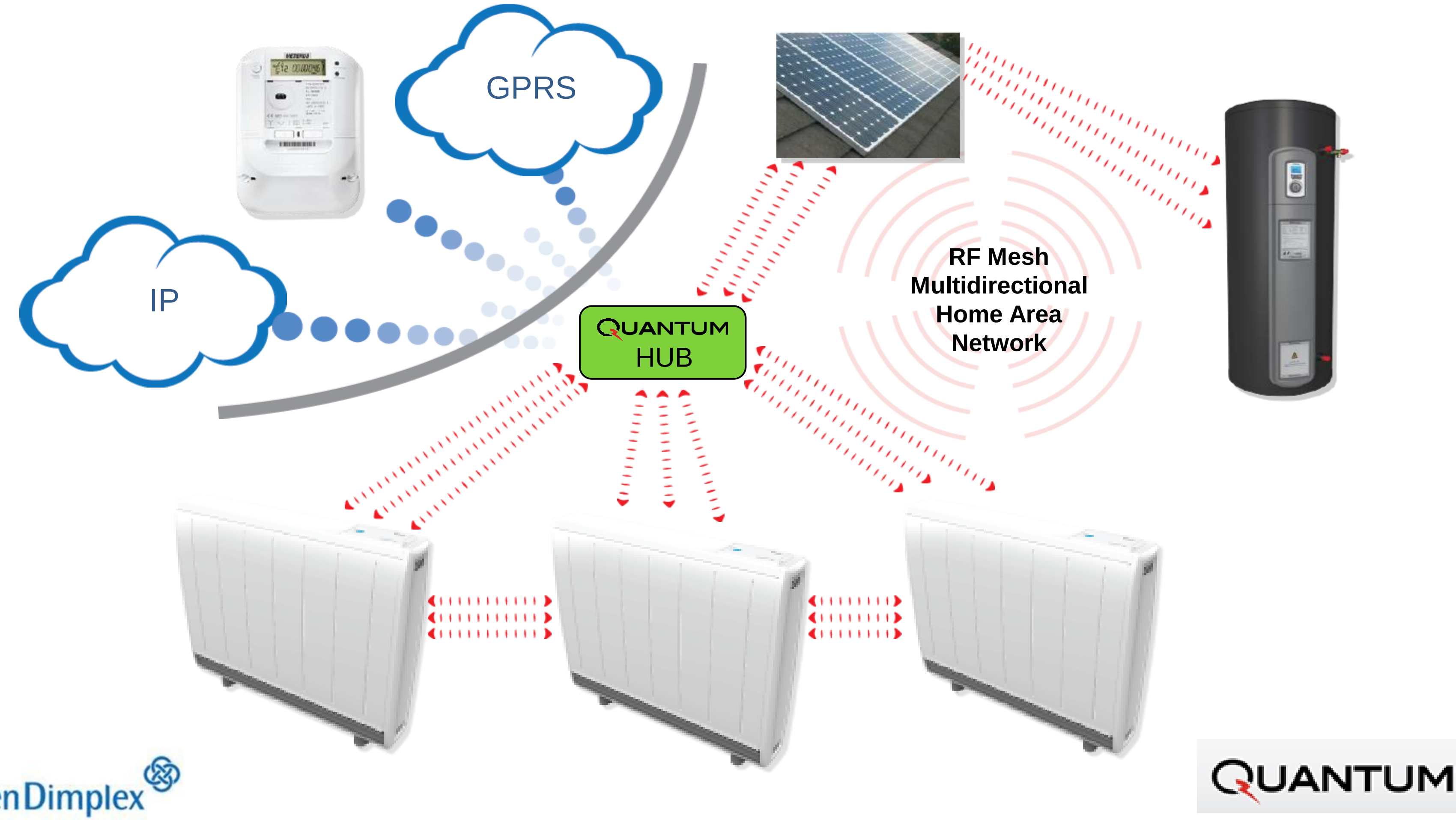
Wind curtailment in China



- **In 2011 wind curtailment in China was 16.9 % that is of the wind that is connected to the grid i.e. approx. 75 % of the 80 GW installed.**
- **May well be just a legacy issue i.e. in China as the load grows the new thermal plant can be made more flexible and system will be designed around the needs.**

http://www.greentechmedia.com/articles/read/Chinas-Wind-Market-Growing-but-Challenged-by-Grid-Real

Electric heat demand is very flexible



- Kiviluoma, J., Meibom, P.; “Influence of wind power, plug-in electric vehicles, and heat storages on power system investments” Energy, Volume 35, Issue 3, March 2010, Pages 1244-1255
- Papaefthymiou, G.; Hasche, B.; Nabe, C.; , "Potential of Heat Pumps for Demand Side Management and Wind Power Integration in the German Electricity Market," Sustainable Energy, IEEE Transactions on , vol.3, no.4, pp.636-642, Oct. 2012

Like people all systems are different

Key Take Away # 4 & 5

- Denmark is the world leader in ESI
- Every system is different

Gas Electricity Interface

Gas/electricity

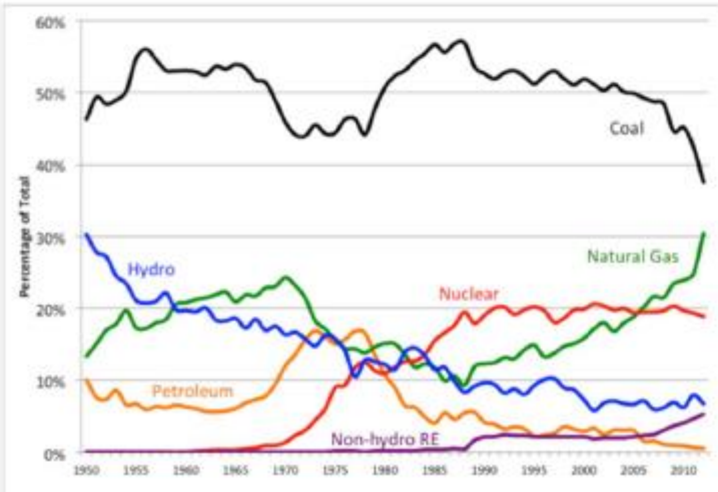


Figure 4 – Change in U.S. generating mix from 1950 to 2012. (Derived from EIA "Electric Power Monthly," January 2013; final month of 2012 estimated.)

- US gas up – CO_2 down
- Europe coal up – CO_2 up
- No joined up energy system thinking from a policy perspective

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

D. Arent, M. Bazilian, P. Statwick, S. Benson, A. Brandt, L. Billman, G. Heath, J. Logan, M. Mann "The U.S. Shale Experience: Toward a Comprehensive Research Agenda", Management Report NREL/ MP-6A50-57977, Prepared under Task No. 6A50.1025, February 2013

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

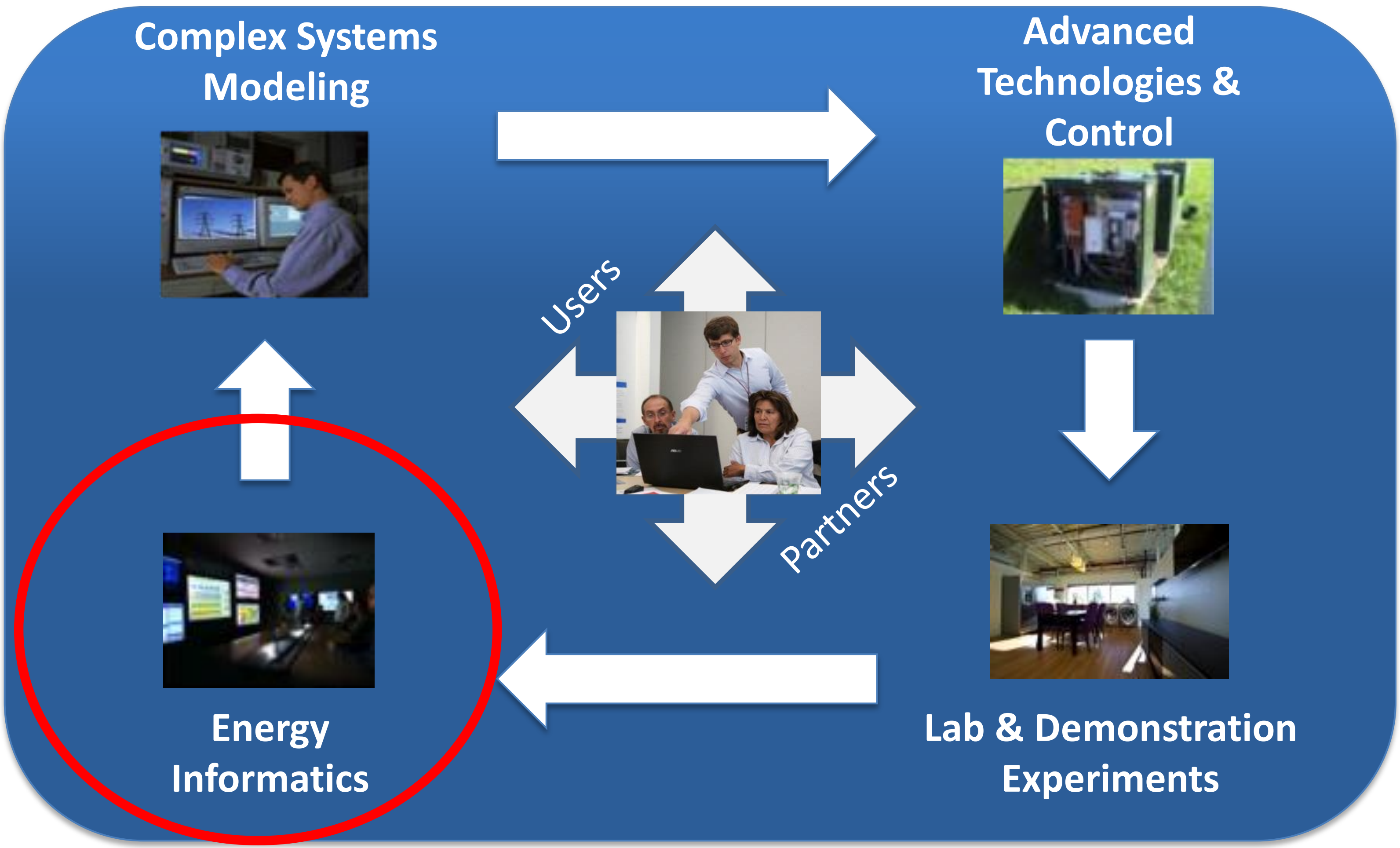
E. Denny, J. Dillon, J. Bialek, M. O'Malley
Ecar Limited

K. Neuhoff
DIW Berlin

Study commissioned by IEA-RETD
www.iea-retd.org
iea_retd@ecofys.com

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

More than Integrating Physical Components



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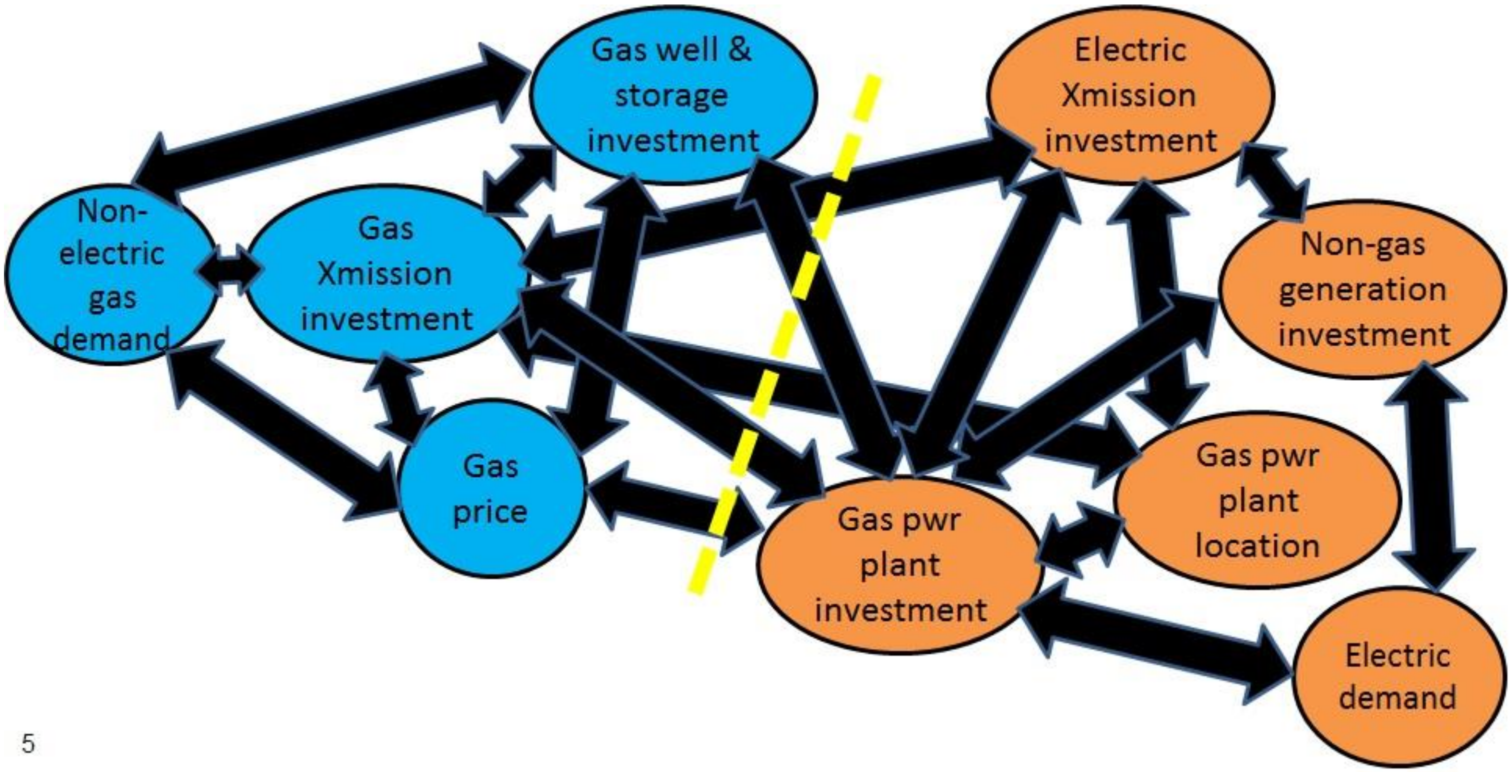
Energy Informatics focuses on generating actionable information from data to enable energy system integration.

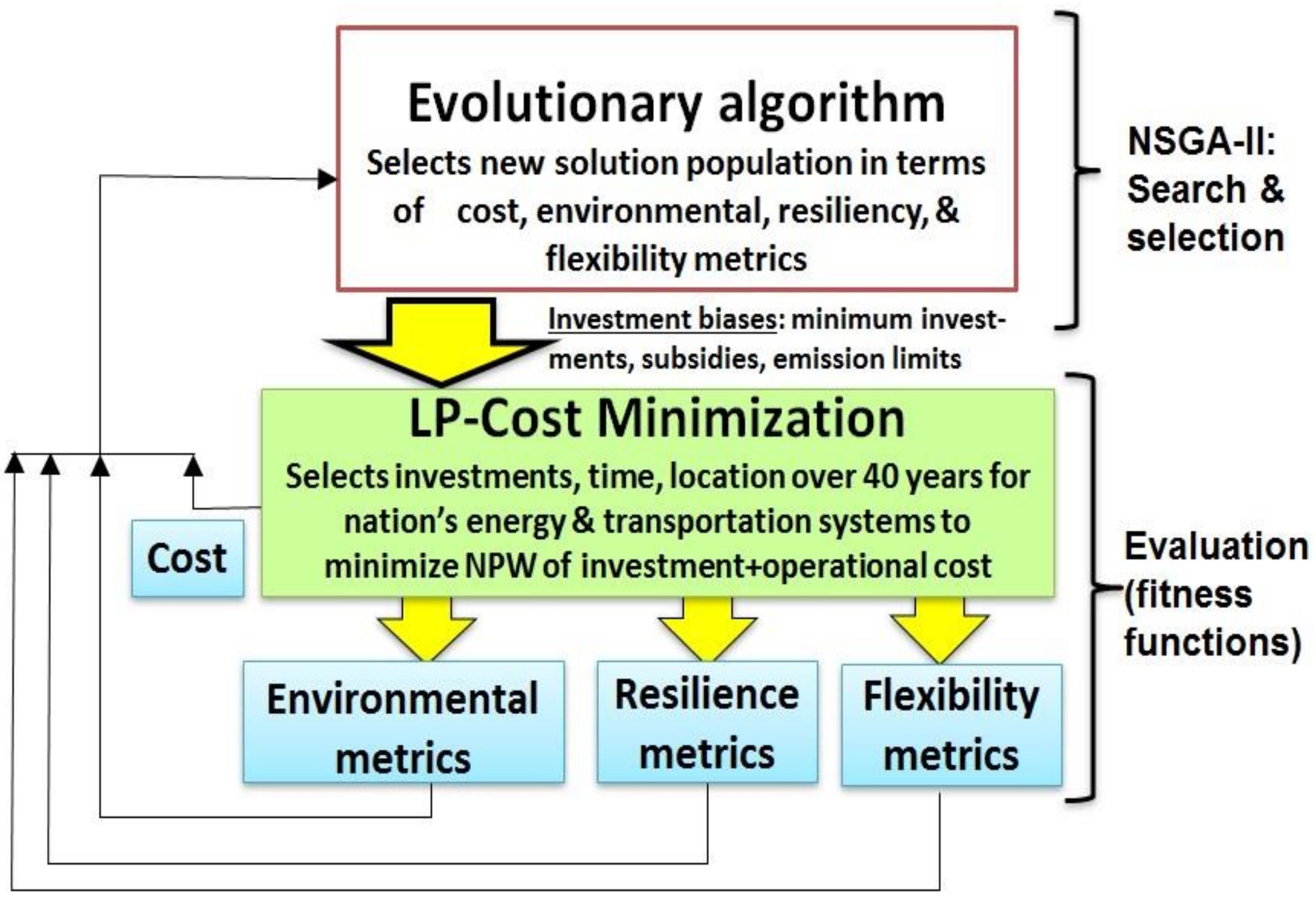
Gas - Electricity - Transport Infrastructure



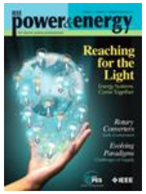
5

McCalley, J.; Krishnan, V.; Gkritza, K.; Brown, R.; Mejia-Giraldo, D., "Planning for the Long Haul: Investment Strategies for National Energy and Transportation Infrastructures," *Power and Energy Magazine, IEEE* , vol.11, no.5, pp.24,35, Sept. 2013. doi: 10.1109/MPE.2013.2268712

Optimisation models

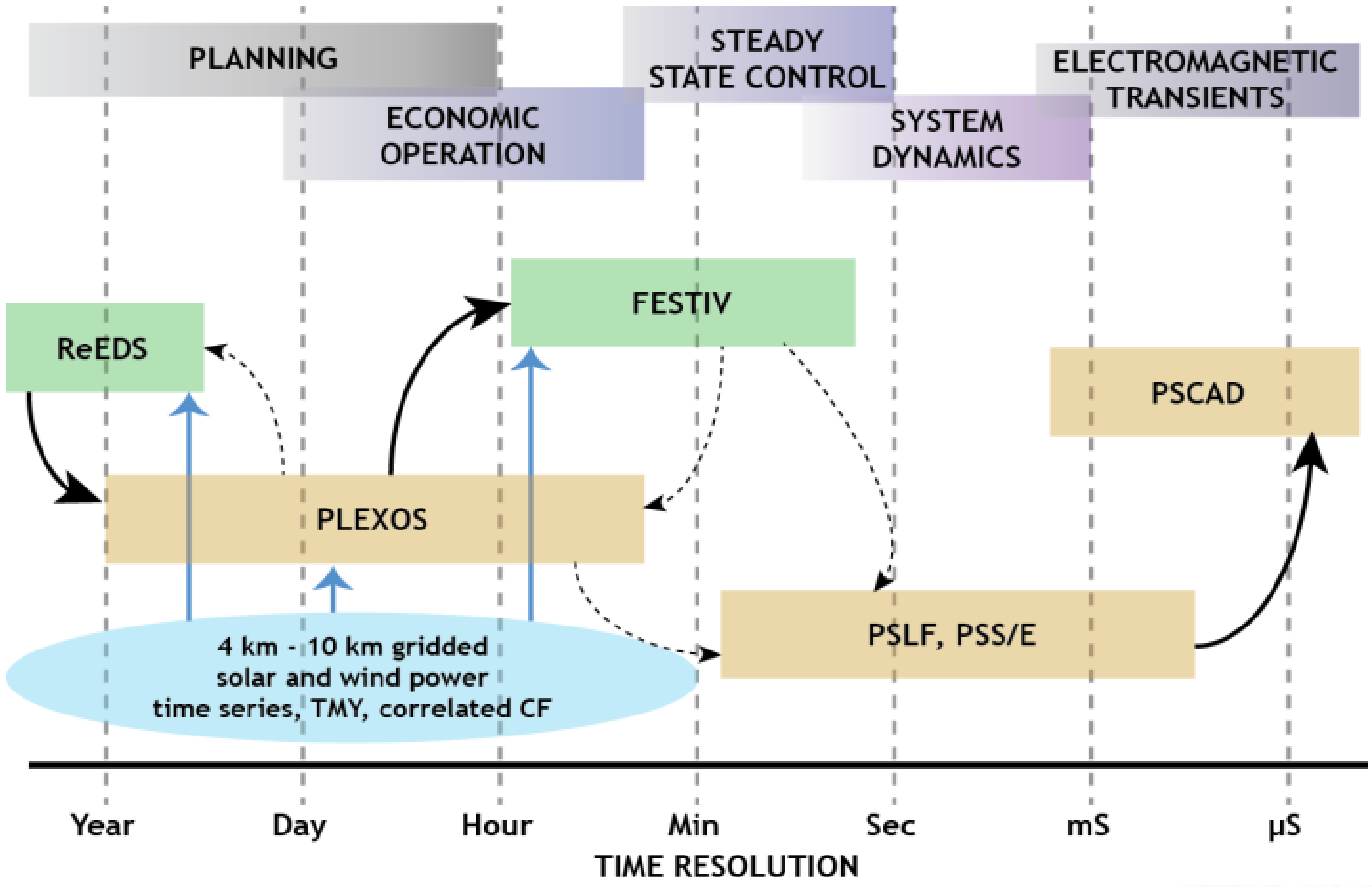


McCalley, J.; Krishnan, V.; Gkritza, K.; Brown, R.; Mejia-Giraldo, D., "Planning for the Long Haul: Investment Strategies for National Energy and Transportation Infrastructures," *Power and Energy Magazine, IEEE* , vol.11, no.5, pp.24,35, Sept. 2013. doi: 10.1109/MPE.2013.2268712



Models tend to be in one domain

Modeling and Simulation at Multiple Temporal Scales



Energy Hubs

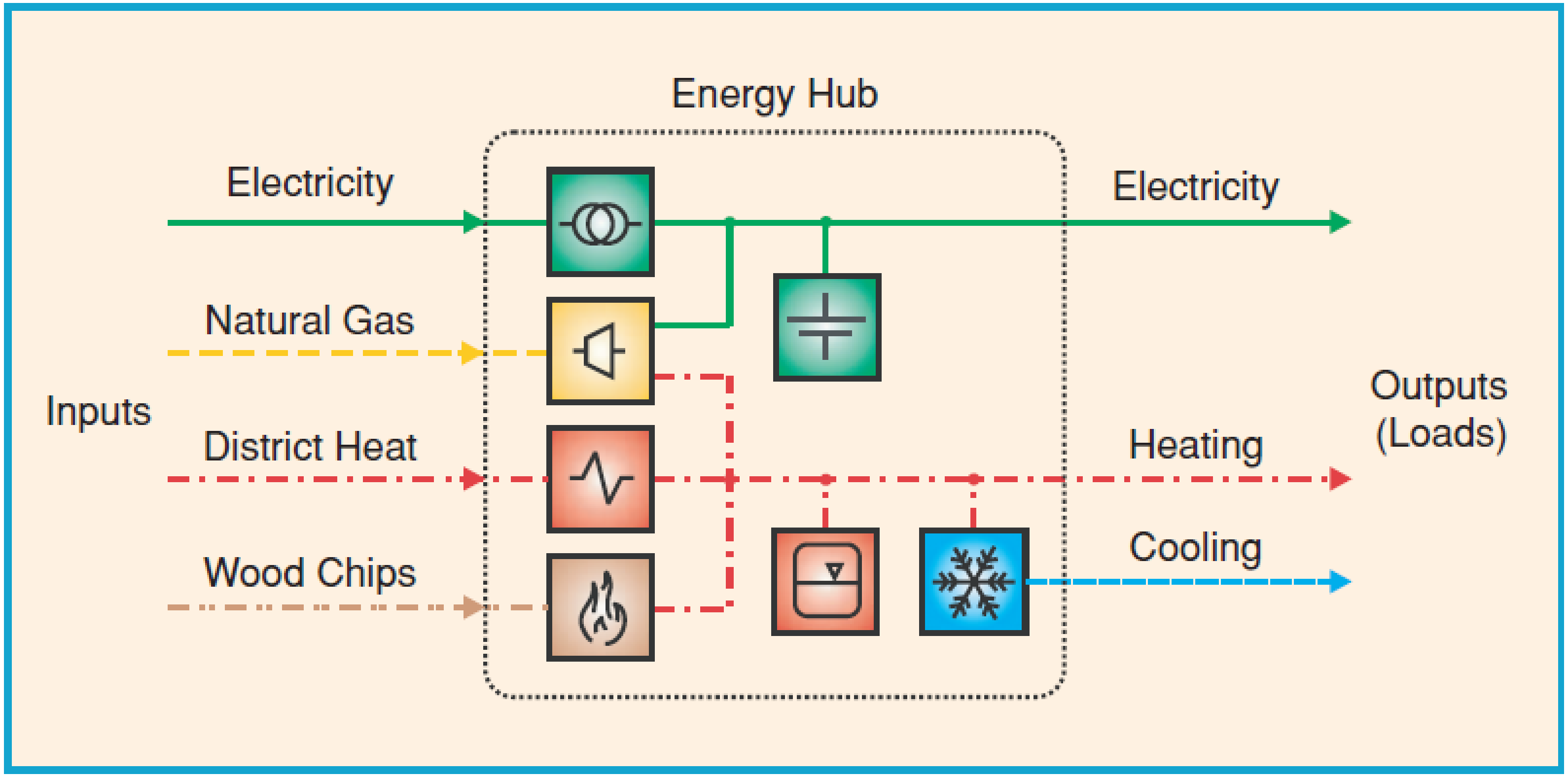


figure 2. Example of an energy hub that contains a transformer, a microturbine, a heat exchanger, a furnace, an absorption chiller, a battery, and a hot water storage.

Geidl, Martin; Koeppel, G.; Favre-Perrod, P.; Klockl, B.; Andersson, G.; Frohlich, K., "Energy hubs for the future," *Power and Energy Magazine, IEEE* , vol.5, no.1, pp.24,30, Jan.-Feb. 2007. doi: 10.1109/MPAE.2007.264850

http://www.nrel.gov/esi/esif.html

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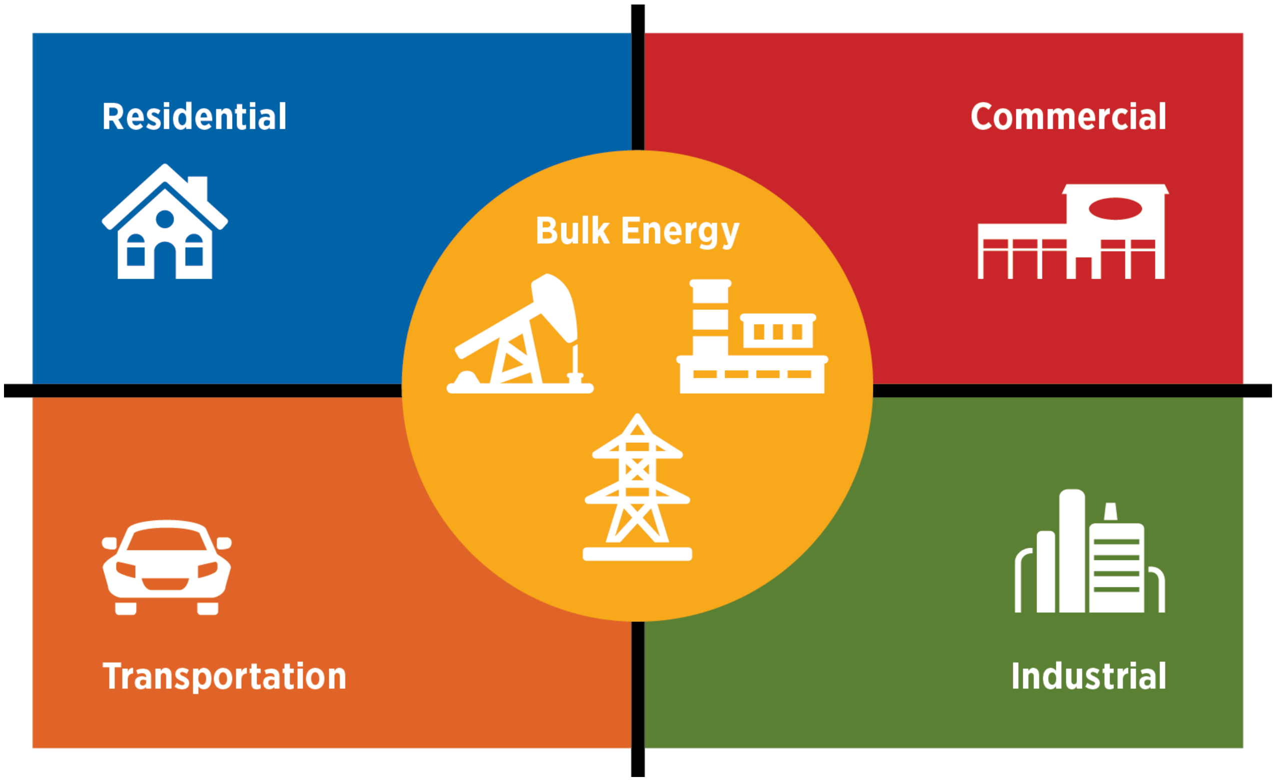
Business models for gas/electricity



Source: Jaquelin Cochran & Jeff Logan, NREL

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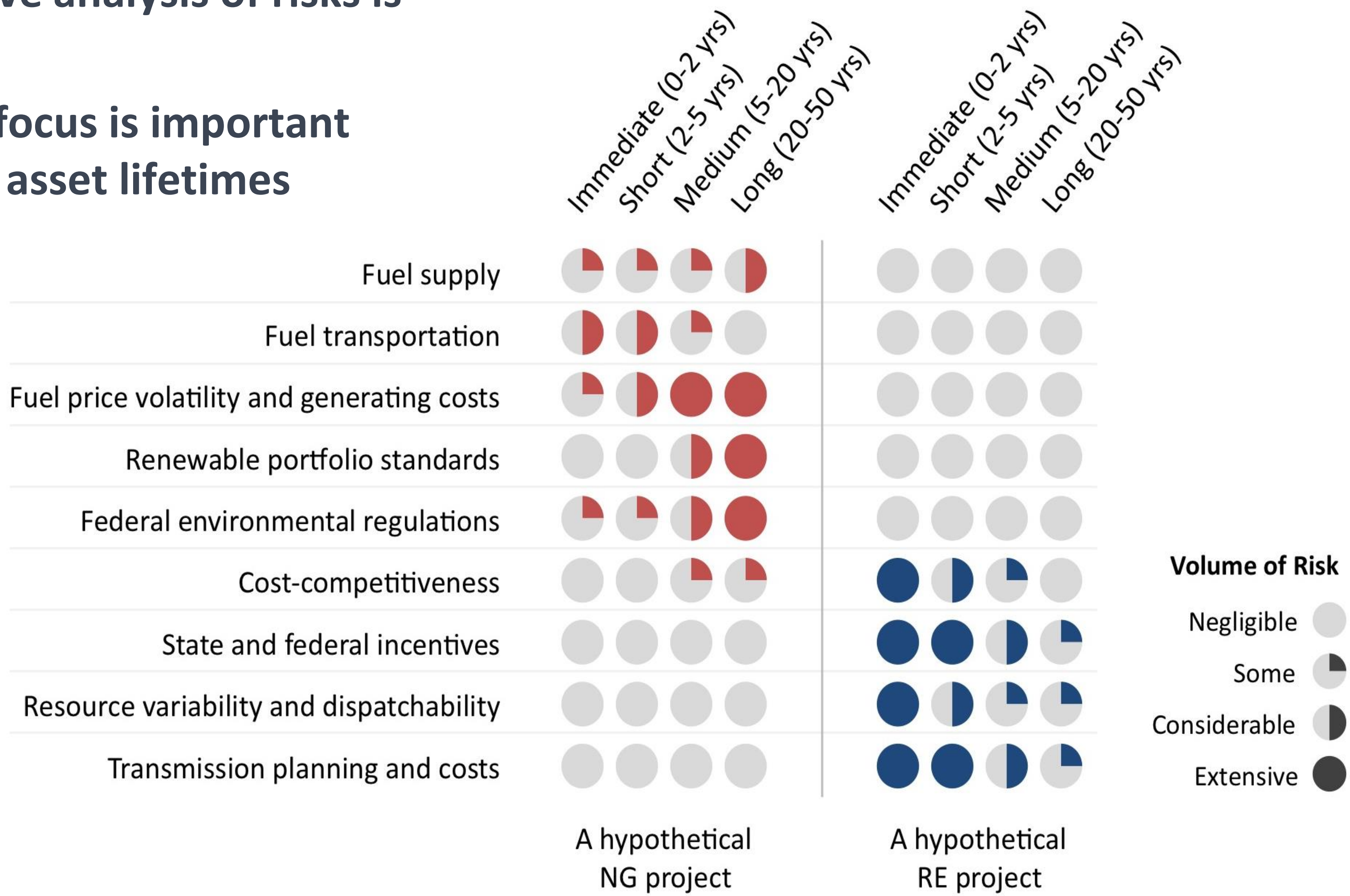
Natural Gas & Renewables: Opportunities for Synergies

- Quantitative analysis of risks is needed
- Temporal focus is important given long asset lifetimes



Lee, Zinaman, Logan, Arent, Bazlian, Newmark: Electricity Journal Dec 2012

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 %

Gas

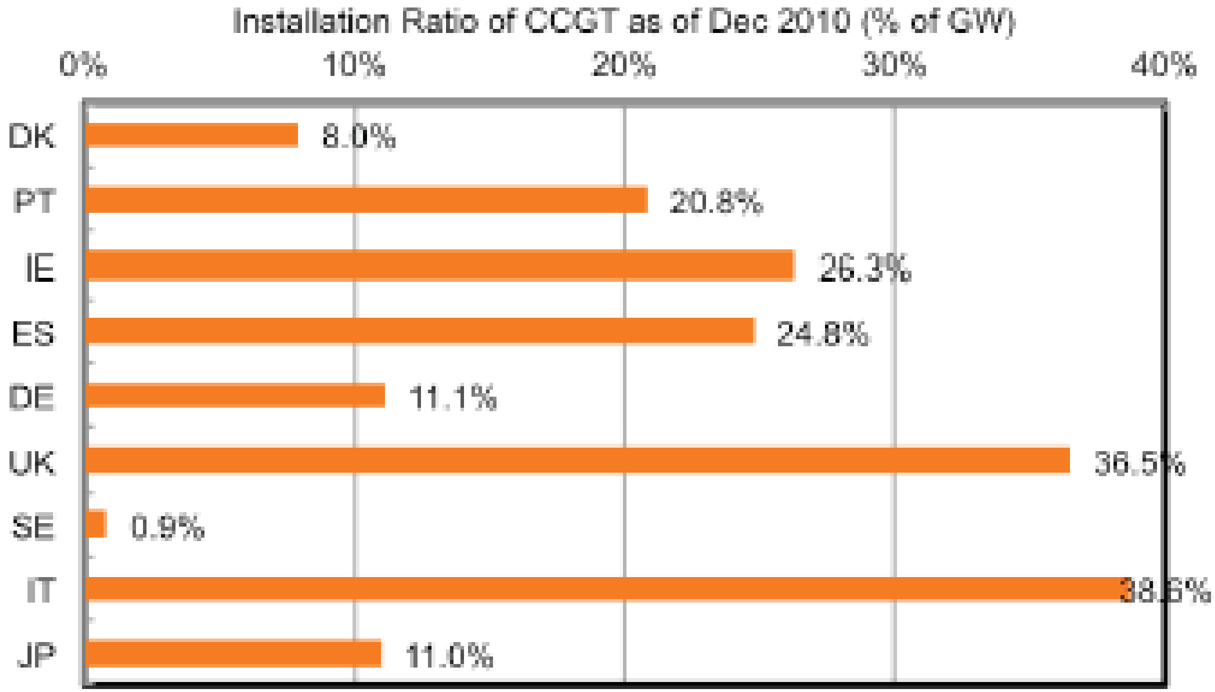


Fig.9 Ratio of Installed Capacity of CCGT: CR_{CCGT}

(note: countries are sorted by ascending oder in Fig.1)

Source: Yasuda Yoh, Kansai University, Japan

Key Take Away # 6

- ESI is about
  - Hardware, communications and control
  - Experimentation & demonstration
  - Planning & operations
  - Modelling & simulation & data
  - Policy, business models

Who needs to understand ?

ESI built on fundamental laws across may disciplines

Maxwell

$$\oint \mathbf{E} \cdot d\mathbf{A} = \frac{q_{enc}}{\varepsilon_0}$$

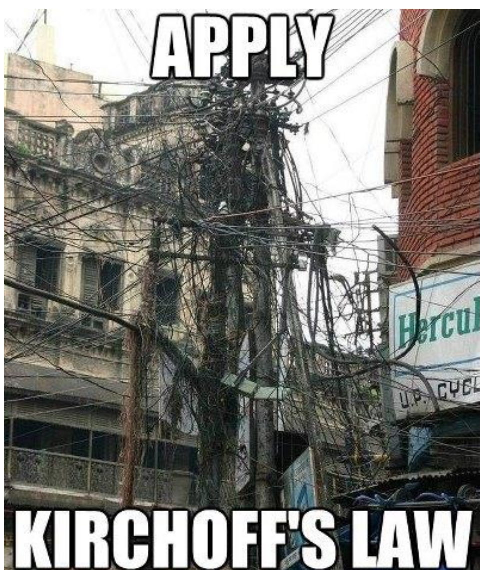
$$\oint \mathbf{B} \cdot d\mathbf{A} = 0$$

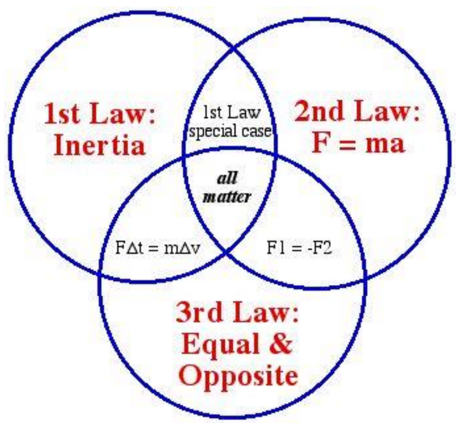
$$\oint \mathbf{E} \cdot d\mathbf{s} = -\frac{d\Phi_B}{dt}$$

$$\oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt} + \mu_0 i_{enc}$$

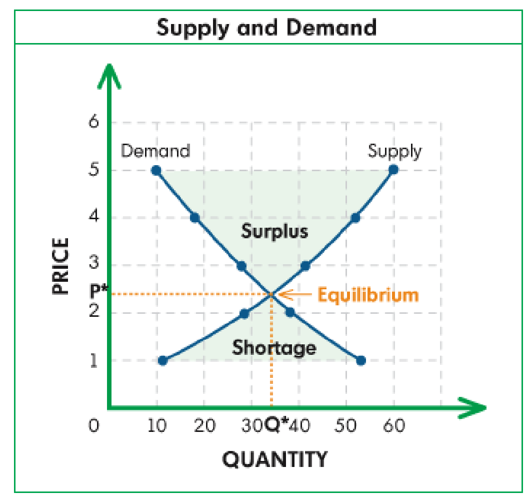
Laws of Thermodynamics

Zeroth: *"You must play the game."*
First: *"You can't win."*
Second: *"You can't break even."*
Third: *"You can't quit the game."*





Newton's Laws



The "Iron Law" of Climate Policy

"When policies on emissions reductions collide with policies focused on economic growth, economic growth will win out every time."

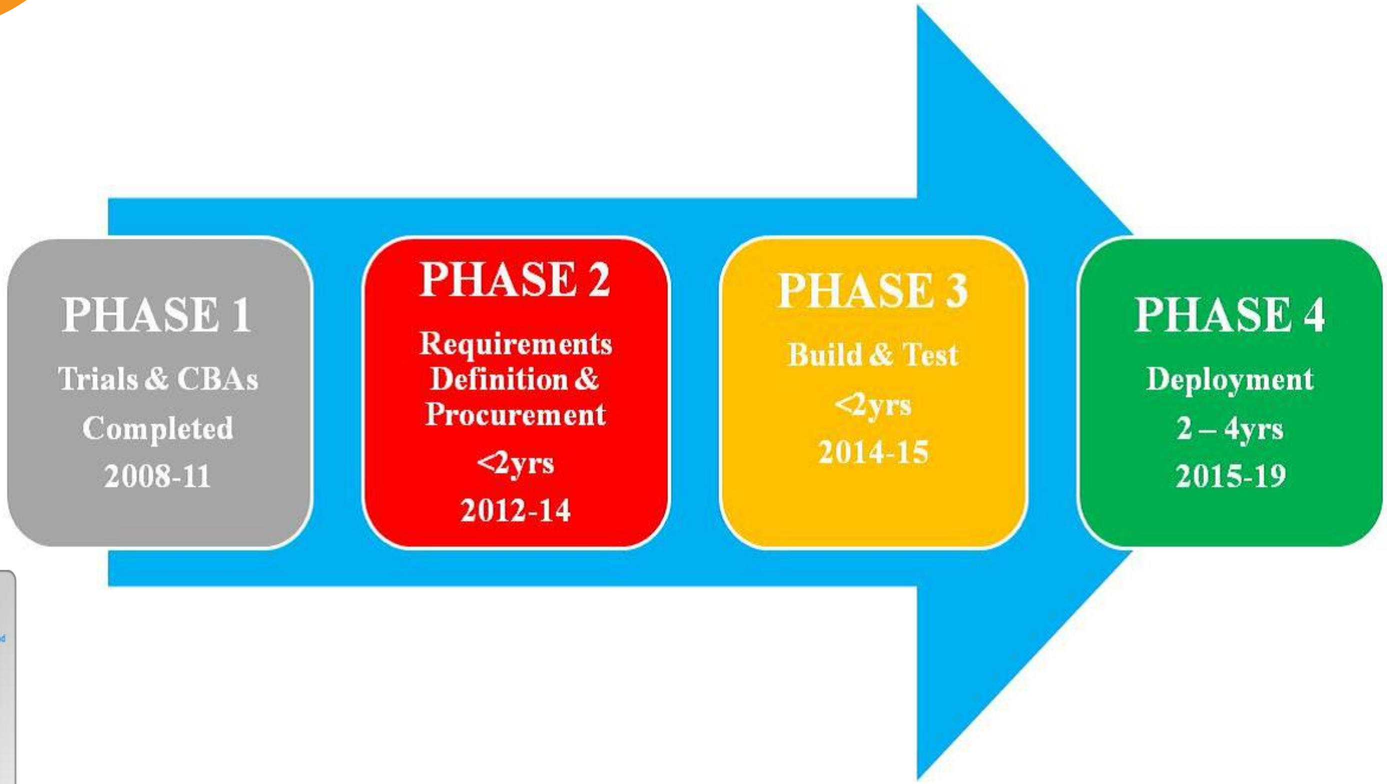
Source: Roger Pielke, Jr, Colorado University

The Consumer

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

Source: Janusz Bialek, Durham University

The Consumer and Their Education



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


education
is the

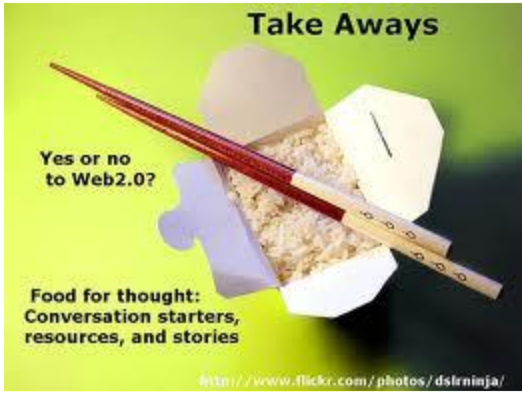
Does your laptop keep running out of power? No longer! Use the natural power of your own laptop to recharge itself!

Use the USB Laptop self-charger cable

and never run out of power again!

Key Take Away # 7 & 8

- The consumer is king
- Education is important



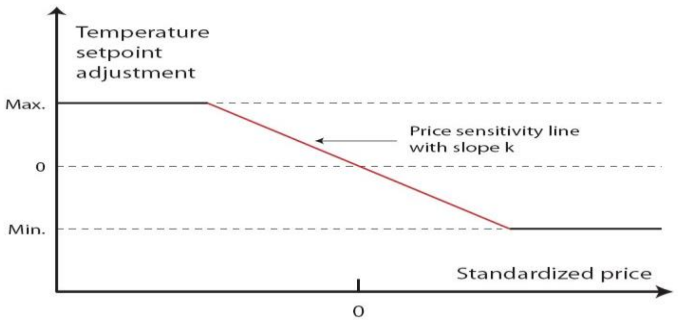
Demand (consumer) Response

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

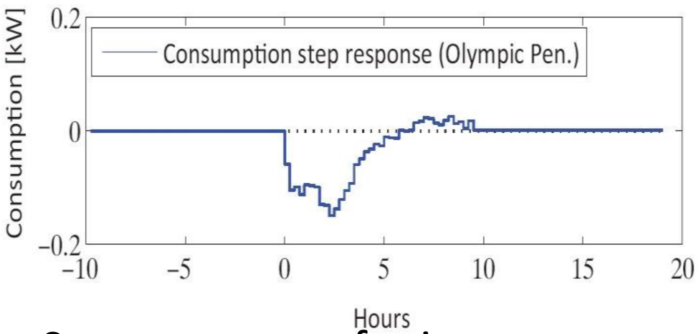
http://www.mckinsey.com/client_service/electric_power_and_natural_gas/latest_thinking/mckinsey_on_smart_grid

Demand Response

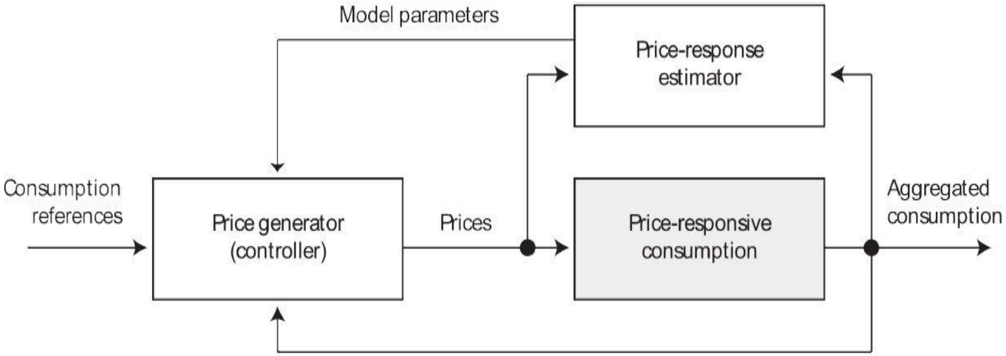
- Control of electricity consumption using a price signal



Temperature response to price changes (heat pump driven heating system)



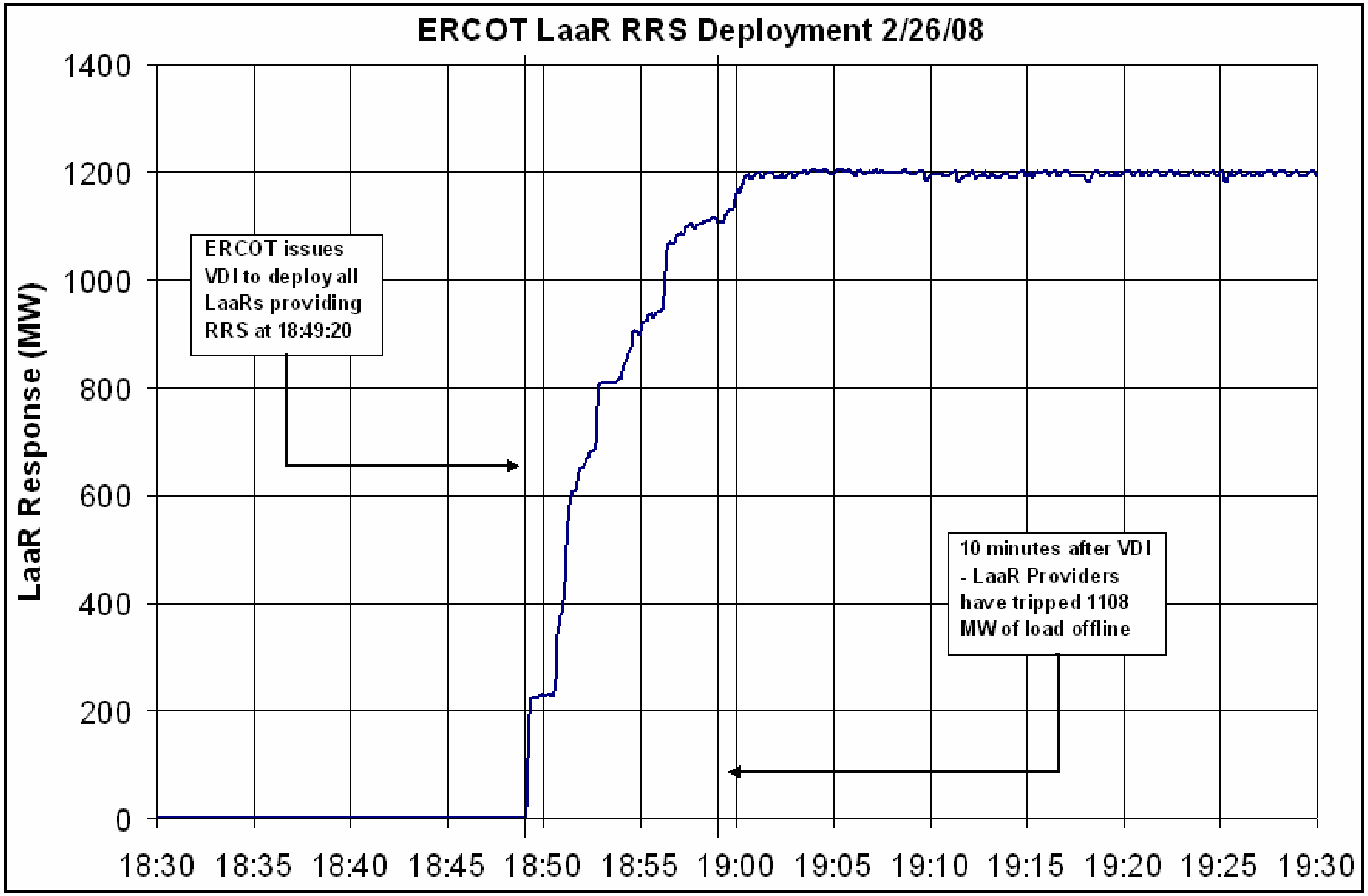
Step response of price responsive electrical demand



Source: Henrik Madsen & Niamh O'Connell, DTU

Corradi, O.; Ochsenfeld, H.; Madsen, H.; Pinson, P., "Controlling Electricity Consumption by Forecasting its Response to Varying Prices," *Power Systems, IEEE Transactions on* , vol.28, no.1, pp.421,429, Feb. 2013
doi: 10.1109/TPWRS.2012.2197027

ERCOT Event: Feb. 26, 2008 (3pm to 9 pm)



Demand Response with renewables

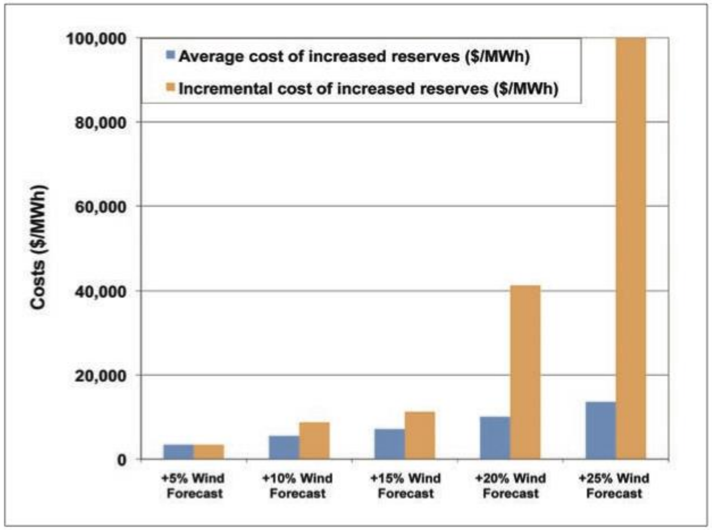


Figure 12 – The cost of increasing spinning reserves increases with higher percentages of spin. The incremental cost increases sharply at higher percentages of spin, indicating that the cost of reducing those final reserve shortfalls is prohibitively high. *The five bars show the effect of increasing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

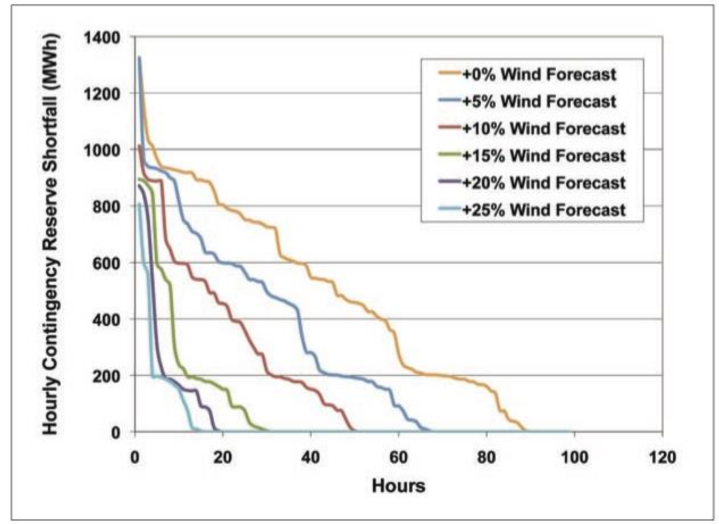
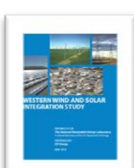


Figure 13 – A demand response program which requires load to participate in the 89 hours of the year that there are contingency reserve shortfalls is more cost-effective than increasing spin for each of the 8760 hours of the year. *Hourly contingency reserve-shortfall duration curves for the In-Area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

Office of Energy Efficiency and Renewable Energy
Office of Electricity Delivery and Energy Reliability

Demand Response and Storage Integration Study

Ookie Ma, PhD

IEEE PES General Meeting, Vancouver, BC

July 24, 2013

Ma, O., N. Alkadi, P. Cappers, P Denholm, J. Dudley, S. Goli, M. Hummon, S. Kilicotte, J. MacDonald, N. Matsony, D. Olsen, C. Rose, M. D. Sohn, M. Starke, B. Kirby and M.J. O'Malley, "Demand Response for Ancillary Services", *IEEE Transactions on Smart Grid*, in press, 2012.

Value of demand response

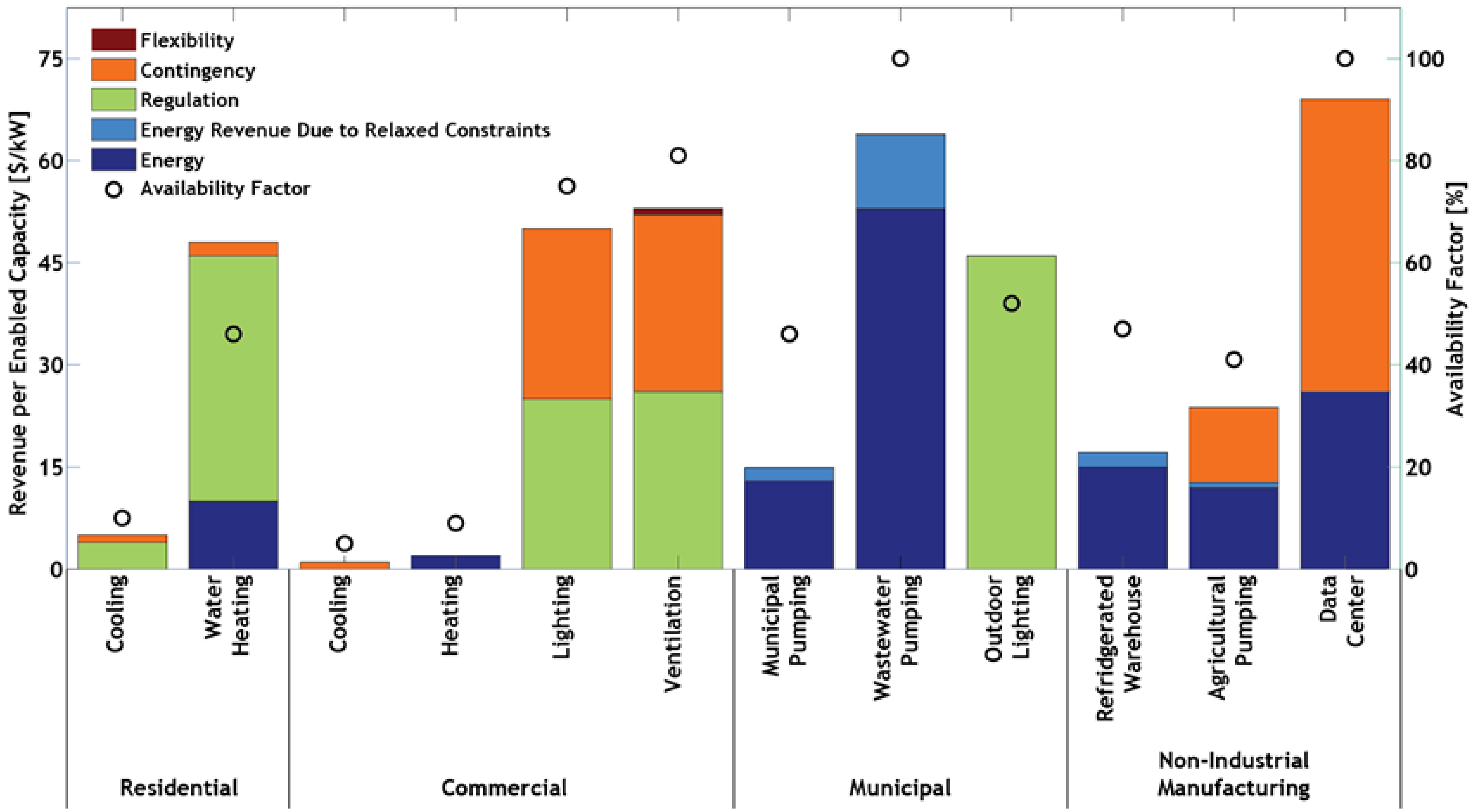

Figure 15. Annual revenue (left axis) from the day-ahead market per total enabled capacity for each type of demand response resource in the Colorado test system and the DR resource availability factor (right axis).

Source: Marissa Hummon

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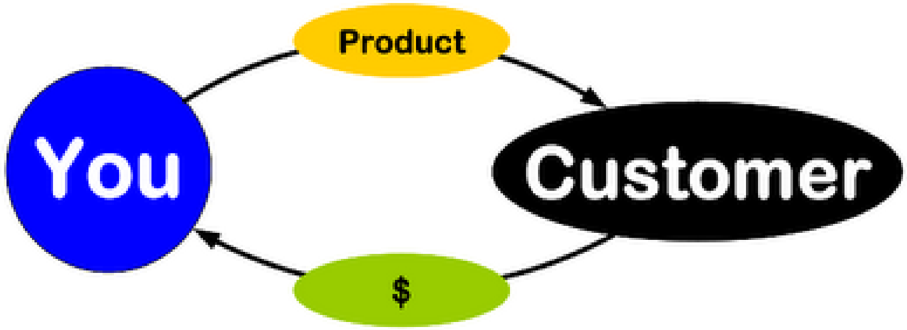
Business model

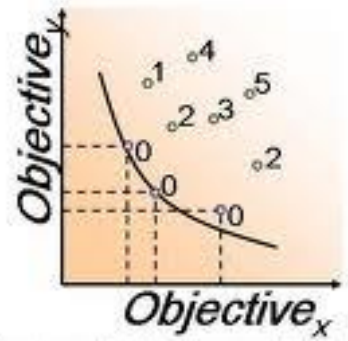


Energy Informatics

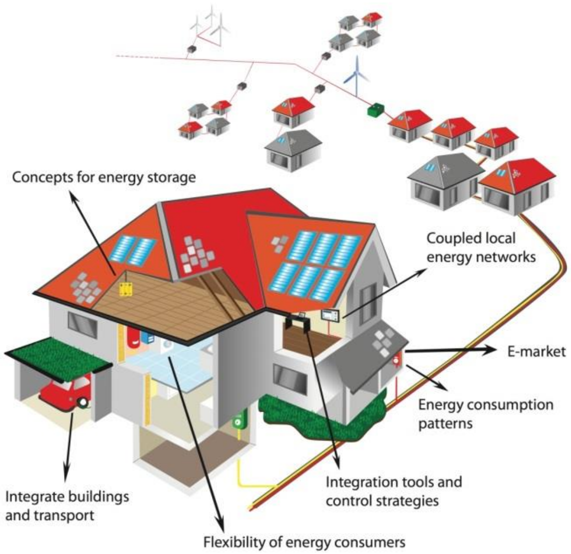
- Automatic energy labelling
- Screening of possibilities for energy savings
- Recommendations:
  - Should they replace the windows?
  - Or put more insulation on the roof?
  - Or tigthen the building?
  - Should the wall against north be further insulated?
  - ......
- Better control of the heat supply
- Optimized integration of renewable energy

Source: Henrik Madsen & Niamh O’Connell, DTU

Building efficiency and the grid

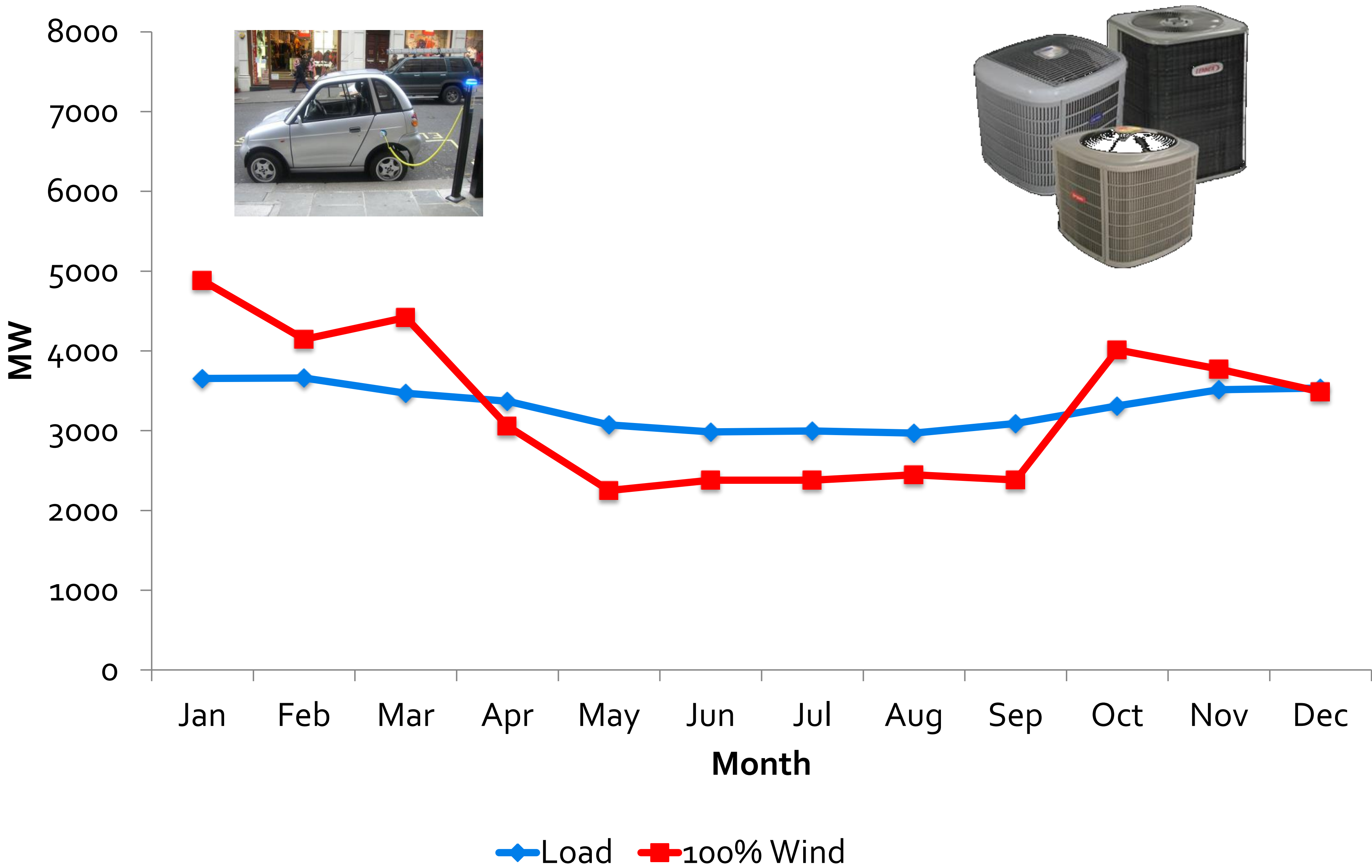


A bi-objective problem is a simplified form of a general multi-objective problem. Each point represents a solution to the bi-objective problem. The curved line represents the Pareto-front, identified non-dominated solutions are labeled with a Pareto rank of zero, and the Pareto rank of the other solutions refers to the number of solutions dominating it. Note that the problem requires minimization of both objectives.



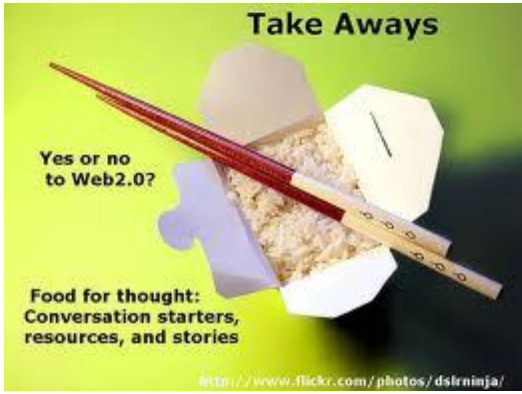
Kroposki, B., Komomua, C. and O'Malley, M., From the Building to the Grid: An Energy Revolution and Modeling Challenge, National Renewable Energy Laboratory, Technical Paper NREL/TP-6A00-56056, January 2013. http://www.nrel.gov/docs/fy13osti/56056.pdf

100 % Wind we will have to change how we live



Key Take Away # 9

- Demand response is not a technology issue it is a business and societal issue



Reading Material

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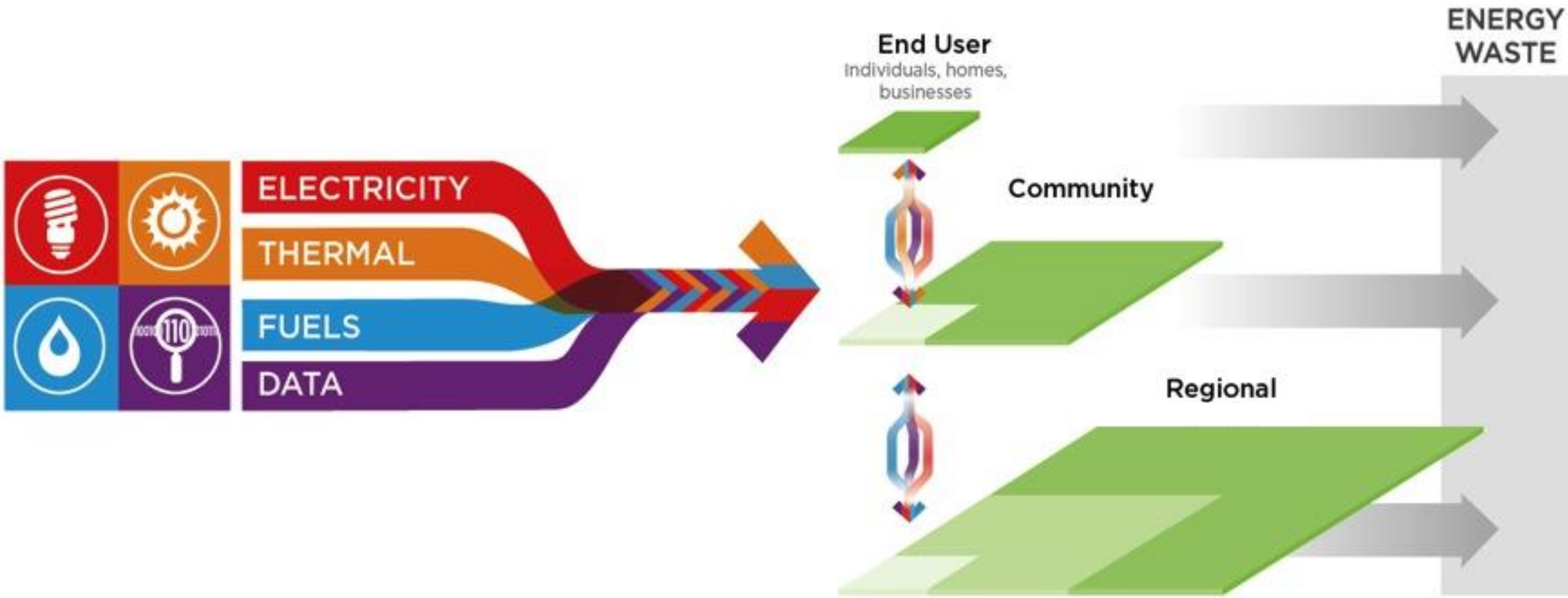

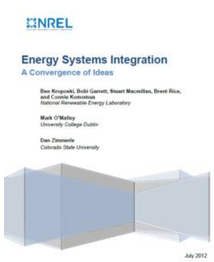
NREL

Energy Systems Integration
A Convergence of Ideas

July 2012

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ESI 101 Summary

- It is not all about Electricity, and the presenter is out of his comfort zone.
- It is very important, evolving & new
- It is international and at all scales
- Denmark is the world leader in ESI
- Every system is different
- ESI is about; Hardware, communications and control; Experimentation & demonstration; Planning & operations; Modelling & simulation & data; Policy, business models
- The consumer is king
- Education is important
- Demand response Is not a technology issue it is a business and societal issue

- ESI 101 at NREL July 2014

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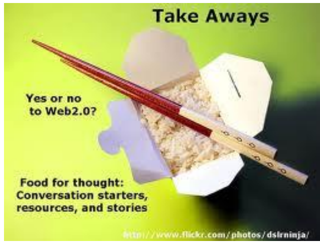

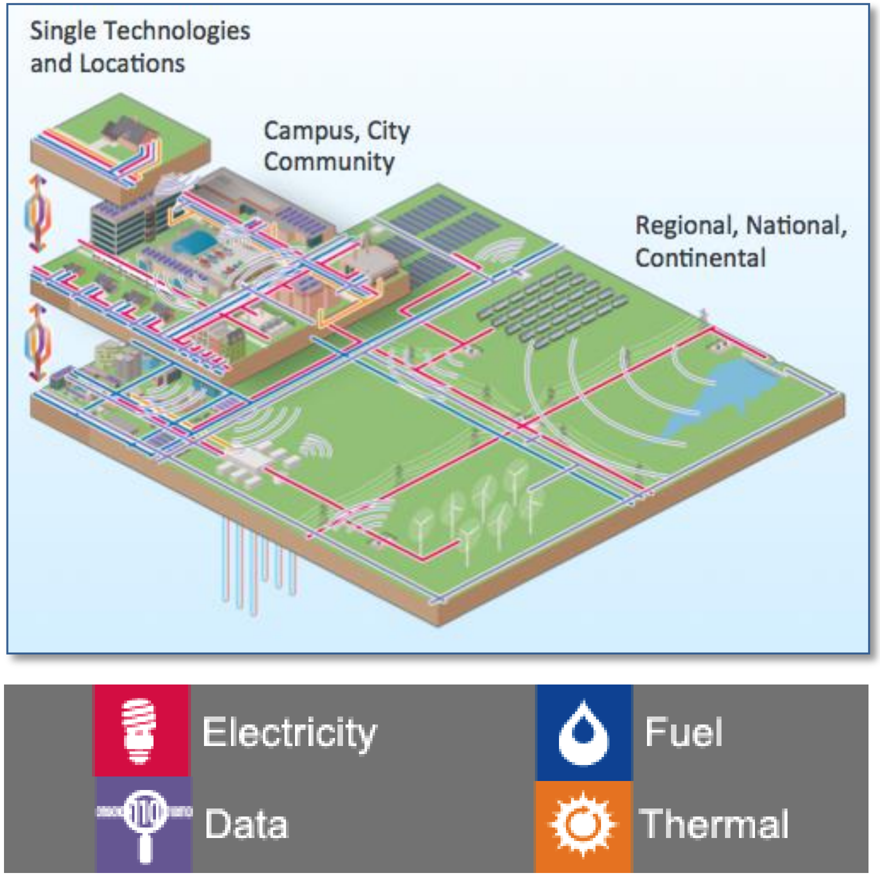

Energy Systems Integration (ESI) 101

NREL, Golden Colorado

Mid July 2014

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