



Grid Enablers of Sustainable Energy Systems: Conclusions and Research Directions

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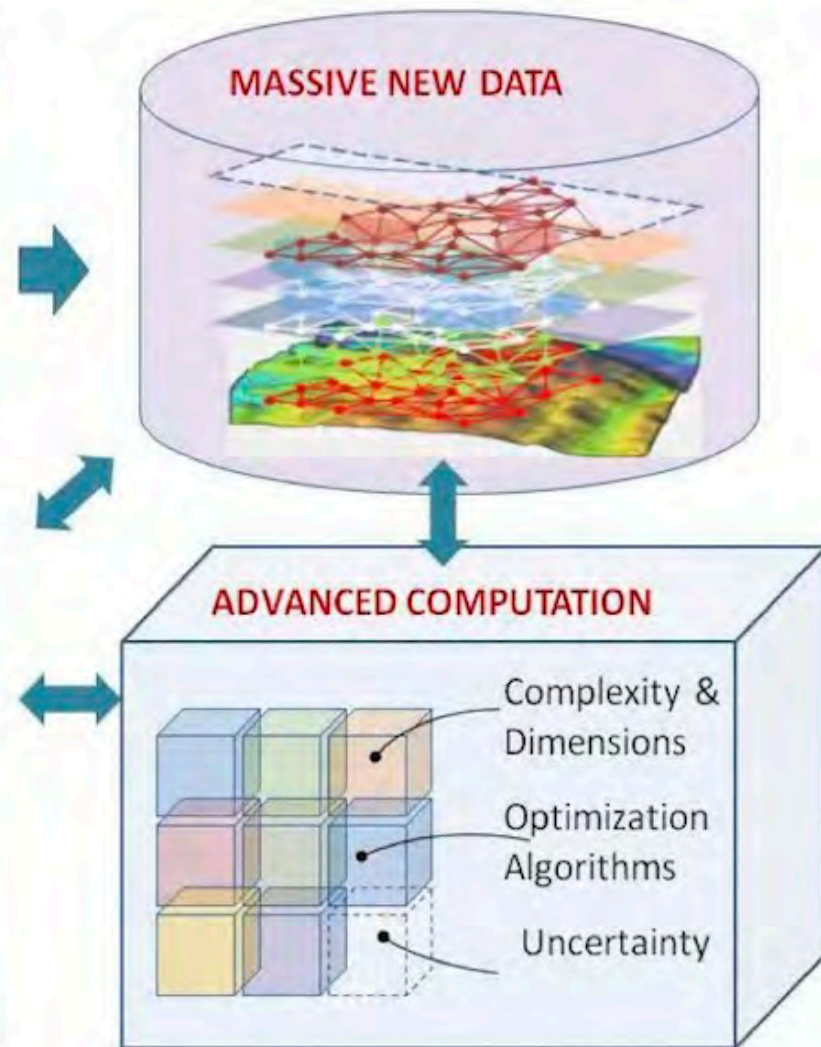
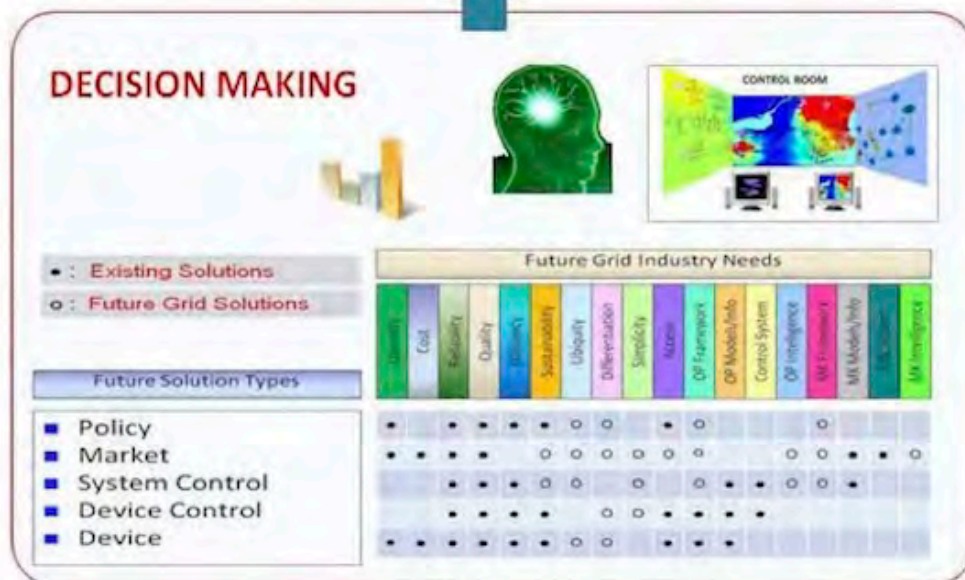
Presentation Overview

- PSERC “Future Grid” Initiative
(see <http://pserc.org/research/FutureGrid.aspx>)
- Broad analysis white papers
- Summary of 5 “Grid Enablers” white papers
- For each of the 5 papers:
 - Objective
 - Conclusions
 - Research needs
 - Related publications
- Conclusions

The Future Grid to Enable Sustainable Energy Systems

- A PSERC-wide 3-year project, funded by DOE
- Objectives:
 - Identify requirements of a grid with
 - high penetrations of sustainable energy systems
 - heavy cyber reliance for sensing and communications
 - Stimulate discussion among academic, industry and government communities on what it will take to shape the future grid for the mid-21st century
- Involves 13 universities, 40 faculty, and 40+ graduate students, along with interactions with many companies, DOE, and national labs

The Future Grid to Enable Sustainable Energy Systems



The Future Grid to Enable Sustainable Energy Systems

- Research thrusts in the Future Grid Initiative:
 - Electric energy challenges of the future (Jerry Heydt, Arizona State)
 - Control and protection paradigms of the future (Chris DeMarco, Univ. of Wisconsin-Madison.)
 - Renewable energy integration and the impact of carbon regulation on the electric grid (Shmuel Oren, Univ. of California, Berkeley)
 - Workforce development (Chanan Singh, Texas A&M)
 - Computational challenges and analysis under increasingly dynamic and uncertain electric power system conditions (Santiago Grijalva, Ga Tech)
 - Engineering resilient cyber-physical systems (Tom Overbye, UIUC)
 - Broad analysis papers (Pete Sauer, UIUC & Jim McCalley, ISU)
- Upcoming thrust research presentations: on 12/7 at the PSERC Industry-University Meeting, Golden CO, and public webinars starting in mid-January 2013

The Future Grid to Enable Sustainable Energy Systems – Broad Analysis Needs

- Resulted in 2 sets of white papers:
 - 4 papers: “The Information Hierarchy for the Future Grid,” led by 4 “lead authors,” coordinated by Pete Sauer (UIUC)
 - 5 papers: “Grid Enablers of Sustainable Energy Systems,” led by 5 “lead authors,” coordinated by Jim McCalley (ISU)
- Each paper
 - ...identified questions beyond scope of typical research projects; generally mix between engineering and policy, stakeholder perspectives, public interest...
 - **to *lead thought*, providing context for addressing engineering problems and policy needs in energy, considering national needs in 2020, 2030, 2040, even 2050;**
 - **to identify research directions**

The Future Grid to Enable Sustainable Energy Systems – Broad Analysis Needs

- Each of the nine papers:
 - Had 1 lead author; in most cases, 1 or more coauthors
 - Reviewed by industry experts; comments incorporated
 - Discussed at Dec. 2011 “Future Grid Workshop,” see: <http://pserc.org/research/FutureGrid/dec7workshop.aspx>
 - Published on web & presented in Spring 2012 webinar, see: <http://pserc.org/research/FutureGrid/broadanalysis.aspx>
 - Further discussed & revised at June 2012 Forum, see: <http://pserc.org/research/FutureGrid/futuregridforum.aspx>
- Pete Sauer provided 11/4/2012 summary webinar on “Information Hierarchy for Future Grid,” see: http://www.pserc.org/education/archived_tele_seminars/fgwebinars.aspx
- I am providing summary webinar on “Grid Enablers of Sustainable Energy Systems” today.

Broad Analysis White Papers: “Grid Enablers of Sustainable Energy Systems”

Overall focus of these 5 white papers:

What are key energy system needs at *very high* renewable penetration levels

1. Primary and secondary control for high penetration renewables
2. Towards standards in dynamics for electric energy systems
3. Future grid: the environment
4. Transmission design at the national level: benefits, risks and possible paths forward
5. Centralized and distributed power systems – a comparative approach

Summary of Authors & Reviewers

Topic	Lead author	Co-authors	Industry reviewers
1. Primary and secondary control for high penetration renewables	Chris DeMarco U. of Wisconsin (UWisc)	B. Lesieutre, UWisc; C. Baone, UWisc; Yehui Han, UWisc	J. Gronquist, BPA; V. Gevorgian, NREL; E. Ela, NREL
2. Toward standards for dynamics in electric energy systems	Marija Ilic Carnegie Mellon U		B. Fardanesh , NYPA; G. Arnolds, NIST; M. Patel, PJM
3. Future grid: the environment	Ward Jewell Wichita State University (WSU)	J. Twomey, WSU; M. Overcash, WSU; J. Cardell, Smith Col; L. Anderson, Cornell	F. Galvan, Entergy; L. Beard, Quanta; J. Price, CAISO
4. Transmission design at the national level: benefits, risks and possible paths forward	Jim McCalley Iowa State University (ISU)	J. Bushnell, ISU (now UC Davis), V. Krishnan, ISU; S. Lemos, ISU	J. Caspary, US DOE; S. Eckroad, EPRI; J. Eto, LBNL; J. Fleeman, AEP; D. McLaughlin, SoCo; B. Nickell, WECC; D. Osborn, MISO
5. Centralized and distributed pwer systems – a comparative approach	James Momoh Howard U.	Sakis Meliopoulos, Ga Tech	Bob Saint, NRECA

1. Primary and secondary control for high penetration renewables (Chris DeMarco)

White Paper Objective: Examine aspects of existing control practice tied to characteristics of traditional generator technologies; consider how they may be impacted by potentially very different attributes of a new class of control actuators (renewables) and new sensors and measurement technologies.

1. Primary and secondary control for high penetration renewables (Chris DeMarco)

Conclusion 1: To maximize benefit of high penetration renewables, “open up” design space of their control systems:

- Do not constrain new classes of equipment to replicate old technologies, e.g., inertial emulation for wind and PV power regulation schemes;
- Rather seek to exploit the widely differing control attributes of diverse generation, storage and responsive load technologies

Conclusion 2: Allow renewables to more broadly contribute to grid active power and frequency control via PE interface.

Conclusion 3: PMUs enable control utilizing multivariable system outputs over a wide geographic area, providing for controllers that can make use of dynamic observations of the system state.

1. Primary and secondary control for high penetration renewables (Chris DeMarco)

Research needs:

1. Establish control performance metrics & desired performance:
 - Local: drive-train stress
 - Global: CPS1, CPS2, transient frequency nadir
2. Utilize wide-bandwidth PMU measurements for dynamic observation of system states in feedback control.
3. Apply via renewables, responsive load, and storage to provide desired performance to facilitate higher penetrations of renewables via primary and secondary control
4. Design/test use of new measurement technologies, coupled with optimal control methods (H-infinity, Convex optimization methods/LMI, Linear quadratic methods), to identify best performance in terms of identified metrics.
5. Identify tradeoffs between improved control performance and impact on operational economics of renewables.

1. Primary and secondary control for high penetration renewables (Chris DeMarco)

Related publications:

- C. A. Baone and C. L. DeMarco, “Observer-based distributed control design to coordinate wind generation and energy storage,” in *Proc. of the 2010 IEEE Conference on Innovative Smart Grid Technologies Europe*, Gothenburg, Sweden, Oct. 2010.
- C. A. Baone and C. L. DeMarco, “From Each According to its Ability: Distributed Grid Regulation With Bandwidth and Saturation Limits in Wind Generation and Battery Storage,” to appear 2012, *IEEE Transactions on Control Systems Technology*, IEEE Explore link:
http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6142123&tag=1
- DeMarco, C.L.; and C. A. Baone. “Smart grid control design methods for distributed energy storage in frequency regulation markets,” *Proc. of 18th Int. Federation of Automatic Control (IFAC) World Congress*, Milan, Italy, September 2011.
- C. A. Baone and C. L. DeMarco, “Distributed Control Design to Regulate Grid Frequency and Reduce Drivetrain Stress in Wind Systems Using Battery Storage,” *Proc. of the 2012 American Control Conference*, Montreal, CANADA, June 2012.

2. Toward standards for dynamics in electric energy systems (Marija Ilic)

White Paper Objectives:

- Identify what may become problems with system dynamics as unconventional technologies are integrated into the existing T&D grids;
- Determine how to design standards for dynamics which support system evolution without experiencing near real-time operating problems.

2. Toward standards for dynamics in electric energy systems (Marija Ilic)

Conclusion 1: System dynamic issues & standard development:

- Component-level safety: xfmr harmonic resonance; SSR. Need standards to induce good control vs. component disconnection
- Synchronization of interconnections w/hybrid ac-dc & microgrids: transient/voltage instability
- Local/interarea oscillations arising from decreased conventional gen (PSS) or from renewable controllers
- Quality of service: effects on frequency & voltage
- Cost of cntrl: primary/sec wind cntrl, ramping products in mrkts

Conclusion 2: Four basic functionalities for standards: component safety; maintaining synchronization of interconnections w/ hybrid AC/DC & microgrids; meeting quality of service for freq/voltage; facilitate integration of renewables, demand response & FACTS.

2. Toward standards for dynamics in electric energy systems (Marija Ilic)

Conclusion 3: Existing standards for governor and excitation system response, along with the standards for AGC and/or for European AVC, are control area-level requirements which are not system specific and therefore serve as a good starting point for what is needed in the future.

Conclusion 4: There are no standards for dynamics for demand-side nor for deployment of FACTS; Special purpose controllers implemented for transient stabilization do not have quantifiable standard requirements for their dynamic performance.

Conclusion 5: Central generation and high-voltage transmission planning for ensuring that the N – 1 reliability standard is met at the bulk power transmission system level must be considered in coordination with the lower-level standards and protocols which must be designed for the new distributed energy resources.

2. Toward standards for dynamics in electric energy systems (Marija Ilic)

Research needs:

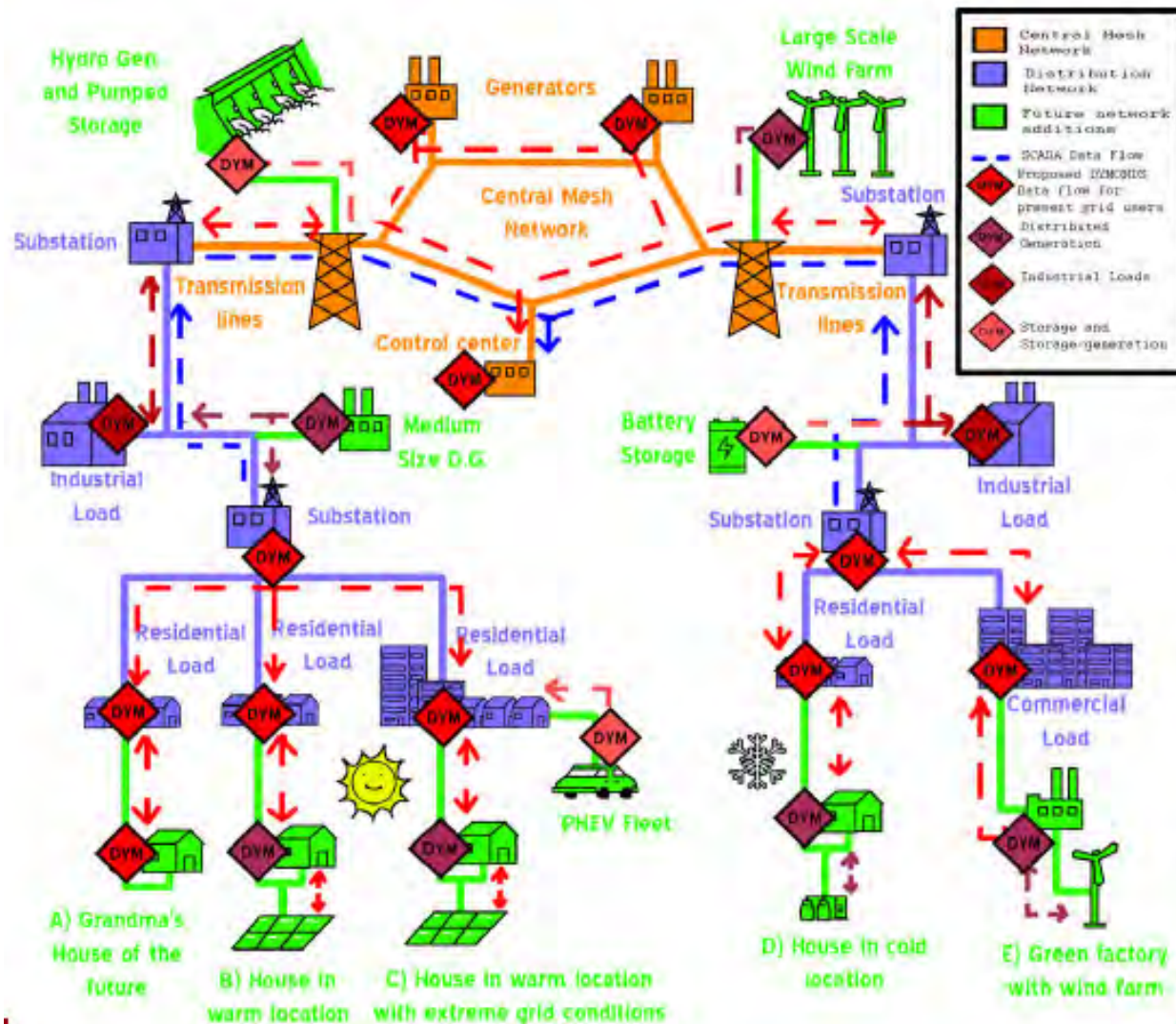
1. A unifying modeling approach is needed to represent the dynamics of component groups within a given system in terms of state variables and group-interaction variables.

2. Need to develop general principles to underlie standard design for dynamics, considering the following:

- Plug-&-play standards: each group of components able to adapt, stabilize itself, and cancel interaction variables with neighboring components. No requirements for on-line communication. Strict standards at component level. Conservative.
- System-level technical standards: Here, each component group stabilizes its own dynamics and participates in minimal coordination of interaction variables managed at system layer → system-level WAMS-based coordination of dynamic interactions between components groups. Cannot assign responsibilities; cannot provide economic incentives to participate in higher-layer coordination.
- Interactive protocols: Ensure technical performance according to choice & value → system-level coordination relying on exchange of info on components' willingness to contribute to coordinated control of interaction variables.

2. Toward standards for dynamics in electric energy systems (Marija Ilic)

Research needs:



2. Toward standards for dynamics in electric energy systems (Marija Ilic)

Research needs:

3. Develop an industry-academia team with a focused effort toward formalizing and adopting standards for dynamics.
4. Present/discuss the envisioned standards for dynamics with NERC, NIST, NASPI, IEEE and IEC and seek their comments.

2. Toward standards for dynamics in electric energy systems (Marija Ilic)

- [2] Talaat, Nermeen and Marija D. Ilic. "ANNs Based on Subtractive Cluster Feature for Classifying Power Quality Disturbances." 2008 North American Power Symposium (NAPS 2008), September 28-30, 2008. Calgary, Canada.
- [3] Allen, E.H., J.W. Chapman and M.D. Ilic, "Effects of Torsional Dynamics on Nonlinear Generator Control," IEEE Transactions on Control Systems Technology, 4, 125-140, March 1996.
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- [5] M.Ilic, J.Chapman, "Decentralized Excitation Control for an Electrical Power Utility System," USpatent 5 483 147, 1996.
- [6] M.D. Ilic and S.X. Liu, "Direct Control of Inter-area Dynamics in Large Power Systems Using Flexible AC Transmission Systems (FACTS) Technology," U.S. patent 5 517 422, 1996.
- [7] Cvetkovic, Milos, and Marija Ilic, Nonlinear Control for Stabilizing Power Systems During Major Disturbances, IFAC World Congress, Milano, August 2011.
- [8] M. Cvetkovic, K. Bachovchin and M. Ilic, Chapter 19 in Ilic, M., Xie, Le and Liu, Qixing (editors), Engineering IT-Enabled Sustainable Electricity Services : The Tale of Two Low-Cost Green Azores Island, Springer, 2012 (to appear) .
- [9] Q. Liu, M. Cvetkovic, and M. Ilic "Toward Stabilizing Linearized System Dynamics in Future Electric Energy Systems by Means of Enhanced Voltage Control," Chapter 16 in Engineering IT-Enabled Sustainable Electricity Services : The Tale of Two Low-Cost Green Azores Islands, Springer, 2012 (to appear) .
- [10] Ilic, M and Liu, Qixing, Toward Sensing, Control and Communications for Frequency Regulation in Systems with Highly Variable Resources, in Control and Optimization Methods for Smart Grids, Springer 2012, Chapter 1.
- [11] Popli, Nipun and Ilic, M, Chapter 14 in Engineering IT-Enabled Sustainable Electricity Services : The Tale of Two Low-Cost Green Azores Islands, Springer, 2012 (to appear).
- [12] Ilic, M., E. Allen, J. Chapman, C. King, J. Lang, and E. Litvinov. "Preventing Future Blackouts by Means of Enhanced Electric Power Systems Control: From Complexity to Order." IEEE Proceedings, November 2005.
- [13] Ilic, Marija and Liu, Zhijian, "A New Method for Selecting Best Locations of PMUs for Robust Automatic Voltage Control (AVC) and Automatic Flow Control (AFC)", IEEE PES 2010, Minneapolis, MN, July 25-29, 2010.
- [14] Ilic, M., Dynamic Monitoring and Decision Systems for Sustainable Electric Energy, Proc of the IEEE, Jan 2011.
- [15] Ilic, M., Smart Grid & Future Electric Energy Systems, Lecture Notes, 18-618, Carnegie Mellon U ECE, Spring , 2012

3. Future grid: the environment (Ward Jewell)

White Paper Objective: present the significant near- and long-term unresolved environmental issues relevant to the electric energy industry, and summarize the technologies that will help resolve them.

3. Future grid: the environment (Ward Jewell)

Conclusion 1: The most important environmental *issues* are: (a) reducing production of greenhouse gases; (b) adapting grid to changing climate; (c) obtaining water for electricity generation and fuel production.

Technologies to address them:

- **fuel switching from coal to natural gas;**
- **carbon capture and storage;**
- **nuclear fission generation;**
- **renewables;**
- **energy storage;**
- **energy efficiency improvements;**
- **designs that reduce water use by thermal generating stations;**
- **seawalls;**
- **asset relocation;**
- **designs reducing vulnerability of assets to storms.**

3. Future grid: the environment (Ward Jewell)

Conclusion 2: These issues are appropriately addressed via govt regulations since they are not intrinsic to markets.

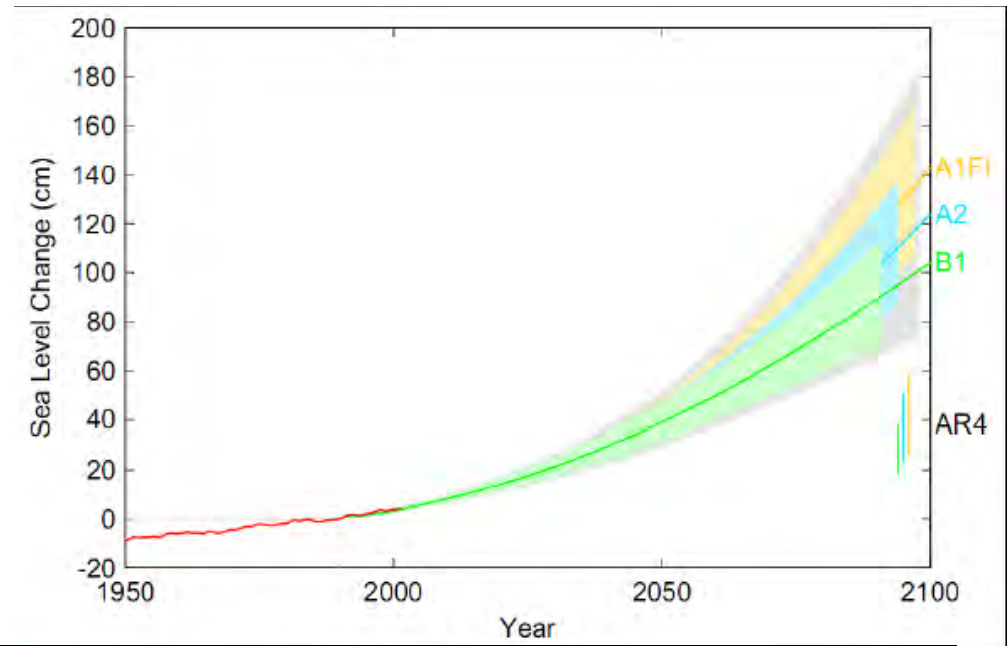
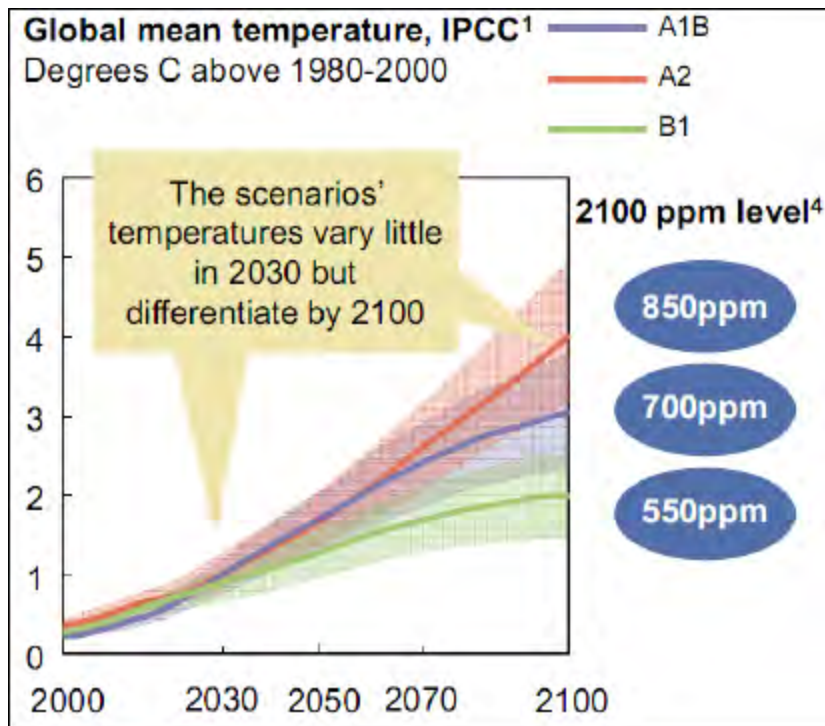
Conclusion 3: Environmental issues, technologies, and regulations all interact and at times conflict; none may be addressed without considering the effects on the others.

Conclusion 4: Effect on cost of producing/delivering electricity must be balanced against benefits of improving, or costs of not improving, the environment.

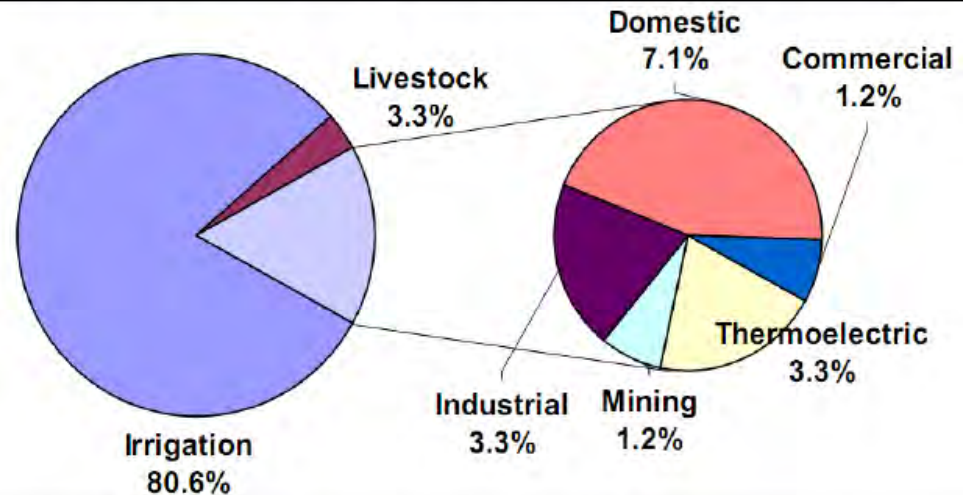
Conclusion 5: Environmental costs/benefits from actions today are forecast to occur over a period of decades, so analyses should use appropriate time horizons.

Conclusion 6: Electricity planning must consider life cycle costs/benefits in optimizing long-term environmental benefits, electric system reliability, and implementation costs.

3. Future grid: the environment (Ward Jewell)



US freshwater consumption by sector



3. Future grid: the environment (Ward Jewell)

Research needs:

1. Issue-specific research:

What is range of magnitudes the nation will face regarding each issue?

What are effects of continued emissions; how much reduction is needed?

When and where should climate change effects be expected, and what range of magnitudes will we see?

Who will be competing for water and how great a need will there be for the electric industry to alter its withdrawal and consumption?

How will climate change further affect water availability?

2. Technologies:

What technologies have been identified to address each of the issues?

What time frame over which those technologies may become available?

What will be the range of costs for each?

How does a technology useful for one issue affect the other issues (e.g., what is the water usage and vulnerability to climate change of a carbon capture and sequestration system?)?

3. Future grid: the environment (Ward Jewell)

Research needs:

3. Electric grid operations and planning:

How can the grid be redesigned and operated in the future to use technologies to achieve the changes needed to address the issues?

Develop operations and planning models for new technologies.

Multi-objective optimization techniques for long-term planning are needed to consider wide range of technology availabilities and costs.

4. Policy:

What are policy solutions to issues; how to incentivize to address them? Which policies will be most effective in addressing environmental issues while maintaining reliable/economically-competitive electric service?

5. Regulations:

What regulations are available to implement the policies?

How to design coherent regulations to address environmental issues while still providing reliable & economic energy?

How will federal, state, regional, and local regulations interact?

Will regulations produce environmental benefits intended?

4. Transmission design at the national level: benefits, risks, and possible paths forward (Jim McCalley)

White Paper Objectives:

A national transmission overlay is a high capacity, multi-regional transmission grid, potentially spanning all three inter-connections, designed as a single integrated system to provide economic/environmental benefits to the nation.

The objective of this paper is to identify benefits to building a national transmission overlay, to lay out essential elements to facilitate continued dialogue on this topic, and to frame possible paths by which it could be realized.

4. Transmission design at the national level: benefits, risks, and possible paths forward (Jim McCalley)

Conclusion 1: Interest in an overlay is motivated by

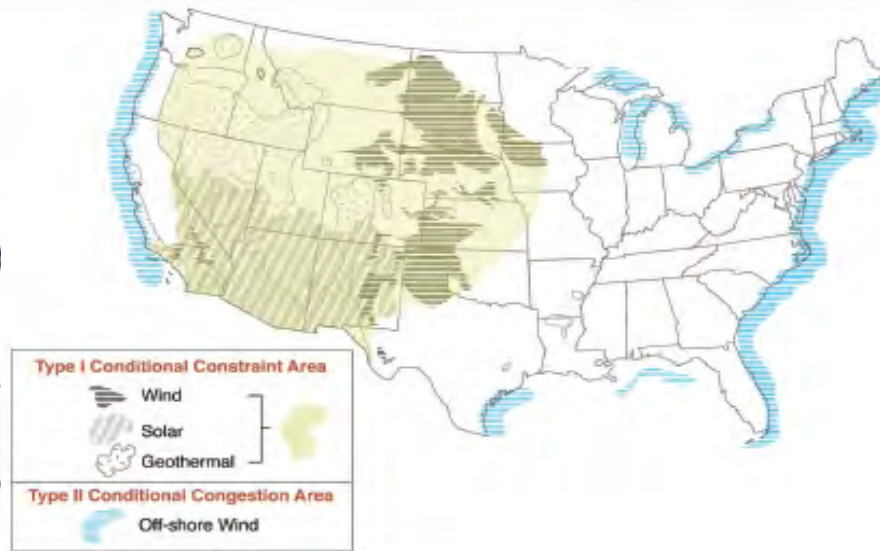
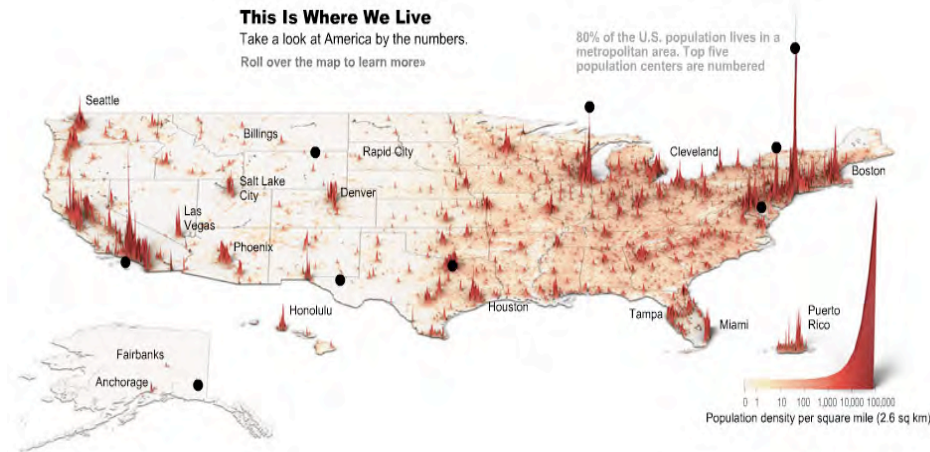
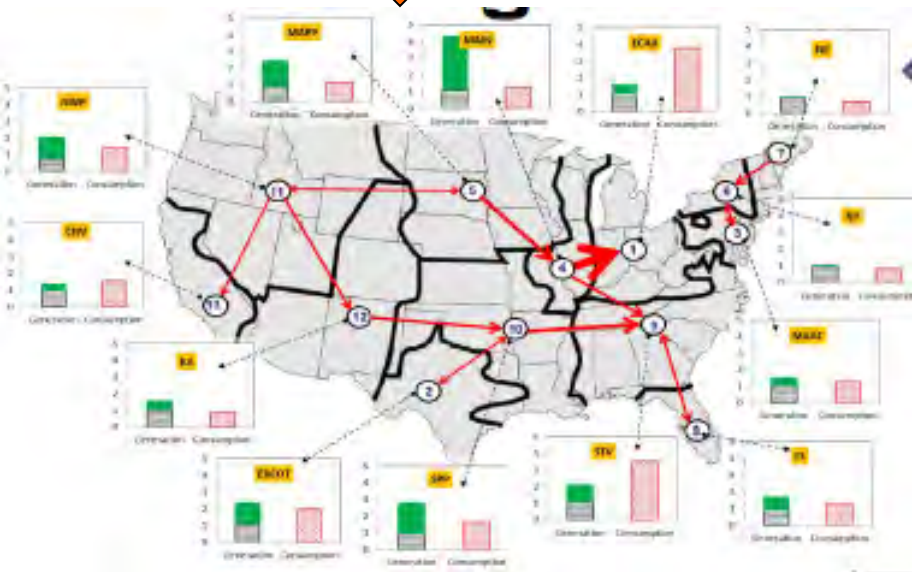
- Location heavily influences economic viability of a given renewable project; this is less the case for non-renewables.
- Renewable energy can be moved only by electric transmission; this is not the case for non-renewables.
- Transmission costs comprise a relatively small percent of long-term power system investment and operation cost.

Conclusion 2: Essential elements necessary to building a national transmission overlay: locations of future generation/load centers, technologies to dominate future generation portfolios, existing interregional transmission capacity and congested locations, transmission technologies and their attributes.

Conclusion 3: Benefits to building a national transmission overlay are long-term cost savings, resilience of energy prices to large-scale events, emissions reduction & energy system flexibility.

4. Transmission design at the national level: benefits, risks, and possible paths forward (Jim McCalley)

Under “mostly” to “all” renewable gen growth, this transmission design saves \$18B→\$34B/year over 40 years.

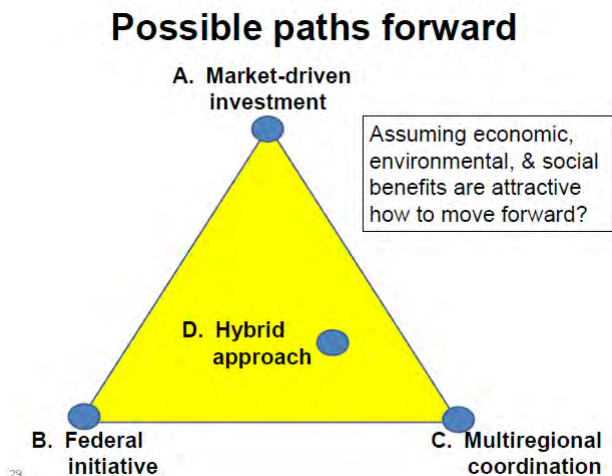


4. Transmission design at the national level: benefits, risks, and possible paths forward (Jim McCalley)

Conclusion 4: Issues/concerns include:

- effects on each state's economic development
- cost allocation
- market impacts (winners/losers)
- policy and technology uncertainty
- obtaining right-of-way
- lack of long-term congestion hedging products
- need for mid-level resource collection networks

Conclusion 5: Possible paths to realize it: market driven investment, fed initiative, interregional coordination, hybrid approach



4. Transmission design at the national level: benefits, risks, and possible paths forward (Jim McCalley)

Research needs:

1. Design process: Transmission of this capacity and geographical breadth has never been built before: what does the design process look like?
2. Performance analysis: Promising topology/technology designs should be evaluated to determine steady-state & dynamic performance, resiliency, and flexibility.
3. Economic analysis: A refined economic analysis should be performed for each topology/technology design to identify relative benefits of the transmission overlay for each geographical region of the country.
4. Path forward and associated policy needs: Additional socio-political/policy research is essential to consider the identified possible paths (market-driven, federal initiative, interregional coordination, and hybrid).

4. Transmission design at the national level: benefits, risks, and possible paths forward (Jim McCalley)

Publications:

[1] J. McCalley, W. Jewell, T. Mount, D. Osborn, and J. Fleeman, “A Wider Horizon: Technologies, Tools, and Procedures for Energy Systems Planning at the National Level,” *IEEE Power and Energy Magazine*, Vol. 9, Issue 3, May/June 2011, pp. 42-54.

[2] E. Ibanez, V. Krishnan, S. Lavrenz, D. Mejia, K. Gkritza, J. McCalley, and A. Somani, “Resilience and robustness in long-term planning of the national energy and transportation system,” to appear in *International Journal of Critical Infrastructures*.

[3] V. Krishnan, J. McCalley and J. Bushnell, “Nationwide Transmission Overlay Design and Benefits Assessment for the U.S.,” under review by *Energy Policy Journal*.

5. Centralized and distributed power systems: a comparative approach (James Momoh)

White Paper Objective: To identify relative strengths (benefits) and weaknesses associated with centralized generation vs. distributed generation.

5. Centralized and distributed power systems: a comparative approach (James Momoh)

Conclusion 1: Centralized investment benefits from economy of scales.

Conclusion 2: There may be reliability benefits to distributed investment.

Conclusion 3: A research roadmap is needed (and proposed) to determine the right balance of long-term investments in

- centralized/distributed generation,
- transmission and distribution,
- control and communication technologies

using metrics to judge *economics, sustainability, reliability, resilience, & flexibility* for the future grid.

5. Centralized and distributed power systems: a comparative approach (James Momoh)

Research needs:

1. Develop computational tools to enable exploration of potential investment strategies among future scenarios.
2. The tools should be capable of modeling centralized and distributed generation, various transmission technologies, renewables, their variability and ramping needs, storage, demand response, transportation/energy system interdependencies, bio-fuels, water and land use, and locational impacts on resources.
3. These tools should assess long-term investment and operational costs, environmental impact, reliability, resiliency, and flexibility.

Conclusions

Renewables and the Future Grid:

1. Control and communications
2. Standards and dynamics
3. The environment
4. “Big” infrastructure
5. Centralized vs. decentralized investment

What is the real 2050/2100+ impact of global warming?

- If serious, we must attempt to mitigate.
- What is the most economic investment plan to address it?
- How to evolve control/communication technologies accordingly?
 - Can “the market” facilitate these needs?
 - If not, how to proceed?

A highly important opportunity to lead thought!