Energy Challenges Facing the Nation – And NSF Opportunities to Address Them

- Getting Funding from ENG Engineering Directorate
- Two Grand Challenges – “Oil” and “Electricity”
  - Why Grand (and small) challenges are important
  - White House position and what the stakes are
- Grand Strategy for How to Meet the Challenges
  - Oil: cut cost of plug-in hybrids and alternate liquid fuels
  - Electricity: true intelligent grid, solar farms, power electronics, storage, “team B” high risk research, incentives (mostly beyond ENG, though planning and markets are part of grid research)

Dr. Paul J. Werbos, Program Director for Energy, Power and Adaptive Systems, NSF. Personal, not official views, government public domain.

Getting Funding from ENG Engineering Directorate

ECCS Funding Rate

<table>
<thead>
<tr>
<th>Year</th>
<th>ECCS Proposals</th>
<th>ENG Awards</th>
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<td>2009</td>
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</table>

Dr. John Zavada

Sensor Devices & Technologies

• Interconnects & Packaging
• Mixed Signal Circuits & Systems

Dr. Samir El-Ghazaly

Novel & Next Generation Devices

• Microwave/mm-Wave/THz
• Novel Energy Conversion Devices

Dr. George Maracas

Stochastic Modeling & Applications

• Distributed & Mobile Networked Control

Dr. Radhakisan Baheti

Electronics, Power, and Adaptive Systems (EPAS)

- Adaptive & Intelligent Systems *
- Transmission & Distributed Systems
- Intelligent Power Grid *
- Quantum Systems & Modeling *
- Neural Networks
- High Performance & Multiscale Modeling
- Cognitive Optimization & Prediction
- Intelligent Vehicles & Robots

Who Gets To The Winning 15%?

- Clearly spell out your targets. What do you really want to accomplish in 3 years that is new? (Always google a lot to be sure what is now and what you add.)
- Why should we believe you can do it (as well or better than anyone else)? New ideas, plan, analysis of obstacles, prior work, track record, research content.
- Prove how important it is. What is the size and the nature of the benefits to (1) understanding of general, basic principles; and (2) future of humanity at large? Can you prove it? How do your goals fit into a larger strategic plan or vision, as real as possible?
Two Grand Challenges

1. How can the US become totally independent from the need to use fossil oil at the soonest time, at minimum cost?
   - Total independence is possible in 20-25 years at little cost or even savings, using combination of plug-in hybrid cars and three-way fuel flexibility, but transition may be hard. R&D can lower costs of new cars, new fuels, connection to grid. Also improve performance and reduce pollution of these.

2. How can the world become able to meet its electricity needs from >80% renewable sources at ≤10¢/kwh with maximum probability at soonest time?
   - Total cost is mainly generation cost plus grid cost. E.g. guesstimate of 10¢/kwh best onshore wind for generation, 40¢/kwh total cost due to backups, storage, long lines, regulation services. 10¢/kwh for earth = $2 trillion/year

What's Important for CO2: Data from DOE/EIA-0573 (2009)

- Total US CO2 emissions: 5426 million tons (Table 7, page 22)
  - 2160 direct CO2 from transportation
  - 1854 direct from electric utilities
  - 1412 all other places, including electricity generation by industry and commercial sectors
- 1404 is the total emissions of industry (direct plus indirect)

New Adaptive Intelligent Algorithms

For Anticipatory Optimization
- At User Sites
- At ISO/RTO
- Elsewhere
- Distributed but an Integrated System

New Pervasive Sensors
New Actuators - Switching, Control
New Communications - Secure Fiber, Interoperable
New Software Platforms

5 Grand Challenges for Adaptive and Intelligent Systems

- General-purpose massively parallel designs to learn

\[ Pr(A|B) = Pr(B|A) \times \frac{Pr(A)}{Pr(B)} \]

Memory Prediction
Optimization

COPN

4th Gen Grid Is ONE Important Battlefield In the War For Global Sustainable Energy

#1 Challenge Today: Xi and Li

www.werbos.com/oil.htm, energy.htm

NSF is currently supporting research to develop a '4th generation intelligent grid' that would use intelligent system-wide optimization to allow up to 80% of electricity to come from renewable sources and 80% of cars to be pluggable electric vehicles (PEV) without compromising reliability, and at minimum cost to the Nation (Werbos 2011).

Werbos 2011: IEEE Computational Intelligence Magazine, August 2011

WE CAN Zero Out Gasoline Dependency: A Definite Option for 100% Renewable Zero-Net-CO2 cars & Total Security for Car Fuel

GEM fuel-flexible plug-ins offer a 100% solution based on near-term technology! www.ieeeusa.org/policy/positions/PHEV0607.pdf

Risk of $10-20/gallon prices if quick shock: How would you cut your gasoline use by 50% or more?

- If output falls, free market raises prices enough to force you cut your use in half or more.
- The only question: how? Lower income? Small car? Or market-friendly new technology?
- Antimarket tricks like price caps, high interest rates, pressures on Arab states only lead to worse outcomes (Nash)

Oil and Economic Security
In the Coming Decade

- Before the September 2008 economic collapse: oil (Brent) about $150/barrel and rising, half due to expectations – Hotelling rent
- **Huge** world economy recovers, many project about $200/barrel… a $ trillion/year bill for US,

Optimal Strategy for Total Energy Security
Maximize Fuel-Flexible Plug-in Hybrid Cars

Open door to US natural gas (e.g. to trucks) while it lasts

Maximize supply of Alternate liquid fuels - Not oil

- Incentives, standards and R&D

R&D for more efficient use of diverse fuels

R&D for batteries for affordable electric cars

Maximize cost and then maximize supply of renewable electricity
Plug-in Hybrids (PHEV): A Large-Scale Opportunity Here and Now

- Hybrids cut liquid fuel use 50% already. Plug-ins cut 50% of that.
  - “Researchers have shown... (PHEV) offering... electric range of 32 km will yield... 50% reduction...” (IEEE Spectrum, July/05). Shown in working Prius.
- Battery breakthroughs in China: from 10/07, 10kwh batteries (larger than) cost $2,000. www.thunder-sky.com. Thus an extra $2,000 per car can cut gas dependence in half.
- Gives economic security in case of sudden gasoline cutoff.
- Does not strain grid – actually strengthens it, if done right.

GEM Flexibly Fuel Vehicles (FFV): One Tank To Hold Them All

- G: Gasoline
- E: Ethanol
- M: Methanol

With an FFV, you choose each day which to buy. At $100-200/car, a more open competition, level playing field, better unleash the power of the free market.

What limits rate of deployment of hybrids & plug-ins? Cost, cost, cost... (and recharge: don’t fall into chademochademo!)

- Hybrid Prius vs. regular Prius: cost penalty = $3000 (2006 data Car & Driver, Financial Times) about enough to pay off at $3-4/gallon without interest.
- About $2000 of the $3000 is for small fast battery, currently nickel hydride less than 1kwh.
- $1,000-$2,000 tax incentive per car, for the first million hybrids from each manufacturer, essential to speed of development, becoming cheaper, in US.
- Outside the US, higher gas price bigger market now.

We can dramatically reduce cost and expand supply of biofuel, present and future, if we stop requiring so much purity in our ethanol/alcohol!

- We need to give this guy permission to compete with Saudi Arabia and Iran for the car fuel market! He doesn’t need a subsidy – only more freedom and an open door! Just give him a chance, and within 15 years... (Also, try a google on “forest industry methanol.”)

Example 1 of Funded Work: Alireza Khaligh IIT

(New integrated power electronics can cut cost of total power electronics for cars like Volt by 1/3 – 1/2 while adding a flexible AC/DC fast recharge capability making fast recharge stations “free” instead of $100,000-$200,000 each. Similar technology crucial to distribution level (Rahman issues) constraints.

To The Rescue: Lonnie G. Johnson

- Founder and President
- NASA (Voyager, Mars Observer, CRAF, Cassini, Galileo)
- Holds over 90 patents.
- B.S. in Mechanical Engineering, Tuskegee University
- M.S. in Nuclear Engineering, Tuskegee University
- Ph.D. (Honorary) in Science, Tuskegee University
- Projects relying on Tuskegee labs and students

“One of the Top Inventors in the World” Time Magazine

Existing credible new ideas (risky but near term) for US to leapfrog the world both in batteries and in more efficient heat-to-electricity for flexible cars...
Batteries Too: Two New Concepts to Use Those Membranes to Outperform Asia on Batteries for Plug-in Hybrids (Maybe Even Affordable True Electrics!)

<table>
<thead>
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<th>Battery Type</th>
<th>Specific Energy (Wh/kg)</th>
<th>Energy Density (Wh/l)</th>
<th>Discharge Rate (C)</th>
<th>Specific Power (W/kg)</th>
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<td>2000</td>
<td>5</td>
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</tbody>
</table>

New: www.excitation.com: Argonne verifies >100 cycles recharge

NEW JOHNSON DESIGN ADDRESSES HISTORICAL BARRIERS TO COMMERCIALIZATION

Notice the need for new membranes – from Tuskegee!

NEW JOHNSON DESIGN ADDRESSES HISTORICAL BARRIERS TO COMMERCIALIZATION

Lithium Anode Corrosion By Water And O2
Plating Surface For Lithium To Limit Dendrite Growth
Safety Issues Related To Volatile Electrolytes
Standby and Operational Shelf Life
Limited Discharge Rate Capability

O2 and Water Vapor
Permeability Limits
10^-4 g/M2/day required for one year operation
10^-5 g/M2/day required for ten year operation

Example 2: Thin AC Converters -- Harley and Divan, GA Tech

Truly intelligent grids require actuation and intelligence…

A New Way to Provide Switching and Conditioning to the Grid:
-- Much Less Expensive Than "FACTS" (Flexible AC….)
-- Graceful Degradation in Case of Fault

Divan estimates:
-- Smart Grid With This and Other Key Items Can Reduce Real Marginal Cost of Wind to Ratepayers from ≈ 40¢/kwh
To = 10¢
-- New transmission line requirements for new solar/wind plans can be cut more than half using this

Example 3: NSF Grant 08016714 Stefan Siegel

Lab scale proof of radically new design for wave energy extraction, designed to maximize efficiency in extraction and minimize material use. 50-fold reduction in material and double extraction efficiency suggests that much lower costs per kWh may result. Large scale demonstrator scheduled for 2011 in Oregon. If all goes well, will then be ready for full-scale ocean demo and cost estimation.

JTEC: A Possible Replacement for Stirling

* Lowest cost solar farms today: 10-12¢/kwh with dish solar (Sanika, SES) with heat to electricity of 30% via Stirling. JTEC at 800°C simulations say they can do 60%-65%.
* But options for 55% Stirling may exist!
* The inventor has had many successes from toys to rechargeable Li-Air batteries, featured in Atlantic and CNN News this year.
* Successful hardware test at 300°C for NSF grant. Uses new basic method to convert temperature differences to electricity. No solid moving parts, cousin of ceramic membrane fuel cell. Design for 800°C is credible, needs further support.
NSF-NASA Workshop on Learning/Robotics
For Cheaper (Competitive) Solar Power

See NSF 02-098 at www.nsf.gov & URLs
Joint funding led by Werbos/NSF & Mankins/NASA

About 10 Independent Systems
Operators (ISOs) Run the US Grid

1st Generation: Highlights From Before 2000
- NSF power grid program from 1987.
- "Large scale nonlinear system.
- With EPRI, main source of R&D in US. $20 million/half-trillion
- Deregulation versus regulation: misconceptions about markets
  - Markets do not always work: Nash equilibrium is not always Pareto optimal (a best outcome).
  - Yet price signals are essential to consistent rational choices especially in the face of complexity.
- Solution: "Market Design" to make the Nash equilibrium become optimal, solve an optimization problem. ISO algorithms are designed markets.
- Breakthroughs with neural networks at grid component level
  - Kwang Lee and Mo-Yuen Chow in diagnostics/prediction
  - Wunsch, Venayagamoorthy, Harley: turbogenerator control to withstand disturbances three times larger than other controls
  - Lefebvre: recurrent networks in 20% of US coal-fired generation

Neural Network in Commercial Power Grid Hardware
- First deployment of recurrent neural network from university in the field in a commercial electric power grid.
  (Improved prediction to allow unprecedented monitoring and control of harmonics.) Harley, Georgia Tech.

2nd Generation: Some Highlights From 2000 to 2002
- Synchronized phasors from Virginia Tech, NSF funding
  - Sensors to measure phase angle allow "more optimal" regulation control, to maintain frequency and keep electricity in phase.
  - Massive deployment now planned in 1st generation efforts, but how can we use them?
- Massoud Amin at Electric Power Research Institute (EPRI):
  - Program in "self-healing" networks, using classical control theory to try to address stability of the grid as a whole
  - Wide dissemination and basis of much of big investment in US today
  - Time of day (real time) pricing: need for price variation over time for market to shift demand over time, as required with renewables, storage and efficient recharge of PHEVs.
  - Rise of ISOs, big decline of EPRI. California crisis, Brazil technology needed for California (2001 workshop)
Synchrophasor Sensors – NSF Award 0215731

Yilu Liu
Virginia Tech

http://en.wikipedia.org/wiki/FNET

Dynamic Stochastic Optimal Power Flow (DSOPF): How to Integrate the “Nervous System” of Electricity

- DSOPF02 started from EPRI question: can we optimally manage & plan the whole grid as one system, with foresight, etc.? Closest past precedent: Momoh’s OPF integrates & optimizes many grid functions — but deterministic and without foresight. UPGRADE!
- ADP math required to add foresight and stochastics, critical to more complete integration.
- New work may deeply cut cost of hooking up solar (e.g. JTC!) to electric power grids. Can we get to enough to get GE or ABB to follow through?

For More Information on DSOPF or brain-style intelligence, see www.eas.asu.edu/~nsfadp

See the Handbook Chapter on DSOPF by James Momoh of Howard University…

www.cesac.howard.edu

DSOPF Can Be a Simple Upgrade to Traditional OPF

\[ U(X(t)) \rightarrow \xi \rightarrow \bar{U}(X(t)) \]

- We can do DSOPF by just adding a new term to the utility function which OPF maximizes
- Can do the same kind of thing with \( \lambda \) instead of \( J \)

Alternating Current Optimal Power Flow (AC OPF): The Next Big Thing

- At economic dispatch time (every 5 or 15 minutes), send out voltage and frequency commands to every generator in the system.
- Ilic 2011 (reported at FERC): huge savings
- Momoh: already available from EPRI, underused (like CSRN and ObjectNets so far)
- AC OPF solves a one-stage nonlinear optimization problem, to maximize utility \( U \) (perhaps using its gradient as input)
- To create foresight, just insert the \( J \) from ADP into \( U \), yielding Dynamic Stochastic OPF DSOPF, just now becoming feasible. Even a rough \( J \) is better than no foresight at all.

From 3rd Generation to 4th: Some Key Elements

- One integrated optimization system – but optimal prices from ISO drive distributed agents, just as our higher brain drives our cerebellum
- Germany’s OGEMA platform can handle this. They have shown (Mannheim) how price-driven intelligent agents in the home can shift loads over 24 hours to match renewable energy supply! With even more intelligent agents, we can do still better.
- Value function networks for dispatch and regulation levels must be trained to “respect each other” for cross-time optimization, also a key issue in brain-like intelligent systems (decision blocks)
- Function approximation, two-stage stochastic optimization, price-based optimization methods and parallel interior point methods are key parts of path to upgrade to ADP
- New technologies for switching, storage, and generation -- examples
But Big Gaps For Day Ahead and Planning (Crucial to Renewables)

- ISOs now use Mixed Integer (Linear) Programming, MIP – one stage optimization, no foresight, integer constraint
- Four important packages for MIP: Gurobi, CPLEX (IBM), COIN-OR, Shanno’s. Gurobi seems best to most today.
- The packages are based on two mathematical methods (simplex and interior point), plus balls of tricks.
- Circa 1995, the new interior point method surpassed the old simplex method, but secret tricks allowed Gurobi’s mainly simplex-based method to do better, for 1 to 14 processors.
- Since interior point can make better use of many processors, it is crucial to develop new tricks for it, maybe open source, to catch up and adapt to the new emerging computer world. Sandia conjectures that COIN-OR with the right tricks and many processors can outperform Gurobi on clock time.
- Since interior point handles nonlinearity, and is much closer to neural methods, this is a crucial step to ADP at these higher levels.
- Nonlinear one-stage optimization also is relevant to error minimization or training of neural networks. But can our EKF outperform the “standard best” BFGS widely used and standard in OR?

Some Topics in Grid Research

- All research aimed at systems-level T&D issues is eligible. EXAMPLES:
  - New and more intelligent algorithms for grid management, like –
    - Better treatment of multistage and stochastic effects and nonlinearity
    - Improving true value-added, use and incentives for renewables, storage, plug-in cars, ramping & price-responsive demand management in the grid
    - Optimal market-based balance of performance and reliability, aimed at improving both
    - Better use of new tools like phasor measurements, time of day pricing, FACTS, and intelligent infrastructure
  - Better and more adaptive prediction, modeling and state estimation as needed for better management and planning
  - Build a bridge to the future, starting from realities described in the June 2, 9 and 23 conferences in 2010 at FERC, posted at www.ferc.gov event calendar.

QMHP: Quantum, Molecular & High-Performance Modeling & Simulation for Devices & Systems

- Goal: enable breakthroughs through better use or partnership of experts in:
  - General-purpose modeling and simulation for systems and devices (e.g. NCN, Nanohub distribution)
  - Fundamental many-body quantum field theory (e.g. coherence, entanglement, N-body models…)
  - High-performance computing (massive parallelism, relevant algorithms and architectures)
- Crosscutting panels – electronics, photonics, phononics. For example, breakthroughs in new chips

See http://phys.lsu.edu/~jdowling/qmhp/