Information Technology and America's Energy Future

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The challenge: Energy discussions generally center on fossil fuel exploration, green technologies such as wind and solar, carbon offset technologies, and policies for reducing energy use. Information Technology (IT) is rarely mentioned, yet IT is critical for every one of these issues, and others. Advances in IT can produce huge "bang for the buck" in reducing energy usage, providing more reliable energy delivery, and improving our standard of living with new applications. However, realizing the promise of IT to shape America's energy future will require significant innovation, not just the application of existing IT knowledge.

This white paper describes the impact of IT on specific energy opportunities, suggests energy-related research involving IT (including fundamental studies of the energy efficiency of computation), and outlines a strategy for moving forward.

1. The impact of IT on specific energy opportunities

The payoffs from bold action in applying IT to energy could be enormous. Five areas of IT application show particular promise for achieving big payoffs: creating the "Smart Grid" for electricity; improved transportation; greater server farm efficiency; simulations to support energy exploration and production; and IT substitutes for energy-intensive products and services.

a. IT and the Smart Grid for electricity

The situation today.   Electricity generation capacity has outstripped electricity distribution capacity due to regulatory changes and NIMBY opposition to new transmission facilities (e.g., high-tension power lines). Parts of the distribution system operate above rated load capacity while others operate below capacity as demand shifts (e.g., air conditioning during heat waves). IT has helped manage this uneven behavior through "cutout" devices that turn off high-consumption devices at the building level – electric water heaters, air conditioning compressors – when demand rises too high. Still, the distribution system remains largely passive: power flows into the system and runs "downhill" via circuits to the customers. The system could be improved greatly through use of Smart Grid technologies.

Smart Grid conservation.   The biggest opportunity for the Smart Grid is smart distribution and consumption, achieved by adding IT: displaying energy prices to consumers, providing disaggregated energy and water bills, real-time feedback to homeowners, and adding sensors and intelligent controls to the distribution network. Customers (or their automated agents) will be able to monitor dynamic energy prices, and control usage, for example:

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[1] For the most current version of this essay, as well as related essays, visit http://www.cra.org/ccc/initiatives

- Smart appliances (e.g., dishwashers that figure out optimal times to run in order to minimize impact)
- Electric vehicles that decide whether to charge or draw power from an electric vehicle battery
- Systems to provide feedback to the consumer on all aspects of energy use (what are you really saving by turning out lights? by changing your thermostat by one degree?) – a disaggregated bill typically enables a 15-20% reduction in household resource consumption

Control of the Smart Grid. Utilities could computationally model customer usage of the grid, enabling them to anticipate usage (integrating fine-grain weather predictions), respond to load imbalances, and automatically isolate failing portions of the grid to reduce or prevent power outages. Distributed IT-based control systems can enable self-healing and reconfiguration of the grid in response to failures or attacks. Machine learning methods can be used to identify and prioritize at-risk portions of the distribution system and drive control decisions such as reconfiguration and dispatching of repair crews.

Engineering the Smart Grid. IT enables engineering of the Smart Grid just as it has enabled the building of far more sophisticated aircraft and cars. IT simulation will enable confident incorporation into the grid of new components such as

- Switches, sensors, and programmable controllers for offices, homes and businesses
- Energy storage systems (e.g., electric vehicles and superbatteries)
- Local generation (wind, solar, hydro, tide, diesel, cogeneration, geothermal, etc.)
- Disaggregation sensing technologies (i.e., systems capable of inferring appliance-level and fixture-level consumption in the home); these technologies must be a simple retrofit solution

IT simulations can ensure and improve power quality, optimize designs for efficiency, reliability, and robustness, and minimize capital costs and on-going expenses. Simulations can allow testing under a variety of challenging near-term and long-term scenarios, including energy cost changes, severe weather, terrorist attack, climate change, demographic changes, etc.

The Economist recently included an interesting article on the IT and sensor aspects of Smart Grid / Smart Home technologies.[2] See also a related white paper specifically focused on the topic of IT and the Smart Grid.[3]

b. IT and transportation

IT advances are already altering transportation dramatically, and there is more to come.

Coordinating passenger transportation. People living in urban sprawl have difficulty achieving efficient passenger transport. Most cities that have grown up since 1945 follow the LA urban prototype, built around the needs of cars. Ride-sharing and public transport have been proposed many times, but have not addressed the "intermodal" problem of getting passengers

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[2] http://www.economist.com/sciencetechnology/tq/displayStory.cfm?story_id=13725843
[3] http://www.cra.org/ccc/docs/init/Energy_Grid.pdf

efficiently to and from the car pool or the metro train. Solo drivers in big vehicles continue to idle in traffic jams. Drivers *say* they support public transit, but usually they just want everyone else to use it so they can use uncongested roads. The only solution is to achieve efficient replacements for the inefficient personal transport of the car, which will only happen if alternatives are faster and reasonably convenient.

Better coordination of intermodal transport using the existing infrastructure of roads and highways is possible through use of IT. Here are a few examples:

- Improved public transit information (e.g., bus ETA's delivered to your cell phone)
- Improved scheduling of neighborhood on-call jitneys that carry you to transit arterials
- Improved congestion avoidance for both transit and personal vehicles – not just knowing where the congestion is now, but knowing where it's going to be when you get there (via machine learning on historical congestion data)
- Improved sharing of vehicles (FlexCar on steroids)
- Increased road use density via adaptive cruise control, stay-in-lane systems, etc.
- Increasingly automated vehicles that optimize operation for efficiency

Vehicle efficiency via advanced IT. The past 30 years have brought astonishing improvements in vehicle engine efficiency through computerized engine management systems (EMS) that reduce emissions and fuel consumption. In the US, much of this improved efficiency has gone to making cars much more powerful rather than to reducing fuel consumption, but that could change quickly. Computer-aided design and dynamic digital testing plus IT-enabled passive safety restraints (e.g., air bags) and electronic stability control systems have also contributed greatly to allowing lighter – and therefore more fuel-efficient – vehicles, without sacrificing safety. Gas-electric hybrids, plug-in hybrids and all-electric vehicles would be impossible without IT-based controls. There is potential for far greater payoffs from this line of investment.

Pluggable vehicles. Pluggable vehicles can draw power from the grid, charging overnight for use in the morning. During the day they might recharge if the commute was long, or they might sell excess energy back onto the grid during high demand periods. Such vehicles could be a significant solution to the problem of electricity storage for use during peak loads. Wiring a city to support such activity would be a major challenge, but it is possible with IT for both design and operation.

Vehicle-infrastructure integration (VII). ITS (Intelligent Transportation Systems) can leverage IT for VII in which vehicles and the infrastructure on which they operate (e.g., a road intersection or traffic signals) can "talk" to each other. Experiments with VII are thus far focused on safety: it's been concluded that the annual US highway fatality rate cannot be driven much below about 40K without enabling the infrastructure to instruct the driver (or the vehicle directly) on actions to avoid mishaps. But in addition the concept has many implications for energy, including creation of vehicle "convoys" that allow strings of cars to operate together with minimal separation front-to-rear in order to conserve on wind displacement, which is a big part of fuel consumption.

Sensors embedded in roads, parking lots and other locations can be integrated and used to control traffic signals. A simple but important example of this is already in use: the IT-enabled

meters at entrances to freeways that eliminate solitons – standing waves that move up and down closed channels of traffic. The relationship between traffic speed and the number of vehicles per lane is non-linear: adding a few too many vehicles slows traffic dramatically. On-ramp regulation of flow, enabled by IT, provides a simple but effective way to eliminate this problem and maximize traffic flow during peak load.

The Economist recently included an interesting article on "The Connected Car"[4]; see also a related white paper specifically focused on the topic of IT and transportation.[5]

c. Improved energy efficiency in computation

Computation is increasingly essential to all aspects of our lives. We're on the cusp of achieving very significant improvements in the energy consumption of computation in terms of "millions of instructions per watt." One kind of gain will come from dramatic improvements in the efficiency of standalone computers – processor efficiency, wireless radio efficiency, display efficiency, "sleep modes," etc. Another gain will come from the increased use of "server farms," which represent remarkable efficiency advantages over other forms of achieving comparable computational power.

Much has been made about how much power server farms consume, and how fast their piece of the energy use "pie" is growing – server farm demand is currently doubling every five years, and they are likely to account for 20% of US energy use within the next decade. However, server farms yield prodigious amounts of computational power, and they potentially offer truly enormous energy savings over alternative ways to produce equivalent computational power. Big improvements are possible for basic power demand through the use of intelligent scheduling and sleep/power-down, huge improvements in HVAC (the greatest source of inefficiency), etc. IT efficiency improvements can be obtained through more efficient algorithms for computer operations such as substitution of cached storage for recomputation, better indexing to minimize searching, and so on.

Another area of potential gain involves the invention of entirely new computational algorithms that have energy minimization as a goal. Since the dawn of computing, we have analyzed and optimized algorithms for their running time requirements and their memory space requirements. We have come to understand tradeoffs between these two – it is often possible to improve running time at a cost of memory space, and vice versa. Energy consumption represents a third dimension.

d. IT simulations for energy's future

High performance computing has been essential to the mission of the Department of Energy and the energy industries, and the Department of Energy and the energy industries have been leaders in high performance computing. Originally DoE used high performance computing for weapons design and stockpile stewardship, and industry targeted geophysical simulations for fossil fuel deposit exploration. Over the years other target areas have been added, among them:

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[4] http://www.economist.com/sciencetechnology/tq/displayStory.cfm?story_id=13725743
[5] http://www.cra.org/ccc/docs/init/Surface_Transportation_3.0.pdf

- Designing and controlling nuclear plants
- The NIF (National Ignition Facility) and tokomak fusion energy projects
- Climate modeling
- Climate engineering (potential emergency interventions).

Most high performance computing of the types above depend on 4-D modeling (3-D plus time) using computational fluid dynamics models. Research advances for these purposes remain critically important. However, the nation's future energy needs are diverse, and there are far more ways for advances in IT to play a role. In particular, we will need to deal with worlds that are represented not as 3-D structures through time, but instead as discrete data structures and programs:

- Graphs (e.g., for the smart grid and consumer networks, and for modeling the inclusion of new energy sources: geothermal, wind, solar, tidal, hydro, cogeneration)
- Market transactions, auctions and databases (e.g., for planning and running carbon cap-and-trade markets, and for understanding the effects of tax and economic policies)
- Data structures (e.g. trees and martingales) for optimal planning (e.g., for environmental remediation of nuclear waste sites, for planning and operating fossil fuel extraction operations, planning conversion to the smart grid, etc.)
- Simulations coupled to sensors and effectors to control large scale systems (e.g., the power grid, power generation facilities, refineries, oil field extraction systems)
- Simulations coupled to machine learning systems to provide anticipatory error detection, and what-if modeling of possible actions to prevent or correct problems

These new uses will require new discrete algorithms, and scaling to very large computing facilities and datasets.

e. IT substitutes for energy-intensive products and services

IT offers many opportunities to save on energy use by substitution of IT services and products for more energy-intensive products and services. Examples include teleconferencing and telecommuting as a substitute for travel, on-line ordering of goods and services vs. personal travel to bricks-and-mortar facilities, electronic medical records vs. paper-based files, home medical monitoring to substitute for visits to the doctor, and many others. Advances in systems biology promises to substitute *in silico* drug discovery and testing for today's *in vitro* and *in vivo* methods, and to facilitate design of drugs and treatments tailored to an individual's genomic profile. The switch from an economy built primarily on tangible products to an information economy in which print is replaced by electronic books, newspapers and periodicals, email, and text messaging will accelerate this process of substitution. Energy can be saved in many ways, for instance, by reducing supply chains for production of paper and the reduction in shipping of heavy, paper-based documents. This substitution process has just begun, and will grow significantly in the coming years.

2. Energy-relevant basic IT research

We do not yet know how to construct algorithms for all the tasks discussed above, let alone algorithms that can scale to very large problems, and in many cases operate in real time (as in the case of sensing and control systems). Basic IT research will be required into methods, algorithms, hardware and software. Such research can have huge impact. Research areas of special promise for energy applications include:

- Modeling, simulation and optimization
- Sensor networks and sensor interpretation
- Adaptive distributed control
- Distributed data storage and access
- Data mining and machine learning
- HCI (Human-Computer Interfaces)
- Large scale software engineering of complex systems
- Communications and networking
- Security mechanisms and systems
- Innovative applications, products, and standards
- Analysis and understanding of the behavior of large-scale systems, e.g., understanding conditions that lead to phase changes in operation

IT applications also promise help in making humans more aware of – and consequently more frugal in – their energy use.

Finally, as noted earlier, improving the efficiency of computation is a critical challenge. There are fundamental advances required in power, cooling, processor architecture, system architecture, and control software. There also are fundamental advances required in the design of algorithms for all applications. Traditionally, the efficiency of a computation has been measured in terms of the time and space it requires. Treating energy use as a third measure of efficiency and designing and analyzing algorithms for efficiency on all three dimensions will require a radical new view of the foundations of computing and communication.

3. Summary and strategy

As noted earlier in this white paper, Information Technology (IT) is rarely mentioned in discussions of America's energy future, yet advances in IT can produce huge "bang for the buck" in reducing energy usage, providing more reliable energy delivery, and improving our standard of living with new applications.

We have briefly explored the impact of IT in five key areas. The applicable technologies span the IT field – from sensors and sensor networks, to artificial intelligence and robotics, to simulation.

As in most other aspects of IT, the necessary advances will come most quickly through industry-university-government partnerships that use real data and provide access to realistic-scale testing facilities. To accomplish these ends, new ideas will be needed for collaborations and data sharing between industries, universities and national labs. The key involvement of industry

means that we will need to address challenges with respect to intellectual property rights, technology transfer, setting of appropriate standards, and assuring security and protection of privacy.

Many topics discussed here cannot be carried out completely within traditional academic departments, but will require interdisciplinary research that bridges computer science, engineering (electrical, mechanical, civil, biomedical, financial, environmental, etc.), finance, law, business, natural science (physics, biology, chemistry, etc.), medicine, public policy, and others. This will require new funding mechanisms and new ways of organizing research.

The opportunities are enormous. Advances in IT are central to America's energy future.