SMART ENERGY DISTRIBUTION AND CONSUMPTION: INFORMATION TECHNOLOGY AS AN ENABLING FORCE

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ABSTRACT

The deregulation of the electrical-energy distribution in California, combined with the increasing cost of natural gas, has brought energy back to the front-page news. In this white paper, **we establish how the effective use of large-scale integrated information-technology systems, combining a wide range of networked devices ranging from tiny sensor and actuators to distributed databases and compute servers, dramatically improves the efficiency of the energy-generation, distribution, and consumption infrastructure**, and streamline the interaction between these three components. These *Societal-scale Information Systems* are bound to have a revolutionary and quantifiable impact on the economics and logistics of the energy-provision chain. As described below, **as little as a 1 percent load reduction due to demand response can lead to a 10 percent reduction in wholesale prices, while a 5 percent load response can cut the wholesale price in half.** This effect is central to the implementation of short-term, low-cost demand reduction techniques. A proof-of-concept demonstration is proposed to illustrate the impact of the proposed techniques.

1 INFORMATION TECHNOLOGY AS AN ENABLING OPPORTUNITY

Information technology has affected our society in many fundamental aspects in the last decade(s). Yet, while transforming lives in many ways, it has not delivered in full on addressing some of the problems that have a major impact on the economy, quality of life, and future success of our society. Active and dynamic management of resources that have a fundamental impact on the operation and well-being of the state infrastructures such as energy, transportation, building infrastructure, health, and education come to mind can have a tremendous impact in each of the above categories.

We believe that the solution of these problems at their core depends on highly distributed, reliable, and secure information systems that can evolve and adapt to radical changes in their environment, delivering information services that adapt to the people and organizations that need them. We call such systems **Societal-scale Information Systems (SISs).** The web, telephone network, and some military and intelligence systems are limited, albeit highly successful, SISs. Yet none satisfies the needs of the societal problems. A SIS must easily and naturally integrate devices, ranging from tiny sensors and actuators to hand-held information appliances, workstations, and room-sized cluster supercomputers. Such devices must be connected by short-range wireless networks as well as by very high-bandwidth, long-haul optical backbones. Data and services must be secure, reliable, and high-performance, even if part of the system is down, disconnected, under repair, or under attack. The SIS must configure, install, diagnose, maintain, and improve itself - this applies especially to the vast numbers of sensors that will be cheap, widely dispersed, and even disposable. Finally, the SIS must allow vast quantities of data to be easily and reliably accessed, manipulated, disseminated, and used in a customized fashion by users.

In this paper, we establish that these **societal-scale information systems constitute an opportunity that can go a long way in addressing and resolving issues that hamper the effective generation,**

distribution and utilization of energy in today's environment. The quantifiable benefits of these systems to the public and the economy turn out to be enormous. While no SIS exists today that meets all of the requirements formulated above, a time-line is established detailing how a roll-out of energy-conscious information technology systems can have an impact in the short, medium and long-term.

Developing the technology that underlies the SIS concept is the prime research agenda of the CITRIS (*Center for Information Technology Research in the Interest of Society*) research center, proposed as a result of the California CISI (California Institutes on Science and Innovation) initiative [Demmel00].

With electricity constituting the vast majority of the energy-consumption, it is featured prominently in this document. After an analysis of the supply-and-demand model of electrical energy, we discuss how SIS's provide efficiency-increasing solutions to both the supply and demand sides of the equation. A short discussion of other sources of energy is also provided. To illustrate the potential of the technology, and the impact it can have even in a short time-span, the paper is concluded with a proposed proof-of-concept demonstration.

2 MANAGING THE ELECTRICAL ENERGY RESOURCE

2.1 A Model of Electrical Supply and Demand

The current model of electrical production, distribution and consumption (as operational in California at present) shows a **major inelasticity at both the supply and the demand side**.

- The short run **supply** curve for energy and reserve capacity is very inelastic.
- Moreover, since consumers face constant prices, the short run **demand** curve is completely inelastic. It is mostly driven by immediate demand, not by pricing. In addition, the demand curve shows enormous variations over the course of the day, requiring utilities to provide for large reserve capacity.

Thus small reductions in supply and small increases in demand lead to very large increases in the prices that utilities have to pay for energy, as shown in Figure 1, which plots the Power-Exchange market prices versus ISO load for California over the summer of the year 2000. Obviously, a small increase in demand during peak periods leads to a major cost increase.

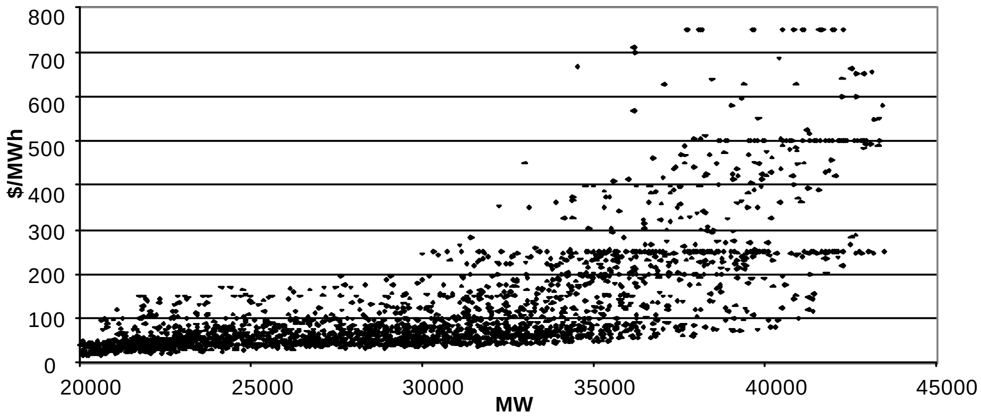

Figure 1: Electrical Energy Market Prices as a function of ISO Load (California, May 15-August 30, 2000) (from [Braithwait and Faruqui]).

Based on this inelastic cost-load model (and barring a major increase in excess capacity), we can identify major windows of opportunity at both the demand and supply sides to bring down the price of electrical energy using the proposed societal-scale information systems.

- ***Spreading the demand over time***, so that its variance is smaller. Reducing peak-time usage has a disproportional impact on the overall price we pay for electrical energy, as is clear from Figure 1. This can only be remedied by increasing the elasticity of the demand model. Doing so requires two changes: (1) the cost of energy for the energy to the end-user should match the load curve. This gives the consumer the incentive to move consumption to the inexpensive periods. (2) the cost of energy at any point in time should be visible to the end-user. This model, called the demand-response approach [Braithwait-Frauqi00] is only possible in the presence of a distributed and integrated metering system, as enabled by the SISs.
- ***Reducing the average demand***. Smart-building and smart-appliance technologies increase the efficiency of the energy-consuming devices at the end-user, and reduce the average energy consumption in commercial and residential buildings with large fractions (potentially up to 30% in commercial dwellings).
- ***Improving the efficiency of the generation and distribution process***. More specifically, information systems can aid in improving the management and utilization of the distributed generation resources, the efficiency of the distribution network, and in dealing with overflow conditions and emergencies

In the rest of this section, we consecutively discuss in more detail the opportunities that societal-scale information systems bring to both the demand and the supply side

2.2 Opportunities at the Demand Side

Energy is used in buildings to provide many services such as thermal conditioning of the space, water heating, lighting, refrigeration, and electricity for operation of electrical appliances and electronic devices. A large proportion of primary energy is consumed in buildings—about one third of the total (See Table 1 for details). Two-thirds of the primary energy use is in the form of electricity and about two-thirds of all electricity generated nationally is used in buildings [Interlaboratory Working Group, 2000].

End Use	Residential	Commercial
Space heating	6.7	2.0
Space cooling	1.5	1.1
Water heating	2.7	0.9
Refrigerator/Freezer	1.7	0.6
Lighting	1.1	3.8
Cooking	0.6	-
Clothes dryers	0.6	-
Color TVs	0.8	-
Ventilation/Furnace fans	0.4	0.6
Office equipment	-	1.4
Miscellaneous	3.0	4.9
Total	**19.0**	**15.2**

Table 1: Primary energy use in US buildings, 1997.
(Units: quads per year = 1.05 EJ y^{-1})
Source: Interlaboratory Working Group, 2000

This large use of energy has commensurately large consequences for society. The direct costs to consumers are substantial: $240 billion in 1997, corresponding to roughly $1000 per capita per year. The environmental consequences are also large. Energy use for buildings is a major contributor to greenhouse gas emissions (CO_2 and methane), acid deposition precursors (SO_x and NO_x), and constituents of urban photochemical smog. Most of this energy derives from fossil fuels, principally coal and natural gas. The long-term sustainability of these sources is of considerable concern. Other prominent electricity sources, such as nuclear and hydropower raise major environmental concerns, waste disposal in the former case and disruption of river ecosystems in the former. In short, there are many compelling reasons to aim to improve the efficiency of energy use in buildings.

Serious attention to efficient use of energy in the building sector began in the mid 1970s, following the OPEC oil embargo and resulting price shock for petroleum in the early part of that decade. Although progress has been made during the past 25 years, energy use in the built environment is not yet very efficient. A recent study has argued that aggressive efforts to reduce energy use in buildings could lead to savings of 18% in primary energy use and 40% in carbon emissions by 2020 [Interlaboratory Working Group, 2000].

During the past few decades, many energy efficiency improvements have been identified. Some have been implemented with reasonable success. Others have languished, even though economic analysis would rationally support their implementing, based on short payback periods.

Among the reasons cited as barriers for the application of technological innovation is a lack of information. Consider the following quote [Interlaboratory Working Group, 2000]:

> *"It is impossible for a utility customer, even one who carefully reads her bills, to determine the contribution of various appliances to the total bill. Attaching individual electricity meters to particular appliances is extremely rare, so that the consumer finds herself in a "supermarket without prices:" the user collects all the purchases in their shopping cart and gets one lump-sum bill to pay at the end of the month, with no separate accounting. No consumer can optimize when she doesn't know the price of purchasing a service."*

Advances in information technology, applied to energy use in buildings, hold the promise of making the system considerably more efficient. Societal-scale information systems, consisting of wireless sensors/actuators enable the control of buildings with information from a much higher density network of sensors than is currently economical.

- ❖ High-density sensor networks will allow **existing** environmental control technologies to operate in more sophisticated and energy-efficient ways, and the redundancy of sensors in such networks will improve the reliability of control by detecting faulty signals.

- ❖ High-density sensor networks will also allow **new** energy-efficient environmental control technologies to become feasible for the first time.

The term 'energy efficiency' above includes both the *total energy* required for a given building service over time, and to the *peak power* demanded at any instant within that time.

Imagine, for example, the following scenario. All significant energy-consuming devices in buildings are equipped with a multifunctional metering, communications, and control devices. These devices provide real-time information to building owners and occupants on rate of energy use (e.g., kW), cost associated with energy use rate ($ per hour), cumulative energy usage and associated costs for past 24 h, month, and year. By itself, this information would greatly enhance the ability of energy users in buildings to make rational decisions that should improve efficiency and reduce total usage. Such decisions could include how much and when to use certain devices. The information would also be useful in deciding when to replace an inefficient device, such as an old refrigerator, with a new, more efficient model. Currently, such decisions must be made blindly with regard to operation cost.

The devices could also incorporate important energy management controls. In addition to reducing total energy use, it is of central importance in electricity system management to limit peak demand. One mechanism for doing this is through real-time pricing. Real-time pricing will require more sophisticated electricity meters than are currently in common use. However, for optimal performance, devices that are moderate to heavy electricity users should also be equipped with controls that would permit rational response to real-time price signals. Therefore, for example, a smart refrigerator could know that it should avoid firing the compressor when electricity costs are high. With the right combination of software and hardware, it could use its electricity mostly at off-peak periods.

In summary, by making the end-users of the energy-supply chain part of an integrated network of monitoring, information processing, controlling, and actuating devices, we enable a wide range of techniques that will both help to spread the consumption of energy over time reducing peak demand, as well as help to reduce the average demand of energy through efficiency increase. While the process of designing, constructing, starting up, controlling, and maintaining building systems is very complex, and changing the building and appliance industry overnight is not possible, we believe that a gradual roll-out plan can show impact in the very near future. We envision a triple-tiered program for the introduction of societal-scale information systems into the demand side of the electrical energy equation.

- **PHASE 1: Passive monitoring**
  The availability of cheap, connected (wired or wireless) sensors makes it possible for the end-user to monitor energy-usage of buildings and individual appliances and act there-on. This information feedback plays a dual role:
  - Primary feedback to the user on energy-consumption statistics
  - Monitoring the health of the equipment and the environment - detect problems at the source. It has been estimated that the operation of "broken systems" may cost at least 30% of the commercial building energy use (more than $45 billion).
- **PHASE 2: Quasi-Active Monitoring and Control**
  By combining the monitoring information with instantaneous feedback on the cost of usage (augmented by an hourly pricing system that reflects wholesale market prices) helps to close the feedback loop between end-user and supplier.
- **PHASE 3: Active Energy-Management through Feedback and Control: Smart Buildings and Intelligent Appliances**
  The addition of instantaneous and distributed control functionality to the sensing and monitoring functions (measuring the operation of systems such as climate conditioning and lighting) increases the energy-efficiency of these functions dramatically, while at the same time improving the comfort of the users.

In the following sections we present each of these phases in detail and predict its impact for both commercial and residential structures.

(A) Improving The Operation Of Existing Infrastructure:

Commercial buildings:
Improve the spatial resolution of sensing temperature/light/sound/IAQ/air movement within the occupied zone, in order to better control the operation of the environmental control system (even if the system has only one actuator per zone). This might involve averaging multiple readings to send to the actuator, or it could look for patterns in the readings that allow the controller to provide the appropriate level of service where it is actually needed by the occupants. In existing systems where there are more actuators per zone (some VAV and lighting systems) the new high-density-sensor readings can better determine the conditions served by each actuator and control it appropriately. An example of this would be to incorporate measurements of window glass temperatures with air temperatures in perimeter areas in order to effectively control those spaces for occupant comfort.

Detect faulty readings from drifting sensors by comparing them to the rest of the sensor readings. Sensor faults are common in existing commercial HVAC and lighting systems.

Residential buildings:
Operate existing residential heating/cooling systems to take advantage of patterns in weather and occupancy patterns throughout the day, allowing the building to be preconditioned so that its

system can be shut off or appropriately turned down during later periods of peak demand. Recommended operation of sunshades, blinds, windows, and whole-house fans could be displayed to the occupant, allowing them to take appropriate actions. Relevant variables would be temperatures within each room, within important parts of the building structure, and outdoors, sunlight, occupancy, indoor and outdoor air quality sensors, and possibly rain.

(B) Improving The Operation Of New Infrastructure/Technologies

Commercial buildings

New environmental control system technologies tend to increase the number of actuators per zone. Examples are underfloor air distribution systems, task ambient conditioning systems, VAV systems with control at individual diffusers, dimmable task-ambient lighting systems linked to daylight and occupancy sensors. These provide the opportunity to condition only the *occupied* spaces within the interior, and that conditioning can be calibrated to the needs of individual occupants. Since a large proportion of commercial office space is unoccupied at a given time, this offers great savings potential in both total energy and peak power demand. The effective operation of such new systems will depend on a sensor density that can distinguish between the occupied and unoccupied spaces. We have computed the energy performance improvements of well-designed underfloor systems relative to well-designed conventional systems, and they exceed 30%.

There are new building types making use of the building envelope and structural mass *in conjunction with* the building's system. These are the mixed-mode, naturally ventilated, thermal-mass design strategies. They offer great energy efficiency gains over conventional air-conditioned systems. In addition, there are daylight lighting schemes linked to variably dimmable electric lighting. These systems operate on schedules requiring frequent feedback. They need to know what is happening, for example, to a building's conditioned air when a given window is opened, or whether a building's structure is cooling as expected under the influence of nighttime ventilation within the space. The sensors needed to make these determinations need to be distributed throughout the building interior at far greater density than in the standard sealed air-conditioned buildings where uniform interior conditions are assumed.

Residential buildings:

The California Institute for Energy Efficiency-funded project: “Alternatives to Compressor Cooling” identified a number of integrated design strategies incorporating thermal mass, natural ventilation, evaporative cooling, solar control, and mechanical ventilation in ways that eliminate the need for compressor-based cooling in the summer time. Many of these systems succeed or fail based on the combined operation of building and system components. Effective operation involves knowing how effectively air is moving, temperatures are behaving, and humidity and radiation is changing. Some of the functions to operate the system can take place automatically, using automated controls, and some could benefit from an informational display/notification system that recommends action by the occupant and reports the environmental, energy, and cost consequences of the actions. The display system could also be coordinated with schemes that shut off appliances or the whole system when peak prices or the utility calls for it, showing the consequences (rising refrigerator temperatures) and giving alarms at predetermined settings.

(C) The Impact of These Improvements

While the ultimate impact of these societal-scale information systems is hard to gauge, several indicators tell us that the impact would be enormous. The major challenge in analyzing the potentials of the technology is essentially the current lack of it. Advanced metering, as enabled by our proposal, would enable a far more precise perspective on where energy is spent, and how much savings can ultimately be accomplished. Yet, some estimation is definitely possible.

- A CEDR report [Warren86] showed that daylighting controls (dimmable ballasts controlled by light intensity sensors) could reduce lighting power by 60% at a large Lockheed facility in the South Bay.
- At 3M corporate headquarters they use the public address system 2-3 times per year to control demand. They broadcast a message instructing workers to close fume hoods, shut off lab equipment not in use, shut off lights, shut off office equipment not needed, close blinds, etc. The net result is that electrical demand drops from 15MW to 13MW in ~15 minutes, and then down to 11MW over ~2hours.
- Dave Claridge [Claridge98], a faculty member at Texas A&M, has performed research on commissioning and control of HVAC systems for a number of years. His work has shown that commissioning consistently reduces HVAC power by 15-25% because of numerous design, installation, and control problems. The design and installation problems could be detected with enough sensors and programmed intelligence. Good controls could take care of the rest.

Consider, for instance, the potential of the smart-building concept for lighting power savings in the commercial sector. Based on current and projected data, it can be estimated that the steady-state penetration without the smart-building technology would be approximately 33%. We estimate that our efforts of introducing wireless sensor networks could boost the steady state-level to 80% (Figure 2). Eventually, light and occupation sensors will become as ubiquitous as temperature sensors are today. Assuming conservatively that this added penetration would reduce lighting power consumption by 40%, this leads to a cumulative national energy savings over a 20-year period of 2 quadrillion BTUs (quads) of source (power plant) energy, a national cost savings of $16 billion, and a cost savings of $2.8 billion in California.

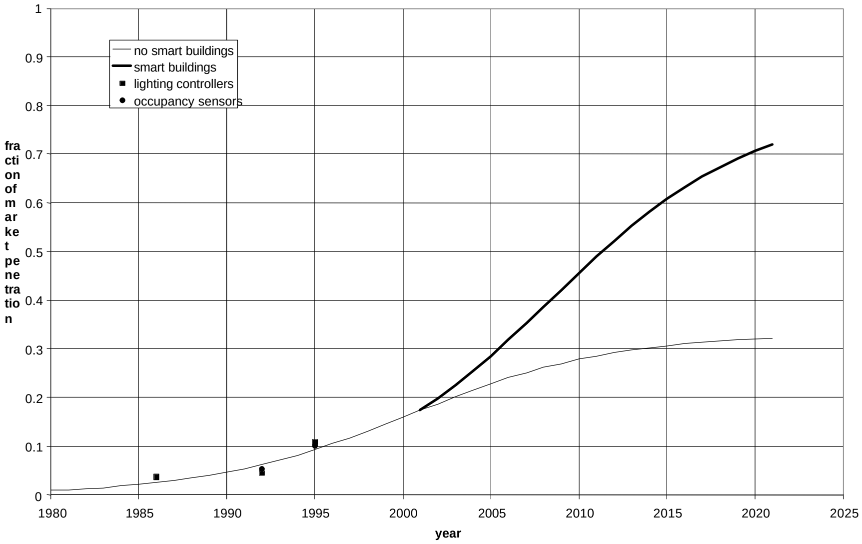

Figure 2: Projected penetration of lighting controls into the commercial building world with and without the smart building technology.

This estimate is only for lighting power savings in the commercial sector. There are a wide number of other ways that smart buildings would save energy and lower demand. Since space conditioning is the dominant consumer of energy in the commercial-building arena, this is also where the largest impact can be made. There is first-of-all a huge potential benefit in addressing the commissioning issue brought up by Claridge. Continuous diagnosing and eliminating of system deficiencies that are either built into the building at the outset or that accumulate over time as things break down or get mishandled by operators, would yield an approximate 20% reduction in energy consumption. This would be in addition to the distributed and ubiquitous sensor/monitor/actuator systems that improve the run-time efficiency of the space conditioning systems, and yield an estimated 30% improvement. The combined factors would reduce the energy dissipation for space conditioning of commercial buildings by 44%, or ultimately save approximately 1 quadrillion BTUs (quads) of source energy per year! We are further convinced that the introduction of SIS's in commercial buildings would yield other savings that we have not even conceived yet. In the long term, the potential is even larger for residential world. Yet, penetration of the SIS's into residential buildings is bound to be slower, and its impact will be substantially smaller in the short to intermediate terms.

Finally, it is important to remember that the ultimate purpose of the Smart Buildings initiative is not only to save energy or to use energy more efficiently. Rather it is to make buildings perform their functions in a better and more efficient manner. Among these functions are the health and safety of the occupants. Information technology holds the promise of improving buildings in these respects, too. Monitoring and control efforts that are aimed at improving indoor environmental quality, reducing the frequency of fires and their consequences, and improving building security also offer the potential for Smart Buildings to be better buildings for their occupants, for their owners, and for the society as a whole.

2.3 Opportunities at the Supply and Distribution Side

The deployment of societal-scale information systems can substantially increase the efficiency and improve the control of the electricity-supply infrastructure as well. Through a combination of metering (sensing), communication, computation, and control, the network can achieve major improvements in

- The management and utilization of the distributed generation resources,
- The efficiency of the distribution network
- Dealing with overflow conditions and emergencies

Especially the fine granularity of the information contents, combined with its timeliness, make it possible to introduce management and control techniques that otherwise would be impossible or useless. Each of the principal areas of impact is discussed in more detail below.

2.3.1 Demand response

As identified earlier, exposing the true cost of energy to the end-user through, for instance, hourly pricing, gives the users the option to reduce their usage during expensive periods and increasing their usage during inexpensive periods. This approach, called *demand response*, deals with a key deficiency in California's market design—the disconnection between wholesale and retail markets.

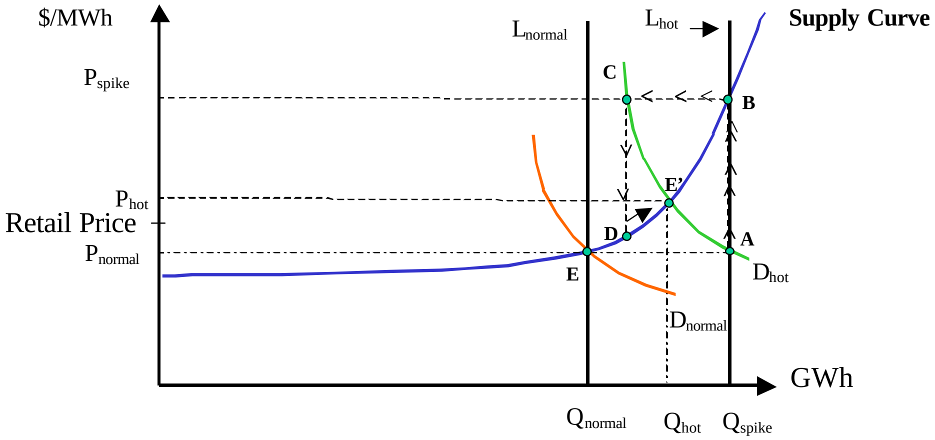

Figure 3: Demand-response approach in steep portion of supply curve yields lower wholeslae prices.

Figure 3 [Braithwait-Frauqi] illustrates how demand response in a connected market reduces load levels at high retail prices, thus reducing pressure in the wholesale power market, and allowing prices to fall. The figure first shows the result of disconnected markets. Customers have completely unresponsive demand curves given by the vertical lines labeled L_{normal} and L_{hot}, representing usage levels under *normal* and *hot* weather conditions respectively. The demand curves have no slope because consumers face the same price under both conditions, and have no incentive to reduce consumption. Under hot weather conditions, the vertical demand curve intersects the steepest portion of the supply curve at *B*, producing a high wholesale price of P_{spike}, which is not transmitted to the retail customers. In contrast, if some portion of the retail load faces prices that reflect the wholesale prices shown, then the demand curves take on the non-vertical shape of D_{normal} and D_{hot}. Under these conditions, market forces will produce a solution at *E*, implying a lower wholesale price of P_{hot} and level of usage of Q_{hot}.

Industry analysts have offered estimates of a factor on the order of one-to-10 between a percentage reduction in load (or an increase in supply), and the resulting percentage reduction in wholesale price during conditions of extreme supply and demand imbalance. **That is, as little as a 1 percent load reduction due to demand response can lead to a 10 percent reduction in wholesale prices, while a 5 percent load response can cut the wholesale price in half.** This observation is central to the implementation of the initial plan and its effect.

Enabling the full power of this technology requires a fully integrated network that combines distributed metering and smart consumption appliances with the global cost setting mechanism. Closing the feedback loop in real time is essential in the long term. In the short time, however, making usage patterns and costs visible to the end-user can go a long way in spreading demand. Consider the case of Georgia Power Company, which operates the largest real-time pricing program in the U.S., with more than 1,600 commercial and industrial customers accounting for as much as 5,000 MW of demand. Georgia Power estimates that it achieved load reductions ranging from 400 to 750 MW on moderate to very high-price days in 1999.

2.3.2 Efficient utilization of generation resources through reduction of response lag to market condition and improved coordination.

The efficacy of price mechanisms in coordinating supply and demand is limited by the response lags. Such lags create the need for reserves that can buffer imbalances and changes in system condition. The shorter the response lag the better the market can respond, thus reducing the need for reserve margin that impose extra cost. Improvement in fine-grained information about demands and supplies will help reduce these margins and improve system efficiency.

2.3.3 Coordination of distributed resources

Proliferation of distributed resources (e.g. photovoltaic, fuel cells, micro turbines) will mitigate supply shortages, improve reliability of the electricity grid and reduce the need for transmission capacity and reserves. However, massive deployment of such resources poses challenges in terms of integration into the system and operation of a system. These challenges can be addressed using IT, particularly sensing, metering and communication.

2.3.4 Improve grid utilization through on-line computation of contingency constraint dispatch.

Operating protocols are designed to maintain system reliability under a variety of contingencies. Specifically the transmission grid is operated so that if any single element fails the system can still operate safely. Due to the intensive computational burden of accounting for all possible contingencies these computations are done offline under worse case scenarios and the system is operated on the basis of static limits that are set so as to withstand the various contingencies. Dynamic online computation of line limits based on relevant contingencies (rather than worse case) could dramatically increase grid utilization without sacrificing reliability. Increased grid utilization translates into shipment of power from least-cost sources, which improves the efficiency of resource utilization and reduces cost to consumers.

2.3.5 Emergency Management

In case of emergencies (either through natural disasters, an overburdening of the power distribution network, or through shortfall in available energy), the utilities have little choice but to lock off complete blocks of the power-grid (for instance, through rolling blackouts). These blackouts have an enormous impact on the economy, and may cause life-threatening situations. The increased control granularity made available through widely dispersed SISs would make it possible to selectively manage power-consuming components and systems, and avoid blunt load-shedding. In the case of rolling blackouts, for instance, it would be possible to keep critical businesses and functions such as traffic lights on line. When even a larger granularity is available, one could even turn off non-essential devices, such as air-conditioning units, individually.

For example, devices could routinely be equipped with a “standby” setting in addition to direct on/off control. This setting would be communicated to the electricity meter to yield a small, direct savings to the consumer (through lower electricity cost). In turn, the system operator would have the ability to switch off these devices if necessary to shed load. With such a system, the electricity problems currently plaguing California could be addressed by means of active load management in a manner much less disruptive than blackouts.

2.3.6 Increase in the transmission capacity of the grid by operating closer to the limits through deployment of sensors that monitor temperature and sag of transmission lines.

Constraints on line flows limit the use of the transmission grid to transfer power from the least expensive sources. Such line flow limits are proxy measures whose ultimate goal is to prevent overheating of transmission line or other transmission equipment and sag of the lines (that could result in touching of trees leading to catastrophic failures). In the absence of direct measurements the flow limits are set conservatively thus unnecessarily limiting the utilization of the transmission grid. Massive deployment of sensors that could measure and transmit data on temperature and line sag coupled with computation that would assimilate such data could significantly increase grid utilization and enhance the efficiency of electricity supply. While power companies currently using global environmental data to determine the load a transmission line can carry at a given time, dynamic and real-time distributed measurements of the weather conditions may increase the peak load of a wire with as much as 30%.

3 BEYOND ELECTRICAL ENERGY

Natural gas is the second most important provider of energy to the consumers. Unlike electricity, natural gas can be effectively buffered and stored, which creates a very different supply/demand and pricing model. While having a far smaller impact than in the case of the electrical supply and demand chain, ubiquitous networks of sensors and monitors still play an important role in natural-gas-based systems as well.

(A) Device monitoring for performance assurance. Natural gas is widely used to supply heating and air-conditioning in buildings. The system of delivering heat or cooling to occupied spaces includes several points at which performance can degrade, causing a loss of efficiency. These include reduced airflow because of overloading of air-cleaning filters; fouling of heat exchanger surfaces; and leaks in ducts. Monitoring networks would provide information on system performance. Owners and operators could use this information to take actions to ensure better system performance.

(B) Safety and health. Many hundred accidental deaths by CO poisoning occur annually in the United States [Cobb and Etzel, 1991]. Sub-lethal doses may increase risks and consequences of cardiopulmonary disease. Malfunctioning natural gas fired heating and air-conditioning systems contribute to these problems. The problem arises from a combination of two factors: improper combustion conditions (fuel rich mixture) and improper venting of the exhaust gases. A monitoring network could incorporate information that would identify these malfunctions before they pose serious health risks. The network could also be used as an emergency alert in case doses exceed acceptable levels and become a lethal risk.

4 PROOFS OF CONCEPT

It may seem that the introduction and deployment of these societal-scale information systems for energy-resource management may take substantial time, and that its impact on the society-at-large will not be for the immediate future. **It is our belief, however, that components and embryonic systems are already available, and could start having an impact in the immediate future.** Researchers in Berkeley have developed an array of wireless sensor nodes, and the network and software layers necessary to operate them. While these nodes (called Smartdust Motes [Pister00] and PicoRadios [Rabaey00]) do not yet meet the cost, size and power requirements that we would ultimately expect for a full-scale deployment of the societal-scale information systems, they allow us deploy small-scale prototypal networks in a short time-span. Examples of these wireless network nodes are shown in Figure 5.

SmartDust Mote PicoRadio

Figure 5. Current incarnations of wireless sensor nodes allow for short-term deployment of societal-scale information systems.

To harden the above observation, we propose a set of demonstrators on the Berkeley campus that could be accomplished in the time-span of 6 months. We have rank-ordered the demonstrators based on the efforts they would take.

- **EASY:**
  - Fully instrument a number of buildings on campus with networked light and temperature sensors in every room, and make the data available on a centralized web site.
- **MEDIUM:**
  - Make a wireless power monitor with a standard 3-prong feedthrough receptacle so that people can monitor power consumption of electronic devices as a function of time. Provide roughly one thousand such devices for rotating use around the campus to educate, chart usage, verify compliance, real-time display of consumption in a given room or lab. The impact of these simple metering devices could be tremendous.
  - Similar device, but passively coupled to high-power wiring to monitor total power consumption through breaker boxes. This would give us a much finer granularity of power-consumption details, and let us look at clusters of rooms, floors, etc.
  - Fully instrument the campus steam network
- **HARD:**
  - Real-time monitoring **and control** of hundreds of power systems on campus. Enforce compliance with load reduction. Charge/reward departments according to their use during peak times.

It is our belief that with the necessary buy-in and resources, we could have this entire campus (more than 200 buildings) wirelessly monitored and controlled in one year. The success and the impact of this experiment can be gauged by accessing the energy savings with respect to the current energy consumption distribution at the UC Berkeley campus, as given in the table below.

UCB ELECTRIC ENERGY USAGE

Lighting 26%
Air Distribution 26%
Pumping 9%
Cooling 5%
Plug Loads 12%
Heating 9%
Other Loads 13%

Total Energy Consumption Breakdown (Electric, Gas, Steam)

Lighting 16%
Heating 51%
Air Distribution 9%
Hot Water 9%
Pumping 4%
Process 2%
Cooling 2%
Plug Loads 3%
Cooling Tower 2%
Other 2%

5 SUMMARY

In this white paper, we have established how the effective use of large-scale integrated information-technology systems, combining a wide range of networked devices ranging from tiny sensor and actuators to distributed databases and compute servers, dramatically improves the efficiency of the energy-generation, distribution, and consumption infrastructure, and streamline the interaction between these three components. It is our conviction that, while the full impact of these societal-scale systems will only be accomplished in two or more decades, a sizable short-term impact on the California and US energy-distribution and consumption landscape is feasible and attainable.

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