LoCal—A Network Architecture for Localized Electrical Energy Reduction, Generation and Sharing

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Project Summary

LoCal (A Network Architecture for Localized Electrical Energy Reduction, Generation and Sharing) investigates Information Age approaches for managing society’s most limited resource: energy. The world’s electric grids are an engineering wonder of last century’s physical age, each with a vast geographic reach, epitomized by a highly centralized, synchronized, and reliable distribution tree that allows electric power to be consumed without concern for its source. But rapidly changing energy demands, incorporation of non-dispatchable renewable sources, and the need to proactively manage load, have pushed this aging marvel to its limit. As the rise in greenhouse gases threatens civilization, it is time to examine how pervasive information can fundamentally change the nature of energy production, distribution and use. Taking guidance from the design principles of the dominant triumph of the cyber age, the Internet, we investigate how to design an essentially more scalable, flexible and resilient electric power infrastructure—one that encourages efficient use, integrates local generation, and manages demand through omnipresent awareness of energy availability and use over time. The crucial insight is to integrate information exchange everywhere that power is transferred.

The LoCal Energy Network is a cyber overlay on the energy distribution system in its various physical manifestations, e.g., machine rooms, buildings, neighborhoods, isolated generation islands and regional grids. Pervasive information exchange will enable a more efficient scalable energy system with improved resilience and quality of delivered power. Our key contribution is to bring together (1) pervasive information about energy availability and use, (2) interactive load/supply negotiation protocols, (3) controllable loads and sources, and (4) logically packetized energy, buffered and forwarded over a physical energy network. Together these yield a system for agile, distributed, and integrated management of energy that can buffer energy on the path to reduce peak-to-average energy consumption, moderate infrastructure provisioning, and encourage power-limited design and operation. Our building block is the intelligent power switch, logically connecting sources to loads by bundling information (bits) with energy (electrons) flows.

This proposal’s intellectual merit is in understanding how information enables persistent energy efficiencies: through intelligent matching of loads to sources, from small to large-scale aggregates, by managing how and when energy is delivered in response to demand while simultaneously adapting demand in time and form to available supply. We construct a series of experimental LoCal Energy Networks at several scales, to show monitors, negotiation protocols, control algorithms and IPSs integrating loads and sources in a LoCal-ized datacenter, building, renewable energy “farm”, and off-grid village. We generalize and validate these experiments through larger scale simulations.

This proposal’s broader impacts will be realized in a new interdisciplinary curriculum in energy systems at Berkeley, enabling the training of a new cadre of experts at the intersection of information and energy science and technology. Through industrial collaborations with information and energy technology firms including Cisco Systems, Google, National, Siemens, Sun Microsystems, and Vestas, the Lawrence Berkeley National Laboratory, and energy markets and cybertrust technologists and analysts on the Berkeley campus, and with opportunities for prototype deployments of LoCal technology in developing regions, we have significant potential to influence how information-centric energy technology, products, and services will develop over the next decade.
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Project Description

1. Need for a New Energy Infrastructure

Our insatiable thirst for energy is the societal problem of our age. The USA average per capita power consumption is 12000 watts (17,520 kWh/yr), six times the world average and twice that of Europe [2000]. And as the rest of the world industrializes, their demand will rise. Energy consumption is expected to double between now and 2050. 80% of worldwide electrical generation will come from fossil fuels, with implications for global warming and climate effects [UBS07]. Even in the developed world, electrical vehicles and new services (e.g., digital television and wind power) will place high demands on the Grid. Efficiency in the electrical energy system is essential for the planet’s future.

The Grid has expensive, centralized generation via large plants and a massive, centrally controlled transmission and distribution system. High quality power is delivered to all subscribers, sized to peak demand at each distribution point. Power is transmitted via high voltage lines over long distances, with attendant inefficiencies and losses. Local distribution is expensive in cost and efficiency, and is a single point of failure for an entire neighborhood. The system demands end-to-end synchronization, and lacks mechanisms for buffering energy, thus complicating subgrid sharing or independent “off-grid” operation during upstream outages. Recent blackouts demonstrate the robustness challenges. Utilities mitigate peak power consumption because it is so expensive to deploy incremental infrastructure. Yet average load is a fraction of the potential peak—a 25 kWh/day home draws on average less than 5% of its 100-amp service. Modest correlation, e.g., air conditioner use on a hot day, drives demand beyond estimated aggregates, resulting in increased supply costs, price spikes and, potentially, blackouts.

We are inspired by how the Internet has revolutionized communications infrastructure, by pushing intelligence to the ends while hiding the diversity of underlying technologies through well-defined interfaces. Any end device is a traffic source or sink and intelligent endpoints adapt their traffic to what the infrastructure can support. Our challenge is to understand how these principles can be suitably applied in formulating a new information-centric energy network for the 21st Century. We believe that an information-centric approach can achieve significant efficiencies in how electrical energy is distributed and used. The Grid assumes energy is cheap and information about its generation, distribution and use is expensive. Looking forward, energy is dear, but pervasive information will allow us to use it more effectively, by agilely dispatching it to where it is needed, integrating intermittent renewable sources and intelligently adapting loads to available energy. This is the genesis of LoCal: A Network Architecture for Localized Electrical Energy Reduction, Generation and Sharing.

2. Cyber Internet + Physical Grid = Cyber-Physical Energy Network

The Internet provides the fundamental cyber ability to exchange information among network endpoints. It also aggregates nodes into hierarchical tiers of independently administrated domains, implementing decentralized and distributed policy-controlled routing algorithms within and among domains to establish end-to-end connectivity.
The Grid provides the fundamental physical ability to deliver energy from aggregated sources to aggregated loads, over a regional transmission and more localized tree-structured distribution infrastructure. Existing Grid architectures make it difficult to manage anything other than dispatchable sources and uncontrolled loads. When a distributor’s load exceeds its supply, the operator either enters the marketplace to procure more supply from peers or increases supply by bringing less-efficient sources on-line, e.g., peaker plants. Alternatively, the operator moderates load, through local curtailment (i.e., brownouts or blackouts) or, if available, by propagating demand response signals to end consumers to incentivize them to reduce their load.

We envision the LoCal Energy Network as overlaying these infrastructures (see Figure 1). The Intelligent Power Switch (IPS) combines processing and decision-making with the directing of information and optionally energy flows. Just as conventional network switch/routers are interconnected and aggregated to form networks from more primitive subnetworks, so too does the IPS connect to peers to form interconnected subnetworks up and down hierarchical tiers of peered energy subnetworks.

![LoCal Energy Network](image)

*Figure 1. LoCal Energy Network overlaid on the Grid and the Internet*

In its most primitive form, LoCal only exchanges information among IPSs representing aggregated loads and sources. It processes monitoring information to generate energy supply and usage profiles. Visibility is as fine-grained as the granularity of deployed IPSs. Even this primitive level provides a foundation for computing predictions forward in time, and thereby for planning how best to allocate aggregated sources to aggregated load demand over time. A more sophisticated version of LoCal incorporates controllable loads and sources at the edges of the energy network. These
enable local IPSs to exchange and process energy profiles via decentralized and distributed algorithms to implement response behavior, e.g., by increasing local supply or reducing local load.

IPSs provide the cyberphysical points of presence to incorporate buffers and intermittent energy sources such as renewables into the energy network. When viewed in terms of matching loads and sources, buffers add new freedom to opportunistically store or draw on energy reserves, providing decoupling from sources while adding flexibility in time and network resiliency. A buffer IPS incorporates the necessary physical components to connect energy flows to the Grid and the cyber interfaces to participate in the information exchange of the LoCal negotiation protocols. The same is true of an IPS that integrates intermittent, renewable sources to the network. LoCal’s information overlay signals when energy from renewables is available, and determines when to connect it to the Grid to allocate it to loads. Through information exchanges, a renewable source can be directed to drive energy buffers, even without the existence of direct energy connections; the renewable source adds energy the Grid, the buffer takes energy from the Grid. Agile loads can be displaced according to availability. In a local deployment, e.g., a solar powered building or campus with local energy storage and grid-tie inverter connectivity to the Grid, appropriately designed IPSs could intelligently and cooperatively direct energy from the renewable source, the Grid, or local buffers, to local loads or buffers or even back into the Grid.

With appropriately designed IPSs, LoCal permits peer-to-peer energy exchange independent of the existence of the Grid, and suitable for rural deployments. Furthermore, with suitable local energy sources and buffers, and appropriate policies implemented in border IPSs, a LoCal subnetwork operates with optional connectivity to the Grid, much like the various microgrid proposals and prototypes [CERTS].

Since IPS communications is essentially tunneled over the Internet, security and privacy are concerns. IPSs mutually authenticate, and all information exchange is encrypted. LoCal will use better Internet Protocol (IP) security as it becomes available [IPSec]. To protect individual privacy, edge policies determine how much individual monitoring and control is visible outside of local aggregations. Suitable aggregation provides a reasonable way to obscure individual activity [Trust].

LoCal improves the resiliency of the energy network by exploiting buffers and adaptive loads locally and distributed throughout the Grid. Supplies are augmented with buffered energy and loads adapt their demand when remote energy supplies are disrupted. Only in the case of significant, long term disruptions are low priority loads shut down.

Another issue is the role of traditional utilities and system operators in LoCal. Grid components are owned by entities that should be compensated for their use. Customers will continue to pay for the energy they use in surplus to their local supplies, and providers of energy are compensated for what they provide. New entities, like renewable energy providers, and services, like on-grid buffers, become participants in the market for energy exchange (see Section d.4.2). A possible role for the Utilities is to run such regional markets, charging and accounting for the service of matching sources to loads and clearing the economic exchanges between suppliers and users.
3. Elements of the LoCal Architecture

3.1. Analyze: Control and Negotiation Protocols
One key goal of LoCal is to investigate distributed decision-making policies and dynamic control algorithms to achieve near-optimality, given the visibility and flexibility inherent in controllable loads, sources and buffers once pervasive information exchange is supported. IPSs introduce points for local control and real-time monitoring, and drive the process of intelligent adaptation. The real-time dynamics of IPS control and measurement enables adaptation of load and source behaviors to changing electricity prices, weather effects, and faults and shocks to the system. Adaptation methods include flattened load profiles, local peak shifting to reduce cost, use of buffers to smooth intermittent sources and loads, and preferential utilization of lower cost resources as available.

Our first thrust examines real-time optimization algorithms to guide individual IPS decision-making and management of its connected energy resources. External inputs include market prices, instantaneous generation capacity, load demand constraints, and available energy from peers. Decision variables include the use of buffers, management of controllable loads and sources, and energy sharing with neighbors. Our objective is to minimize total energy cost, i.e., the traditional cost of utility supply as well as environmental costs that drive overall energy reduction. Our second thrust is mechanism design for our demand/supply negotiation protocols [Var95]. Incentive compatible economic mechanism design is well-established, as are the conditions for achieving equilibrium [Var96]. Also well understood is the progression of market mechanisms from bilateral exchange, to multilateral, to a common currency [Ger01]. The key challenge is uncertainty over time: unpredicted changes in activity modify demand and weather or outages change supply. Forecasts improve cooperation among supplies and loads, and buffering introduces headroom to accomplish the match. We envision a suite of protocols where demand is presented as a load forecast over discrete time intervals. LoCal solicits commits to supply initial “packets” of energy from suppliers, with iterated renegotiation. They respond with pricing structures reflecting decreasing commitment over time. Multiple renegotiation rounds at multiple levels of aggregation may occur, since loads can shape their profile according to anticipated availability and price. We will implement these protocols and market mechanisms at a variety of scales and for different load and source environments, and validate behaviors and algorithms for larger-scale simulation and modeling (see Section 5).

3.2. Observe: Monitoring and Modeling
We follow a paradigm of observe-analyze-act based on in situ monitoring of energy components and environmental and mechanical elements, to collect observations to drive models and formulate control actions. Figure 2 shows our preliminary development of the cyberphysical observational plane. Using existing building-scale ModBus infrastructure we obtain real-time aggregate load of Berkeley’s Soda Hall (Fig. 2.A). Its coarse instrumentation permits only an approximate identification of loads and their dynamics. It shows a heavy continuous load, that can be resolved only through the introduction of finer-grained observation. Fig. 2.B shows our ACme plug-load wireless meter and relay [Jiang09]. We have also constructed branch load meters and devices for inferring load, such as light meters and accelerometers on pumps and fans. Fig. 2.C shows a portion of
Soda Hall instrumented with 50 ACme meters forming a low-power IPv6 network using Berkeley motes [Epic]. This provides a rich set of energy usage data from which to understand various loads, e.g., desktops consuming high load when idle, LCD monitors consuming power when unplugged, and projectors on in vacant rooms. These represent opportunities for load reduction and awareness of consumption patterns. We believe that significant portions of the load in Fig. 2.A can be eliminated by LoCal techniques.

Figure 2. Ubiquitous monitoring and actuation networks supporting the LoCal Energy Network

Building on our experience applying machine learning techniques to manage large-scale datacenters [Radlab], we believe that similar techniques can be used to develop models for predicting energy loads and supplies under a variety of conditions. These can feed simulations or estimate real-time demand. By aggregating models for different loads types at the appliance level and incorporating other physical sensors data streams, we synthesize higher-level models, e.g., for rooms, buildings, campuses, and neighborhoods.

3.3. Act: The Intelligent Power Switch (IPS)
The IPS is the LoCal point of presence, integrating monitoring, processing, and bundling communications with energy transfer. Using terminology adopted from conventional data networks, a Host IPS connects a single load or source to the energy network’s physical and cyber planes. Similarly, an Edge IPS interconnects an aggregated collection of loads and sources to the energy network. A Border IPS is the point of demarcation between the

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Grid and a hierarchical collection of LoCal subnetworks under a single administrative domain. A Border IPS may, for example, connect a building or campus to the Grid.

Energy buffering in the network is essential for flexibly matching loads and sources. IPSs can interconnect buffers to the Grid, or can incorporate local buffers to introduce a degree of Grid independence. We use the term buffering rather than storage to suggest the variety of generalized energy storage mechanisms beyond batteries, including thermal and mechanical mechanisms\(^1\). Where an IPS connects directly to a load (a host IPS), thermal or mechanical properties of the system representing the load can store energy. We gain the benefits of such buffering wherever possible. Just as we use traffic shaping in the Internet, we can use scheduling to sculpt the energy load profile in a manner that could otherwise be achieved with electrical buffering.

Although IP provides routing between arbitrary pairs of hosts, to scale to a billion hosts the routing infrastructure consolidates routing information in the core and exchanges aggregated routing information between Autonomous Systems [BGP]. Similarly, a Border IPS presents an aggregate load to the Grid, or to other energy networks, and negotiates for supply corresponding to how it orchestrates the superposition of the underlying constituent loads and sources. The energy subnetwork represented by such an aggregate may be directly connected to the IPS, which directly implements its Grid or peer connection. Alternatively, it may be logically associated with the IPS, but physically remote from it, and interconnected to the Grid via conventional means. The IPSs exchange information to shape and match controllable loads and sources, while controlling the subnetwork’s energy connections to the Grid.

In typical operation, power flows into an IPS at a rate related to average load with a safety margin. During times of light load, energy accumulates, whereas bursts of activity (peaks) draw down local buffered energy. The rate of feed and capacity of the buffering dictate the magnitude of the burst (peak integrated over time) that can be served locally. The primary grid infrastructure of generation and flows is sized for expected averages, whereas IPS buffering is sized for expected variation. Mechanisms are needed to handle situations where usage deviates from expectations. When load is less than expected over a prolonged period, energy buffers saturate and the subnetwork through its IPS “resells” its excess power to the Grid or its peers. When demand so exceeds expectations that buffers are depleted, a subnetwork either “purchases” additional capacity or reduces its load. Thus, correlated demand bursts can be handled either from local buffers or by market-based mechanisms for demand response.

**IPS Description**

The LoCal IPS is a conceptual collection of energy management functions. These can be mapped to various hardware platforms, centrally or distributed throughout the system. An information/power system constructed of IPS units is characterized by distributed control, decentralized decision making and intelligence at the end points. Each IPS can act on its own behalf performing its required functions, informed by the conditions of the system in which it operates, but based on its local set of policies.

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\(^1\) Demonstrated bulk storage systems, such as pumped hydro storage, account for 2.5% of the installed base load in the USA. At residential scale, storage is dominated by battery technologies, which have been optimized for power density and portability with limited charge cycles. Development of compressed air energy storage, flow-batteries, ultra-capacitors, flywheels and thermal storage are broadening storage opportunities, especially for lower density, stationary, long-lived applications.
In its full generality, an IPS is a multi-port device connecting energy sources with sinks. Power conversions may take place between input and outputs, such as rectification, inversion, voltage, buffering and modification of phase and frequency. Ports may be bi-directional, source ports may change to sinks as system conditions vary. Each IPS optionally has some buffering connected to an explicit port. This gives the IPS the ability to supply power, perhaps to meet power quality requirements, from its local resources for a period of time related to the size of the buffer and the policy governing its use.

Each conceptual IPS port is composed of energy and information channels. The former transports power while the latter carries data using IP. Each energy channel is paired with a (logical) data channel, with the possible exception of load- or source-only ports. In these cases, we meter the energy channel as input to the IPS.

The IPS matches load requests with energy sources under the direction of policies. The latter are rules within the IPS that consider the price of the energy, utilization of the source link or utilization of IPS resources. As an example, the energy price made available from a source to a sink port may be locally modified to reflect IPS utilization. This allows local transmission costs to be captured and reflected to connected consumers.

The following components and functions are proposed as comprising a general IPS:

- **IPS Energy Router**: directs electricity flows from and to connected ports, while performing power conversion, physical layer protection, and measuring parameters like voltage, current, phase, power factor. Ports can be incrementally added.
- **IPS Data Router**: controls information flows at ports. It acts as a traditional router, directing packets via PCIs from source to destination, translates frame formats and so on. It provides functionality typical of application-level proxies to support load profiles and the demand/supply negotiation protocols.
- **IPS Policy Execution Engine**: inputs measurements from the Energy and Data components, and directs the Energy Router (connect, disconnect, limit etc.) to affect energy flows and the Data Router for placement on the network. Higher-level protection is provided by the Policy Execution Engine as directives to the Energy Router. Power connection topology is under the control of the Policy Engine. The execution engine is responsible for security and authentication of communications.
- **IPS Manager**: provides supervisory functions and resource allocation. It scales from a small supervisor to a more complex manager in a larger IPS.

**The IPS Network**

A network of IPS connected sources, loads, buffers and aggregation points provides a reliable, scalable and efficient power system interconnected to other such networks through IPSs—an energy inter-network. Reliability and availability beyond that of the Grid is achieved by routing over redundant links, embedded buffering, delayed load activation across outages, and local generation. Scalability is achieved through endpoint intelligence, limiting the complexity of the core, minimizing hard state, decoupled layering despite media variation, and continuous monitoring and adaptation. Efficiency is realized by matching aggregated loads to collected sources, plus statistical multiplexing of larger aggregates. Average end-user power quality can be reduced since end-points can boost perceived availability, just as transport protocols provide reliable delivery over a best-effort core: by detecting loss, buffering, retransmission, and rerouting.

This “smart receiver” approach is particularly valuable for developing regions where power quality is quite low. Based on power measurements in rural India, we found
extended sags and swells and spikes to 1000V [Surana08]. Remarkably, this level of quality generally works for the traditional uses, like heating and lighting. However, power quality is a barrier to IT deployments and to LED lighting. India also suffers from roughly 50% loss of power due to leaks and theft, compared to 5% or less in industrialized nations, so the IPS approach can have broad impact immediately just via diagnosis of power losses. Finally, our data shows that it costs 20x more to clean power in India than to buy it, primarily due to the ongoing need to replace batteries damaged by poor quality power. An IPS designed for this environment, which we will do via our rural testbed, easily pays for itself by providing cleaner power and enabling efficient lighting.

4. Application of the LoCal Architecture

4.1. Demand Reduction

To reduce electricity’s contribution to global warming, substantive demand reduction must be an essential component of a future energy network. It reduces the load presented to the rest of the system, extends independent operation of its subnetworks, and increases the opportunity for shaping the remaining load. IT equipment is a microcosm of the larger problem of energy inefficiency and consumption management. Today’s typical desktops consume 200w when active and almost as much when idle [Barroso07]. The hardware is capable of dropping below 10w in suspend mode, but the ill-defined interplay of OS, network, and application software prevent it from doing so, or from resuming effectively [Chen08. Ganesh08]. Concretely, Fig. 2.A shows that 200 kW of the 500 kW load of Soda Hall is servers and their support, even when they are idle (about 75%). Fig. 2.C shows the same for desktops and appliances. Even the HVAC and lighting loads largely maintain empty environments. The single largest contributor to energy efficiency is to “do nothing well.” Any idleness is an opportunity to save energy, but it must be detected and the opportunity seized without unduly compromising overall performance. Making consumption visible to every load in LoCal is an essential step. Locally, actions are taken to decrease demand when idle.

We will investigate reducing IT equipment power demands in large-scale datacenters [Boher02, Carrera03, Gunaratne05, Gupta03]. These consume tens of megawatts and are limited by power, cooling, and power distribution, rather than by computing costs, so datacenter operators have strong incentive to reduce IT equipment power demands [Mitchell-Jackson03]. Since operators have administrative control over their equipment, datacenters are an ideal environment for investigation. The insights we gain can then be generalized to other more challenging environments.

Significant opportunities exist for reducing power consumption in CPUs, disks, memories, and networks through CPU frequency scaling, batching, duty cycling, etc. [Chase01, Fan07]. But the published work has achieved no more than a 30-40% decrease in power demands through tuning the active portion. As a point of departure, our strategy is to focus first on lowering consumption when the system is idle, even for short periods. The emphasis is on overall cost to deliver required results, rather than peak behavior. We believe there is a 10- to 100-fold potential improvement in average energy consumed through the holistic design of hardware, operating systems, protocols, APIs, and applications [Dutta05, Klues07]. Our desktops should consume 1 kWh per week, rather than today’s 3 kWh per day. Portable devices should need monthly, rather than daily
charging, except as limited by active use. The most widespread embedded devices should operate on milliwatts. When nothing is to be done, do nothing well.

4.2. Cooperative Energy Economy
Eliminating idle consumption reduces average power, but actually increases the peak-to-average ratio. Storage, demand scheduling, and aggregation are utilized to shape the remaining profile to best fit available supply. LoCal, through its aggregated subnetworks and protocol interfaces, creates cooperating ensembles of loads. An ensemble acts as a community to manage its shared generation and storage capabilities, present an adjustable load to the infrastructure, and to adapt internal operations to match negotiated availability and pricing of energy from the Grid. We envision several components to form a local, cooperative energy economy: Physical energy monitors that expose internal demands, cyber systems to analyze load patterns, cyber systems that decide how to reduce, shift, or otherwise optimize loads, and physical actuators to carry out the optimization decisions.

For example, each participant’s IPS computes local supply and demand profiles, and communicates it to others in the energy network. These incorporate past and anticipated tasks, their corresponding schedules, the state of local energy storage, as well as user input indicating task utility. The IPS also monitors the supply, demand, and pricing curves presented by the encompassing infrastructure. The computation engine in the IPS then solves an optimization problem and decides which local loads it should admit.

This is a dynamic optimization problem. The IPS decides not only which loads to connect, it also schedules when each should be connected. It models each load with a rich data profile, capturing their expected time behavior and time constraints, e.g., the IPS may model local loads and global electric price curves a day in advance, with per-hour granularity. The IPS computational engine solves a dynamic optimization problem that results in a 24-hour execution plan. The actuators controlled by the IPS then implement the execution plan, with the plan being updated as necessary with the latest data.

The static and dynamic optimizations are understood, and the necessary economic pricing information can be fed to standard algorithms [Var95, Var96, Hedm08a, Hedm08b]. Missing are the physical monitors to provide the input demand and price curves, and the physical actuators to implement the decisions presented by the optimization algorithms. The IPS combines this analysis with action, so that dynamic optimization of energy loads becomes a reality instead of just a theoretical possibility.

5. Constructive Plan: Iterative Development the LoCal Architecture

Our experimental approach iterates design-implement-evaluate embodiments of our architecture while progressively expanding its scope and completeness. We interleave empirical studies of its elements with simulation studies of their use in a broader context.
5.1. LoCal-ized Datacenter

Our first implementation of the LoCal Energy Network (innermost in Figure 3) incorporates a moderate industrial load in the form of a several hundred processor datacenter (lower-right portion of Figure 4). It will be designed around DC power distribution within racks and nodes, and utilizes storage, scheduling, and service quality adaptation to actively sculpt the load power profile to meet a negotiated target. No local generation is involved and we use conventional, battery-based energy buffering.

A Border IPS will connect this machine room energy network to existing building energy network, while providing the platform for implementing the power/pricing negotiation protocol. Based on internal service estimates, it presents a load forecast to the external network, in the form of discrete requests over an immediate fixed window and a forecast. It receives pricing and availability responses reflecting short-term energy commitment and forward-going energy demand intent. This negotiation process provides the internal load target, which may be preempted by critical external events. It progressively delivers the metered actual consumption profile to continue the transaction.

The datacenter energy network consists of AC PDUs and Ethernet to the internal IPSs, providing metering, conversion, storage, and DC distribution to hosts. Two kinds of Host IPSs are implemented, for individual node and full rack. Storage supports operation during outages. It also supports load sculpting by servicing peak demands locally and accumulating energy when idle, while adjusting the apparent load to match the target profile. This requires the servers to be power proportional, i.e., the power consumed is proportional to the machine utilization [Barroso07]. On an individual node, the OS kernel
drops the system into a very low power state during idle periods. Across racks of servers, this can be approximated by service migration and powering off idle servers. We will implement these for an IPS-integrated power proportional service platform. The services participate in the energy aware control loop. They relinquish resources to reduce power during periods of low demand. When demand would cause the service to exceed its target power consumption by more than it can draw from local storage, it degrades quality to meet the target profile. Heat, vibration, and noise modes will be integrated with server and service management. Thus, the LoCal-ized datacenter presents a smooth controllable load with demand that corresponds to a negotiated load profile. Its cyber services adapt to the physical constraints of available power over time. The achieved energy reduction and tracking to profile are the primary metrics of evaluation. These will form the model basis for a scaled-up simulation of much larger sized Internet datacenters.

5.2. LoCal-ized Building

Our second target for implementation, a LoCal-ized building, addresses a different load. It includes high current AC loads for HVAC and lighting (center right of Fig. 4) and different kinds of monitoring and actions. A Border IPS represents the building energy network and its internal subnetwork of Host and Edge IPSs. The building energy network is overlaid on its electrical system and network infrastructure. The LoCal-ized datacenter is a controllable load. Others are pumps, fans, chillers, and economizers for the HVAC system. We focus on scheduling and control to sculpt the load profile. Energy buffering is provided primarily through thermal mass. Rather than control the HVAC system directly, we manipulate it indirectly by modulating set-points and thresholds provided by the facilities management system. We augment the building SCADA control system with a wireless sensor network to measure temperature, light, occupancy, air flow, damper movement, and energy consumption at building-scale.

We will develop a distributed building OS that computes a load profile forecast and...
affects a negotiated load profile within constraints dictated by the safe, stable operating regime of the HVAC system and occupants’ needs, e.g., it eliminates peaks by orchestrating SCADA set points to multiplex large AC loads in time. We provide feedback to the occupants so they can adapt their energy use to a more efficient profile. Our sensors are used to detect inconsistencies in the building feedback loop, as well as to detect failed components or suggest maintenance.

The LoCal-ized building appears to the campus grid as a controllable substation load. We will measure our ability to achieve reduction in average consumption and peak-to-average ratio, conformance to target profile, and service quality to consumption ratio. Models derived from this effort will be used in simulations of large populations of commercial buildings, to assess the dynamics of our approach to aggregated load adaptation.

5.3. LoCal-ized Renewable Generation Facility

Concurrent with the development of load side energy networks, we will implement a LoCal-ized renewable generation facility. Its key attribute is that it dictates its own production schedule. Our approach is to augment existing renewable sources with IPSs, i.e., monitoring, communication, and participation in the negotiation protocols to appear as an independent generation authority to LoCal. We will build an IPS energy meter that can be attached to residential solar facilities and a home network, as well as to wind turbines already available at the UC Richmond Field Station. These sources, illustrated at the left in Figure 4, will deliver power into the Grid conventionally, but logically we view them as tunneling power through the Grid to remote LoCal-ized loads. The IPS will report power production in real time to a pseudo power authority service that makes a market with the various members of the LoCal Energy Network.

5.4. LoCal Negotiation Protocols and Market Mechanisms

With our aggregated experimental LoCal-ized sources and loads, we will demonstrate the our negotiation protocols and market making mechanisms, e.g., load and production forecasting, profile exchange and demand-supply commitment, and sculpting of load to match the production profile of sources, including intermittent renewables. Our IPS prototypes will incorporate computational elements upon which to define and implement and evaluate our negotiation protocols. To evaluate the protocol dynamics at significantly larger scales, we will engage in protocol and physical system simulation studies, particularly at the campus, district, and regional scales.

5.5. Energy Buffer Demonstration

Buffering amplifies the ability to sculpt load and production profiles. While alternative storage technologies are available, we will focus on battery storage to demonstrate the efficacy of the energy network transport layer. We will assess its ability to provide end-to-end energy availability exceeding the reliability of the basic energy delivery service. A conventional UPS is this in a rudimentary form. A buffer LoCal IPS provides a deeper reserve that can be interactively filled or drawn from.

5.6. Rapid Assembly of LoCal Infrastructure

To integrate the LoCal network elements, independent of the existing infrastructures of
the Grid and the Internet, we will implement a rapidly assembled, stand-alone energy network, targeted for village-scale deployments. Rural villages in developing regions already use local, albeit limited, generation. Single-home solar, e.g., popular in Kenya, typically uses a single panel and a car battery. This is inefficient and environmentally unfriendly, as the (toxic) battery has a short life under such conditions. We already have experience building a low-cost solar controller that increases efficiency by 15%, simply by tracking peak power to optimally charge the batteries. This doubles their life, due to efficient trickle charging that avoids deep discharges [Surana08]. Adding an IPS allows residents and business in the village to share power, creating an efficient independent LoCal-ized microgrid while accounting for how energy is shared. This is important to limit asymmetry in use versus generation, and to settle payments. Sharing allows participants to generate energy sufficient to meet average rather than peak needs, thus making the village as a whole more efficient in its generation and use of electricity.

6. Broader Impacts

We are committed to developing curriculum for training the next generation of interdisciplinary electrical engineering and computer science students in the field of cyber-physical systems, particularly intelligent energy networks and systems. Berkeley’s Environmental and Sustainability Portal [Enviro] provides a gateway to a number of courses on energy and the environment. Sanders created EECS 290C: Power Management Systems and ICs. Katz offered CS 294: Architecture of Internet Datacenters in Fall 2007 [CS294]. This course led to projects in energy reduction in datacenters. In Spring 2008, Culler offered an undergraduate course, CS 194: The Internet of Everyday Things [CS194]. This led, in part, to the development of the ACme Energy Sensor. Culler, Sanders, and Katz are co-instructors of a current interdisciplinary graduate course, EE290N-3, Contemporary Energy Issues [EE290N]. Course materials are available on the Internet, and many lectures are available as streaming video. We will evangelize our developments to other universities, and where appropriate, to secondary schools.

Berkeley’s College of Engineering has been a leader in offering opportunities to underrepresented undergraduates to work on research projects through the Summer Undergraduate Program in Engineering Research at Berkeley (SUPERB) Program [SUPERB]. Each of the investigators has worked with excellent SUPERB students in the past, several of whom went on to graduate school in EE and CS, and we are committed to working with SUPERB students during the duration of the LoCal project.

Berkeley has developed a comprehensive campus sustainability plan [Sustain], and we have explored opportunities to work with campus facilities as part of our experimental plan. The University is highly motivated to understand opportunities for integration of local generation technologies in campus-scale deployments, as well as energy reduction.

We have a record of industrial technology transfer, and are forming a diverse industrial consortium, e.g., Cisco Systems (Networks), Google (Services), National Semi (Power Electronics), Siemens (Power Generation/Transmission), Sun Microsystems (Computers), and Vestas (Windmills). Collaborations are developing with energy researchers at LBNL. The NSF Tier Project [Tier] adds insights into the energy needs and technology limitations of deployments in developing regions. The NSF TRUST Project provides additional insights and technologies for implementing security and privacy in
critical infrastructures [Trust]. He enables the deployments of our standalone energy system in Africa and India, which has large impact given their fast growth of energy usage and their high demand for local generation. We are also investigating working with the Government of Turkey on a joint deployment in Southeastern Anatolia.

7. Related Work

Considerable work is underway in “Smart Grids,” a vision we share for a next generation electrical energy system. Elements include Grid instrumentation with pervasive monitoring and control points at the distribution and consumer levels to improve reliability and grid resiliency against faults and attack, facilitate integration of intermittent renewable resources, add load adaptation, and enable dynamic pricing of electricity. Many of these efforts consist of industry-driven reference architecture and standardization efforts, e.g., Intelligrid [Intel] and GridWise Alliance [GridW].

EPRI’s Intelligrid, for example, provides energy equipment integration through network interfaces for its intended customer, the Utility. This is in contrast to our focus on the conceptual foundations of a distributed energy system and the application of cyber-physical system principles for its realization. To the extent that these efforts provide equipment with standardized, networked control interfaces, they provide us with large-scale grid components that can be incorporated into the LoCal energy network.

Industrial ventures focus on two applications. Utility-managed demand response, e.g., GridPoint Energy Manager and Tendril Residential Energy Ecosystem, enable utilities to remotely control home loads. Personal energy monitoring equipment and software informs users of usage patterns, e.g., Greenbox, Google’s PowerMeter [Google].

The DoE’s Consortium for Electric Reliability Technology Solutions [CERTS] is developing tools to enhance real-time grid monitoring, with the customer being the Independent System Operator. CERTS also considers how deregulated energy markets affect the Grid, with a focus on utility-scale transmission and bulk power markets. No information granularity exists below the level of the high voltage substations.

These initiatives improve existing grid infrastructure, but leave the underlying architecture unchanged: a centrally controlled system, with distributed control points operating as its delegates. This does not have the scalability and aggregation of a true distributed architecture, adding complexity and information overflow. The LoCal architecture is distributed and scalable. By using IPSs to aggregate and encapsulate system components, perform load shifting and smooth generation profiles, it reduces grid complexity, is inherently scalable, and avoids retrofitting an expensive infrastructure.

Utilities have deployed Advanced Metering Infrastructure [AMI] to monitor energy usage, communicate pricing signals, and aid in demand response. AMI smart meter providers, e.g., Aclara and CenterPoint Energy, report interval usage and deliver pricing signals and load control messages to consumers. AMI is an endpoint in a centralized scheme, while IPSs are distributed throughout the LoCal network, logical peers, speak the same protocol, and make decisions through inter-ISP negotiation.

Demand response programs can be incentive- or market-based. In the former, consumers cede their right to use electricity at certain times for reduced rates, e.g., PG&E’s SmartAC program. Similar programs are available to large industrial customers. The second approach simply passes real-time pricing information to the consumer, who
acts in his/her best interest and reduce their electricity consumption by ceasing or delaying unnecessary consumption. LoCal IPSs can accept such pricing signals from the Grid, for presentation to consumers, but more generally to drive local load adaptation.

An area of related work is microgrids: distributed generation resources co-located with loads and designed to optionally service some of that load when disconnected from the primary grid. The CERTS microgrid’s Point of Common Connection (PCC) is a controllable connection for islanded operation. While this is well developed for the physical action points of controllable generation and loads, it lacks the cyber layer of information collection, aggregation, analysis, and reaction. CERTS does not allow microgrids to act hierarchically or as peer-to-peer aggregates, negotiating to cooperatively share generation sources or in load adaptation. Nevertheless, there is an opportunity to extend the CERTS PCC with the necessary communication and control capabilities to implement IPS functions for prototype deployments. We are working with colleagues at LBNL to pursue such collaborations further.

LoCal departs from microgrids in two regards: system observability and distributed ownership. While the microgrid presents a benign aggregate of loads and generation, there is no infrastructure to exchange information with the Grid. The microgrid is centrally operated. Even if its control is distributed, there is assumed cooperation between microgrid elements, particularly when a single PCC exists. This is appropriate when operated by a single owner such as a business or campus, but becomes problematic for multiple owners, such as at neighborhood-scale. Non-cooperative agents are a challenge for microgrid. A more appropriate use would be as a single realization of a LoCal IPS.

The Future Renewable Electric Energy Delivery and Management Systems Center [FREEDM] is a complementary effort to replace analog and mechanical devices with more efficient and controllable solid-state equivalents. Their “internet for energy” is focused on the ease of plug-and-play, whereas LoCal focuses on the underlying design principles that allow centralized infrastructure to become decentralized, by pushing the intelligence towards the edges. We intend to collaborate with FREEDM and eventually utilize their intelligent devices as an additional substrate upon which to deploy LoCal cyber communications and analysis elements, particularly for deployments at the megawatt scale. LoCal would provide the missing communication architecture for collecting observations, negotiating among points of control, and distributing actions for load control and managed sources.

In summary, there is considerable work to standardize energy and information interfaces while building intelligent monitoring and controllable components of the energy system. What is lacking is a scalable cyber-physical system architecture, bundling information flows with energy flows, enabling new ways to flexibly and efficiently match sources to loads, and exploiting buffering and pervasive monitoring to simultaneously smooth delivered energy and adapt loads. Such an architecture must operate across all levels of aggregation, scale and administrative boundaries. Such an architecture is LoCal.
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