**Applying Internet Architecture to Energy Systems**

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## Introduction

Internet technology and energy concerns intersect in a variety of ways, including the direct use of network equipment, data center servers, electronics in buildings, and more. Energy is a key component of the overall environmental, and specifically climate, impact of Internet communications. More recently, a diverse set of new and traditional non-electronic devices are becoming IP-connected. Apart from the Internet itself, its highly functional architecture can also inspire other domains of technology. Perhaps the only technology that has a physical reach comparable to the Internet is our electricity systems, which are long overdue for an architectural reconsideration.

The old phone system and the electricity grid were invented in close temporal (and physical) proximity about 140 years ago. Both shared many characteristics in their structure and operation, driven by being organized on a 'unitary' model - one big system. We essentially threw away the old phone system technology, and replaced it with Internet technology, which required rejecting many of the architectural foundations of the phone system. With the dramatic improvements in communication functionality enabled by Internet technology, it is natural to consider how to apply it to energy systems (most particularly electricity).

Before we could deploy Internet technology, it was of course necessary to have digital communication; however, that was not enough - we also needed data storage (to store and forward packets among many reasons). It is the storage which enabled loosely-coupled distributed systems, rather than the tightly-coupled unitary system. Now that we have electricity storage that can be functionally integrated at scale with electrical systems, we can consider alternatives to our 19th century model. We already have examples of small-scale loosely-coupled power distribution all around us; a notebook PC can operate grid-connected or islanded, and distributes power to attached USB devices; the notebook is thus a grid[2] (despite being small in electrical capacity and geography). However, the principles involved can be scaled in both dimensions.

## Internet and Energy Systems: Similarities and Differences

Some Internet design principles can usefully be applied to electricity, and some not. Part of this is due to the fundamental difference between data packets and electrons. Packets are unique in their source, destination, and content. Electrons are all the same. For this reason, it is essential to route data packets to their destination, but 'routing' of electricity makes no sense. For electricity, it is timing, quantity, and location that matter - not identity.

At a high level, Internet technology is divided into two domains - wide area and local area communication. While many core mechanisms are used in both (including IP, the 'fundamental mechanism'), there are some differences, with some protocols being used only within WANs and others only within LANs. This difference recognizes the different context of each. LANs are dominated by hosts, and WAN networks contain only (or nearly only) network equipment. Figure

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[2] A notebook PC functions specifically as a 'nanogrid controller'.

1 illustrates how this applies to electricity, in which there may be a complex internal structure within a customer site and a complex structure within the grid, but none of the details of either need to be passed across the interface, including the identity or status of any particular device. This is directly analogous to the relationship between LAN and WAN systems for data networking[3].

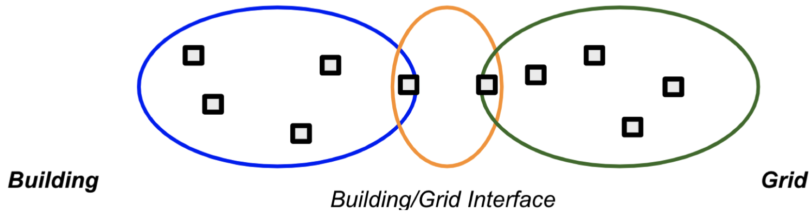


**Figure 1. Separation of local and wide area domains**

While the presence of hosts is a hallmark of LANs, for buildings, it is the presence of loads - devices that deliver services to people - that is distinguishing. These are services such as heat, light, information, hot water, food storage, etc. No grid devices directly serve humans. Power distribution today is managed with application-layer protocols, principally OpenADR and IEEE 2030.5. This makes sense today in a unitary grid context, but in future, we may have multiple power domains in each building, with different prices, and devices that coordinate for functional control may be powered in different ways (DC power domains are inherently distinct from the main AC distribution). In this context, the power coordination should really be associated with the power itself. This is done today with USB and PoE, and both have power distribution capabilities that are logically (and in the case of USB physically) completely separate from the application layer content that flows across the same link. This leads to a principle called Network Power Integration (NPI; see Figure 2)[4]. This adapts the OSI model and operates in parallel with it. Application layer protocols are unchanged from today. The physical layers are of power distribution (and its coordination) and as with the OSI model, are completely disjoint from application layer protocols. The USB and PoE models map onto this perfectly. An individual device internally integrates its functional goals with its power distribution context (available capacity and current and forecast prices) and then decides how to operate.

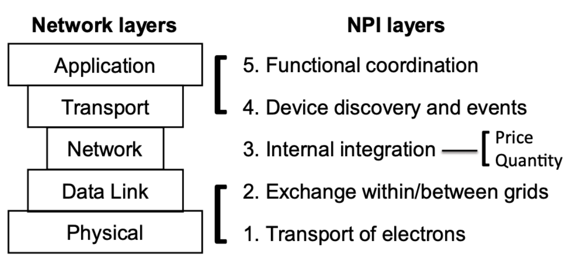


**FIgure 2. Network Power Integration**

[3] For application layer purposes there is of course identity and status information shared across the boundary, but that is conceptually separate.
[4] Early version of this in Nordman, Bruce, and Ken Christensen, “Local power distribution with nanogrids”, Green Computing Conference (IGCC), June 2013 ; full model in Nordman, Bruce and Ken Christensen, “DC Local Power Distribution with Microgrids and Nanogrids”, First International Conference on DC Microgrids, Atlanta, GA, June 2015.

While NPI is the model, it does not need to be followed to the letter. A device can 'export' its own decisions to another device that does the optimization for one or more loads (a furnace does this by exporting control decisions to a thermostat). And, we can continue to use application layer protocols for price distribution, but over time will need to be increasingly attentive to providing loads with the *right* price.

**Customer / Grid Coordination**

One foundation of Internet technology is that one mechanism is used at all scales and for all application contexts - the Internet Protocol. Its definition is not long, and it appears that most of the features are rarely or never used. For electricity, it is becoming increasingly clear that *price* (and quantity) can be the universal mechanism for managing flows of electricity (and other forms of energy such as district heat) over space and time. Price is used pervasively in wholesale markets, for retail transactions, and in future can be used within customer sites to do the same thing - manage the flow over space and time. Price can also be used to manage power flows over a single cable; for example, the Ethernet standard includes a 'Power Price Index' to convey the value of electricity being carried[5]. Historically, retail prices have been flat, which eliminates their potential for shifting electricity use over time (including with storage). With the increasing penetration of renewable electricity sources (that vary with the clock, calendar, and weather), flat prices incorrectly value electricity; its availability varies over space and time. Shifting load is necessary to better match load to its generation, to minimize the need for non-renewable sources and expensive (and less efficient) battery storage. Dynamically varying prices can be a universal mechanism to enable this transition, and the pace of change in retail pricing is increasing. Why all other mechanisms are inferior as a universal mechanism is a topic beyond this paper. As price is used in most aspects of modern economies, it should not stretch the imagination to embrace its use here, to encourage customers to behave in a way that is best for the current conditions of the utility grid.

Figure 3 outlines Price-Based Grid Coordination (PBGC), which summarizes the communication among the grid, flexible loads (and batteries, EVs, and dispatchable generation), and related entities. It identifies that any of the four entities in the bottom half of the graph can do the integration of price with the application layer context of device goals. GreenHouse Gas (GHG) marginal emission data impose a burden on the environment that can be readily converted to a retail price by multiplying the emission rate by a currency/ton burden value, and add this to the retail price; either the retailer or customer can do this.

The communication protocols used for the green arrows are today OpenADR 2.0b (primarily) and IEEE 2030.5. OpenADR is currently being modernized. Today, many protocols are in use for functional control, but the Connectivity Standards Alliance (CSA) led Matter protocol[6] may over time greatly reduce that number. It would probably be helpful if Matter were also able to carry dynamic prices in a way that is semantically harmonized with OpenADR.

[5] P802.3bt-2018, IEEE Standard for Ethernet - Amendment 2: Power over Ethernet over 4 Pairs, 2018.
[6] https://csa-iot.org/resources/developer-resources/

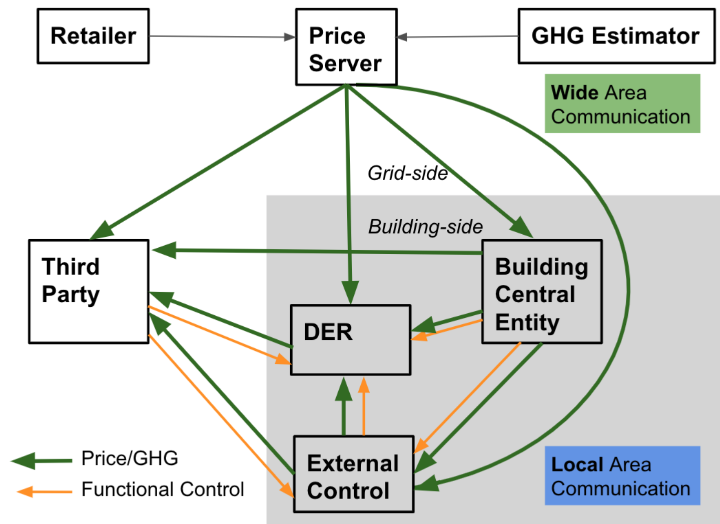


**Figure 3. Price-Based Grid Coordination**

| **The Three Dimensions of Grid Coordination** |
|---|
| This paper only covers coordination about *energy* flows - managing these over space and time - but there are two others critical to system operation. |
| The second is *power* coordination, principally functions implemented by inverters, most commonly found with PV systems, batteries, and electric vehicles. This covers power quality, and requires a distinct mechanism from what is used for energy[7]. |
| The third is *capacity* coordination, something which is in general not done today[8]. This covers managing the total power flow to individual customers, or through individual grid entities such as distribution transformers or feeders. While price can balance energy flows across large numbers of customers, with a sufficiently small number a different mechanism is needed. |

There may be niche cases in which the grid finds it necessary or expedient to coordinate more intensively. Electric vehicle charging stations and large industrial customers *may* be an example. However, these can be narrow exceptions and be built on top of the price-based model.

### Intra-building Coordination

PBGC is focused on the grid/customer interface, but this still leaves the question of how a 'local area network' of power should be constructed. Figure 4 shows an example local grid network as enabled by Local Power Distribution (LPD).

[7] IEEE 2030.5 is the standard protocol used most for this purpose.
[8] See Dynamic Capacity Management (DCM), https://docs.google.com/document/d/1yGTTATHXMu1k8gTFH_rDNu7im4wGP7TYV6TIxK5_MOE

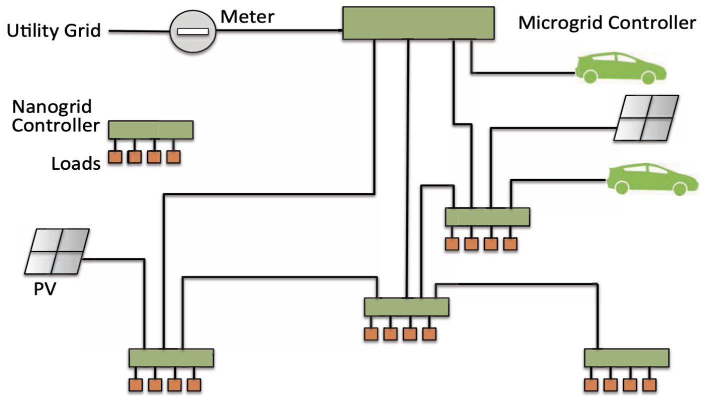


**Figure 4. Local Power Distribution - example microgrid/building**

LPD is a 'network model of power'. Power is exchanged between nanogrid controllers, or sent to loads, based on digital negotiation including a 'local price'. Each nanogrid controller determines its own local price (and forecast), and broadcasts this to immediately connected devices. Links to loads are one direction for power. Links between grid controllers can (usually) change direction. Like the Internet protocol, the messaging for LPD is quite simple, and mostly already present in USB and PoE. To be clear, LPD only addresses power distribution. It says nothing about functional control. A hardware device that is a nanogrid controller could also host application-layer functionality, and that functionality would likely be informed by the local price, but the power distribution functions would be unaware of this.

How the utility grid should be internally organized is outside of the scope of this discussion. Many of the architectural features from above may apply there, though practical use may take technology not yet economic today and take decades to apply to existing systems. That said, there is increasing discussion about using 'locational' retail prices so that the price for a given tariff may be different in different regions of a utility grid. This clarifies to retail customers that the availability of power varies over geography.

### Summary

Our systems for distributing electricity - the utility grid and that within buildings - can leverage principles from Internet architecture. In addition, a price-based coordination model between the grid and customers is needed to accommodate for the increasing penetration of distributed renewable energy sources and make best use of energy storage systems. Price-based coordination is a necessary ingredient for plug-and-play integration of generation and storage. All of this is built on Network Power Integration, which identifies power distribution as architecturally separate from systems for functional control.

Collectively, the proposals above for electricity exhibit many features of Internet architecture. These include the end-to-end principle, scaling, keeping things as simple as possible (and no simpler), modularity, practicality, unpatented technology, and facilitating privacy. There are other innovations to offer as well, including the processes by which the IAB and subsidiary activities operate.