Nanogrids

Evolving our electricity systems from the bottom up

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Abstract— **The conceptual framework of the "Smart Grid" naturally takes the viewpoint of the grid, then works down into the details of its individual components. This is good and necessary, but there is an alternative approach that can complement and strengthen the "macrogrid" — to start from (very) small "nanogrids". Nanogrids can be interconnected and aggregated into microgrids, and ultimately, through the meter, to the macrogrid. Nanogrids are already common today, in the form of USB-powered devices off a PC, Power over Ethernet distribution systems, and the electricity systems in cars and other vehicles. In addition, an increasing number of developing nation households have a nanogrid with local generation and battery storage. This paper defines nanogrids, delves into their existing and potential characteristics, and proposes some principles for standard interfaces between nanogrids and with microgrids.**

I. INTRODUCTION

The "Smart Grid" has many different definitions, but all share a common "top-down" approach to understanding the problem and potential solutions. This assesses each component of the grid for how it can meet grid goals of reducing costs, increasing reliability, and gaining environmental advantages. Because the electricity grid is a single interconnected system, it is tempting to see this as the only way to improve how we distribute power.

An exception to this dominant paradigm is the topic of "microgrids", in which methods of operation of electrical connectivity and control are significantly altered from normal grid operation, but only within a circumscribed domain of the microgrid. Microgrids have been around since before the "macrogrid" was created, though for the most part only exist in industrial facilities, large campuses, and off-grid houses. Microgrid expansion has been hampered by real or imagined complexity in implementing them, and a lack of standard off-the-shelf technologies that can be readily, and cheaply, utilized.

There is now a "third way", which is not an alternative to the other two, but rather a useful complement — "nanogrids". Nanogrids take the general approach of microgrids (and many design principles), and carry it considerably further. Nanogrids offer the possibility of attaining a critical mass of technology, affordability, and familiarity to enable nanogrids, and then microgrids, to flourish.

Each nanogrid is a single voltage, reliability, price, and administrative domain, and can contain implementation details within it to enable interoperability with other grids. The information and control architecture for interconnecting nano and microgrids should be independent of the physical layers within them.

A key feature of nanogrids is their ability to be interconnected with each other, as well as implemented within microgrids, as well as, through the meter, connected to the macrogrid. Doing this requires interface standards that can be reliably implemented.

Nanogrids are already common today, in the form of USB-powered devices off a PC, Power over Ethernet distribution systems, and the electricity systems in cars and other vehicles. The fact that they are small and simple does not mean they are not useful and important.

One notable absence in discussions around the Smart Grid is how it will help people who today have no access to electricity. Many countries are skipping the land-line telephone phase that industrialized countries spent many decades embedded in, going directly to much newer mobile technology. Similarly, many areas may skip the phase of a capital-intensive traditional grid, for economic and environmental advantage. They also may gain the services of electricity much earlier than if they waited for the traditional grid to reach them. This does not preclude their later joining a macrogrid, but possibly a leaner and different sort than we have today. The consequences of this possibility affect at least hundreds of millions of people so should not be ignored.

The rest of this paper is organized as follows. Section II presents a definition of a nanogrid. Section III delves into the origins and motivations for nanogrids. Section IV reviews a number of examples of nanogrid technologies currently in use. Section V discusses some implementation issues. Finally, Section VI proposed elements of what research and policy should be doing next.

II. DEFINITION

A nanogrid is a single domain for voltage, reliability, and administration. It must have at least one load (sink of power, which could be storage) and at least one gateway to the outside. Electricity storage may or may not be present. Electricity sources are not part of the nanogrid, but often a source will be connected only to a single nanogrid. Interfaces to other power entities are through "gateways". Nanogrids implement power distribution only, not any functional aspects of devices. Components of a nanogrid are a controller, loads, storage (optional), and gateways. A schematic is shown in Fig. 1.

Nanogrids can be highly dynamic, with the set of devices part of it changing over time. This includes loads, storage, and connections to other grids (particularly sources). The concept of nanogrids have been mentioned in other papers (e.g. [1][2]), but with somewhat different meaning and no reference to their already being widely deployed. There is a range of nanogrid functionality, and for convenience the endpoints are called "minimal" and "full".

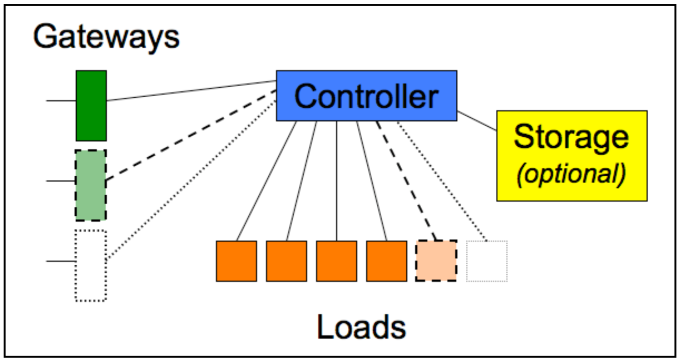

Figure 1. Schematic of basic nanogrid.

A. *Loads*

Loads in a nanogrid can be any electrical device of any size, though generally they will be under 100 W, and sometimes under 1 W. Other than requesting power from the controller, the

B. *Controller*

The core of a nanogrid is the controller, which has the ability to provide or deny power to loads, to negotiate with other grids through gateways, to set prices, and to manage internal storage. The controller is *the* authority in a nanogrid.

In a full nanogrid, devices are always entitled to a minimum amount of power, to enable basic communication functions, and with this, can request more power from the controller. The controller can grant this request fully, grant it partially, or deny it. In addition, the controller can revoke a grant of power.

Controllers may have knowledge of usage patterns from past operation, and use that in decision-making. They also can have embedded preferences about their behavior such as how much storage capacity to try to always maintain under different circumstances. It is not necessary to standardize controller algorithms.

C. *Storage*

Storage can be included internal to a nanogrid, or in a second attached nanogrid that may only contain storage. When storage is present, the controller will store or withdraw energy as needed, being cognizant of its technical characteristics.

D. *Gateways*

Gateways can be one-way or two-way, and have a capacity limit. Each gateway has two components: communication, and power exchange. The communication should be generic, at higher layers, and will run across various physical layers. The power exchange will be defined for a variety of voltages and capacities; a challenge is to determine what the best sets of these is, but certainly the voltages already in use today—5V, 12V, 24V, 48V, 380V, etc.—are good candidates.

The nanogrid does not know what is on the other side of the gateway, just the basic price, capacity, and availability information passed across the interface from the counterpart gateway.

E. *Price*

A full nanogrid uses price as a way for devices to express preferences about their relative importance. When more power is requested than is available, those with the lowest price have their allocation revoked or not granted. The nanogrid has a current price that may reflect the price of the marginal devices. This price also affects decisions to store or withdraw energy from storage, and is exposed to the wider world through gateways.

Entities connected to gateways may do nothing (that is, exchange no power), offer to sell power to the nanogrid, or offer to buy it. This way, the nanogrid can seek optimal behavior for the entire system.

To account for losses through gateways, in wires and in possible voltage conversions (and between AC and DC), the buy and sell prices may be different, much as with currency exchanges. The actual price and other algorithms implemented in a nanogrid are internal to it, so do not need to be standardized; only the gateway definition and behavior needs to be interoperable.

Gateway connections and loads may come and go or rise and fall in size over time. The controller simply reassesses the situation each time such an event happens and adjusts its behavior as needed.

Whether costs for exchanged energy is actually "paid" is not the point – there is no barrier to that but within a single building, that may not be worth doing. Both gateways at a connection will track accumulated energy and costs protecting nanogrids from malfunctioning or nefarious other grids.

III. ORIGINS

A. *Macrogrids*

The macrogrid is an impressive system in that it is highly reliable with little direct coordination between sources and loads; balancing the system is accomplished primarily through the usual predictability of loads at the very aggregate level, and (excepting emergency conditions), an absence of sharp changes in demand. As the size of a grid decreases, it becomes increasingly necessary to have some mechanisms for coordination of supply and demand, particularly to ensure that the system functions optimally. In the past, the cost of technology to provide coordination was prohibitive, but that is no longer true.

B. *Microgrids*

Features of microgrids [1][2][3][4] that have made them an attractive option to pursue include the abilities to:

- better integrate local (distributed) generation
- better integrate local storage
- provide a variety of voltages, and both AC and DC
- provide a variety of quality and reliability options
- operate independently of the macrogrid (or connected)
- optimize multiple-output energy systems (e.g. combined heat and power, CHP).
- hide microgrid details from the macrogrid

Microgrids have great potential to deliver economic, environmental, and other benefits, but have been hampered by being a relatively small market, too small to have industry-wide technology standards that enable large price reductions and high degrees of interoperability.

C. *Nanogrids*

Much literature on microgrids focuses on electrical compatibility and control issues [3][4]. These are generally much larger in electrical capacity than nanogrids. Nanogrids already work, so have much less need for this type of concern.

Nanogrids address a much reduced set of problems, though with much greater application potential; thus, they enable the development of standard technology that can quickly become widespread.

A nanogrid follows many of the principles of microgrids with some key exceptions: they seek to provide only a single voltage and level of quality/reliability; they do not address systems with complex optimization (such as combined heat and power)—in fact they do not address power sources at all; and they have only one entity that controls power distribution within it, and exchange of power with adjacent grids.

D. *LoCal*

LoCal [X] is a concept for how to interconnect electricity systems at various scales, first described several years ago. It has much in common with the nanogrids approach and is a significant inspiration. There are differences, though some may ultimately be as much a matter of presentation as of practical implementation.

One difference between data networking (in the Internet) and "grid networking" and, is that in the former, it is necessary to have a consistent architecture across the entire network to enable end-to-end connectivity. LoCal envisions a hierarchy of IPSes in the network, eventually spanning the entire grid, like the end-to-end connectivity of the Internet. For power, connectivity in the nanogrid concept, connectivity is only needed between adjacent grids, as communication and knowledge only extends to adjacent grids. It seems likely that both approaches will be valuable going forward,

While LoCal conceives of an Intelligent Power Switch (IPS) as sitting equidistant among loads, generation, and storage, with nanogrids one controlling authority is tightly coupled to its loads, with the links between nanogrids much looser. Put another way, the internal links of a nanogrid are of a very different nature than the external links.

LoCal begins from an overall concept that can eventually be applied to large-scale electricity systems and works down to specific implementations. Nanogrids start from *existing* technologies for local connectivity, and explores how these could be connected to each other. Again, both approaches are needed.

LoCal presumes storage, for the great benefits it offers in enabling the system to adjust to varying supply and demand conditions. Nanogrids do not assume storage, but can (and often do) include it.

LoCal and some other source [1] have at least the abstract concept of "packetizing" energy, much as data is packetized on the Internet. Nanogrids lack this explicitly, though there is some expectation negotiated about timing of changes in loads and exchanges of power, which provides a limited notion of 'chunks' of energy rather than simply just continuous power.

IV. EXAMPLES

Often it is easiest to understand a concept through a series of examples. Those presented here cover a range of types of nanogrids from minimal to full.

One purpose of reviewing them is to understand how well the generic nanogrid architecture from above maps onto these examples, to derive common terminology and principles. Nanogrids built on data communications standards are of interest only for their power distribution angle.

A. *Universal Serial Bus (USB)*

For many people, it will stretch credulity to call a few USB cables and devices emanating from a PC a "grid", but it is a minimal nanogrid. A USB port provides power, and the connected device is a load (if it wants to be). Multiple USB ports on the same PC or same hub are part of the same nanogrid. Unpowered hubs enable connecting more devices to a single port. A powered USB hub becomes its own nanogrid, independent (for power) from the upstream PC.

The original USB specification [7] provided for 2.5 W of power that connected devices could share (any device guaranteed 0.5 W, with the ability to request more). USB 3.0 increased the power capability to 4.5 W, with even more available when charging a battery. When a USB master device goes to sleep, it can provide a reduced amount of power to connected devices.

There is also a variant of USB, originally USB PlusPower and now PoweredUSB [8] that adds connectors and cables to provide higher voltages and much more current.

B. *Power over Ethernet (PoE)*

Standard modern Ethernet cables are capable of carrying power according to IEEE 802 standards. The latest version, 803.3at [9] provides for up to 26 W and even 51 W. This can be accomplished by a "mid-span" device that sits between the network switch and the edge device, or, the entire switch can be capable of providing PoE power over some or all of its ports. While a mid-span device is just an external power supply, with a switch we have a nanogrid. A PoE switch often is not capable of powering all ports at their maximum individual capacity, and so has a mechanism (LLDP) for devices to request additional power over some guaranteed minimum. As with USB, the most common deployment is when both data and power are utilized, but it is quite possible to have PoE devices that only use the power functionality.

C. *Vehicles*

Many components of a car (lights, radio, etc.) are powered by the 12 V battery used to start and maintain its electrical stability. The cigarette lighter has long been a standard "outlet" in cars to plug in many accessory devices. Modern cars have an increasing amount of entertainment electronics, and sometimes provide WiFi inside; these need high-speed communications wires, which may be able to also provide power. An increasing number of cars also have a 115 V AC outlet—essentially a second nanogrid. There is also a move to shift to a higher standard voltage (42V) by using multiple batteries to get more power. With electric cars and plug-in hybrids, we will have many more road vehicles that connect intermittently to the grid.

Aircraft and ships have a variety of non-standard AC and DC "grids" within them, and so serve as important examples. They also already operate connected to the grid (at the gate or port), and off-grid.

D. *eMerge*

The eMerge Alliance is backing a technology which distributes 24 V DC power for use in commercial buildings, from external AC or DC sources [10]. It provides up to 100 W on each distribution channel. Lighting is a key application, but it is not limited.

E. *Proprietary solutions*

Some companies such as Redwood Systems [11] have technologies for distributing DC power and providing communications, also intended for commercial buildings. This system is beginning with lighting, but not limited to that.

F. *Off-grid developing nation households*

A large portion of humanity lacks grid electricity for their homes. In these cases, 12 V car batteries are often employed to provide power for a few devices, either to be charged off-site, by a generator, or via some local renewable source. See Section V for more on this application.

G. *NexTek*

NexTek Power Systems sells devices that interface between the macrogrid, local renewables, local storage, and AC and DC building loads [12]. These thus implement several interconnected nanogrids, and the NexTek hardware serves as a controller for each with several gateways.

H. *Green Plug*

Green Plug Inc. sells enabling technology for single and multiple-outlet DC power strips that negotiate voltage and current to be delivered with the attached devices [13]. Ignoring the possibility of different voltages, these are a nanogrid. There is a proprietary protocol, *Green Talk*, which accomplishes the needed communications.

I. *Microgrids*

Microgrids are a superset of nanogrids, and so some current implementations serve as examples of nanogrids, either in entirety, or in some components.

V. IMPLEMENTATION

As noted above, nanogrids take from microgrids their primary goals: making available power with diverse characteristics; better matching the needs of the devices being supplied; better matching the power source(s); and possible energy efficiency advantages. They merit attention for energy efficiency research and policy to understand how they can be used and promoted where they do save energy. To the degree that they do and will get increasing use for their other benefits (regardless of their energy impact), it is worth making them as efficient as feasible.

As nanogrids are already relatively inexpensive to purchase and install, they should see quick uptake. This enables price reductions of components to make them even more accessible.

A. *Interconnecting nanogrids*

Most nanogrids are connected to the macrogrid (vehicles mostly an exception, but plug-in vehicles will change this). Usually this is only for power, not communication, and usually, power only flows into the nanogrid. If a nanogrid has non-dispatchable power (e.g. solar or wind), and all storage is full, then it can export any excess power, but this is a simplistic and limiting notion of when sharing power might make sense. By adding the price characteristic to electricity, then connected nanogrids can share power when their offered and bid prices are compatible. As with any normal economic transaction, both parties are better off (assuming they have correctly specified their price preferences).

Gateways between nanogrids have some economic cost to purchase and maintain. They also have some efficiency loss, for wire losses between nanogrids and for conversion if they are at different voltages). The purchaser of the gateway can ensure that there is a price difference between the selling and purchase price, so that it can be dedicated to covering these costs, ensuring that the system is fair. Such a price difference also inserts some "friction" in the system which should enhance stability.

B. *Developing countries*

Consider the example of an off-grid household in a developing country, with a car battery and a PV panel, and a number of devices of varying priority (lighting, TV, ….). This nanogrid can operate in isolation or could connect to adjacent houses and other structures, e.g. a school or clinic. A school will have days off, in which case its excess power can be readily sold to its neighbors. Any time a household has unexpected high demand, low demand, or equipment failure, the system can better serve the occupants than they could without any interconnection. Electricity production capacity expansion is also much more flexible with this system, with the easy sharing of any surplus power.

Now consider a village with dozens of nanogrids (and perhaps a few microgrids), interconnected in some haphazard fashion. In principle there could be a net flow across many "links" of the grid, with many nanogrids simultaneously buying and selling power on different "ports". The cost function of the transactions introduced by the price difference should help keep the amount of this that occurs to a manageable level. This raises the question of how the amount of power exchanged among the connected nanogrids should be determined. A central controller solution would impose costs, communication needs, and administrative burden, and be a potential single point of failure for the whole system. A much better approach is one that is fully distributed, with each nanogrid periodically reconsidering its selling and buying based on its own needs, quantities available or desired, and prices. This is an important research question.

C. *Communication standards*

Interoperation of nanogrids with each other and with the macrogrid, as well as optimal operation internally, all require some forms of communication across the gateways. Some nanogrid technologies are built on data or network communications methods, and so naturally have one available for internal use. For others, identifying a single standard for each for adding communications would be helpful. Data rates can be low; Internet Zero (IØ) [14][15] deserves consideration. For interconnecting grids, it seems unlikely that a single physical layer could be agreed on, but the number of different ones in use should be kept as few as possible. In addition to having some means of exchanging data, it is necessary for interoperability to have standard higher layer protocols. Even if communication within a nanogrid is different fro that between nanogrids, it would be helpful if they had common higher-level concepts to minimize the difficulty in creating gateways between such domains. This argues for creation of one or more "meta-standards" that define nanogrid behavior in the abstract, with each particular technology implementing it in its own way.

A key point is not to consider creating any standards for interoperation of products for functional purposes. There are already many standards for doing that and the difficulty of doing so would likely derail the process. Nanogrids need to be kept only to distributing power, so the communication should be limited to what is needed for that purpose. For functional communication, devices may be as likely to coordinate with devices on other nanogrids as on the one they are powered by, so the functional networks and the power distribution networks should be kept logically distinct.

VI. THE WAY FORWARD

Nanogrids will evolve on their own, but with active research and development, we can make better use of them. Some key steps in this are as follows.

A. *Better understand nanogrids*

It would be informative to have an estimate of national and global energy use that occurs in nanogrids. Today, it is most likely dominated by power used in vehicles, even keeping aside power used for actually driving wheels in electric and hybrid cars.

B. *Define a standard architecture*

Harmonization in the basic structure, common concepts ,and features, will enable greater interoperability between nanogrids, with microgrids, and with the macrogrid. Some nanogrid standards are still being defined, and others will only be so in future, so there is still time to drive some useful commonality.

Devices that connect to the nanogrid as energy users need to identify themselves to the central controller, and expose basic characteristics such as minimum and maximum power requirements, speed of changing demand on request, and consequences of forced demand reduction or cutoff. This is a candidate for a meta-standard, to specify how power levels are represented, an itemized defined list of "consequences", etc.

The standard architecture can also be used to selectively expose power consumption information about individual loads and the entire nanogrid. An example of this in the IP realm is the concept of a Power MIB [X], which is now being pursued in the IETF.

C. *Define gateways*

A single specification for nanogrid gateways can ensure maximum interoperability between them. The types of functionality needed will necessarily vary widely, so there will be ranges in the capability of gateways, and the features negotiated to be used for a given interconnection. The core specification will address only communication. The communication will include how prices are treated, how frequently conditions are renegotiated, and capacities of various parts of the systems. Related specifications will address physical-layer power distribution; these, will be diverse and evolve over time.

D. *Keep power and functionality separate*

When a communication mechanism exists in a nanogrid, it will be tempting to use it for functional purposes, but this should be resisted. Fundamentally, the relationship that devices have in how they are powered need not have any correlation to how they function. Devices may be on the same nanogrid but have no functional relationship, or may be tightly coupled but powered completely separately. This does not mean that data paths (as on USB or PoE) on the same wires cannot be used for functional purposes, but those should be separate mechanisms.

E. Identify promising applications

Companies that sell hardware for nanogrids have an interest in presenting them as most beneficial for energy saving purposes. It is necessary to have an independent assessment of applications and technologies, so that those considering using nanogrids can make the best decisions, and do so with confidence.

F. Demonstrate nanogrid interconnections

Assertions about the possibility of connecting nanogrids to usefully share power only go so far. Much more compelling will be actual case studies with detailed measurements about behavior and performance between and within grids. This will be most compelling in examples which are mostly or entirely off-grid, so that the electricity price varies significantly as real capacity limits are reached.

G. Bring nanogrids to the poor

Nanogrids have great promise for bringing basic electricity services to people who currently lack them. Deployment here for demonstration purposes could help clarify what this large population needs and wants from nanogrids, and any issues there may be in interconnecting them.

VII. SUMMARY

Nanogrids are already with us, and can be expected to grow significantly in number, usefulness, total energy distributed. They will enable some capabilities and energy savings not otherwise possible. They are highly complementary to top-down approaches, and a useful and effective way to introduce price-responsiveness. They need further research, development, and implementation.

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