Local Power Distribution with Nanogrids

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***Abstract*—Matching electricity demand to supply will be a growing challenge in the future. We argue for the need for further research into local power distribution with a focus on "nanogrids". We define a nanogrid as a small electricity domain with distinct voltage, price, reliability, quality, and administration. We seek to improve upon existing nanogrids (such as USB and PoE) by the addition of electricity price information to enable power distribution to be managed in a distributed bottom-up and fair manner to optimally match demand to supply, and to more easily and efficiently integrate local generation and storage. This approach, modeled on Internet principles, offers the possibility of moving to a less reliable utility grid, providing quality and reliability at the edge, and saving capital and energy. We illustrate the operation of a simple nanogrid driven by rules governing controller and load behavior in response to varying electricity availability from a renewable source.**

Keywords—Matching energy supply and demand; local power distribution; nanogrids.

I. Introduction

Matching electricity demand to supply is a growing challenge. On a large scale, this challenge is central to the emerging Smart Grid where demand will need to be managed to match intermittent renewable energy sources [16]. The Smart Grid offers the reporting and control mechanisms to enable matching such variable supply to demand at the large scale of grids. At a small scale, this challenge is central to systems of electrical equipment, or devices, where an overall electricity use budget must be met to maintain a desired battery life, remain within an available peak power budget, and/or minimize operational energy costs. A compelling example of a small-scale system where power control is critical is a village in a developing nation with local generation and/or storage of electricity. There may be different priorities for electricity use; refrigerators to store medicine (high priority), lighting and communications devices (medium priority), and entertainment devices (low priority). Matching demand to supply given priorities for electricity use is the challenge that we address in this paper.

Increasingly, buildings have multiple sources of power, both AC and DC, where each source may have different levels of availability (predictable or unpredictable) and cost. For example, a facility may have DC power that comes directly from solar panels on its roof that is highly intermittent and low marginal cost, and AC power that comes from the grid with predictable availability but at a higher (and, in the future, variable) cost.

The challenge of matching demand to supply can be met by combining communications with power distribution, so power consumers can communicate their demand and power suppliers can communicate their supply availability. We believe that electricity price – and the ability to communicate this price between suppliers and demand units at all scales – is central to the ability of making intelligent choices in when and how electricity is used. In this position paper, we address this challenge with the notion of a *nanogrid*. We will argue that limited nanogrids already exist and are widely deployed, but need further research and additional capabilities to fully realize their potential.

A nanogrid is a single voltage, price, reliability, quality, and administrative domain that can isolate implementation details within it and enable connections with other grids [19]. A nanogrid hides complexity and enables interoperability. A nanogrid may include electricity storage. The information and control architecture for interconnecting nanogrids should be independent of their internal grid architectures. Limited nanogrids are already common today in the form of USB-powered devices connected to a PC, Power over Ethernet (PoE) distribution systems, and the unmanaged electricity distribution systems in vehicles. Nanogrids enable a bottom-up approach to power distribution; an "Internet style" approach first advocated in [8]. Nanogrids were first described in a website posting in 2010 [18], in public presentations in 2011 [17] [14], and have been described in a magazine column [19]. The contributions of this position paper are to:

- Define the nanogrid concept and present examples of existing limited nanogrids
- Describe rules-based nanogrid operation
- Outline future research needed to realize the full potential of nanogrids

The rest of this paper is organized as follows. We first present a definition and description of a nanogrid, and then describe the origins and motivations. We review a number of examples of nanogrid technologies currently in use and discuss some implementation issues. Next, we briefly describe rule-based operation of nanogrids. We then describe a compelling example application of nanogrids to developing nations. Finally, we present our position on the way forward and summarize.

II. DEFINITION AND DESCRIPTION OF A NANOGRID

A nanogrid is a single domain for voltage, price, reliability, quality, and administration. Components of a nanogrid are a controller, loads, storage, and gateways. Electricity storage is optional but adds stability. Electricity sources such as local generation 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. Figure 1 is a schematic of a nanogrid showing the key components and their interconnection. Electricity and communications flow via the gateways. Communications with loads or across gateways may take place over the power cabling or out-of-band on other cabling or by wireless. Nanogrids implement power distribution only and not any functional aspects of the loads that connect to the nanogrid.

A nanogrid exists for any domain of distinct voltage, quality, and/or reliability. We call nanogrids that do not include communication with loads about power distribution "unmanaged." Nanogrids with power distribution communications we call "managed", and nanogrids that include a local price and the ability to buy and sell power over gateways we call "price managed". The remainder of the paper describes price managed nanogrids, which we will call "nanogrids" for convenience.

A. *Loads*

Loads in a nanogrid can be any electrical device. We expect that such devices will initially be most commonly in the range of 1 to 100 W in power demand, however there is no limit. Power use will vary in response to the function or use state of the devices. For example, a display may draw variable power across a small range of demand in a short time scale depending on what portion of the display is black at any given time and variable power across a large range of demand depending on its power state (on, off, or sleeping). The display may be able to reduce its brightness and/or area of active display during periods of high electricity price.

B. *Controller*

The core of a managed nanogrid is the controller, which has the abilities to a) control the level of power supplied to its loads, b) negotiate with other grids through gateways, c) set the local electricity price, and d) manage internal storage. The controller is the "authority" in a nanogrid. Loads request 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 can use this knowledge in decision making. Controllers can also have embedded preferences about management such as how much storage to try to maintain under different circumstances to enable minimum acceptable function wherever possible. We call such embedded preferences "rules" and will illustrate their operation later in this paper.

C. *Storage*

When storage is present in a nanogrid, the controller will store or withdraw energy as needed within the capabilities of

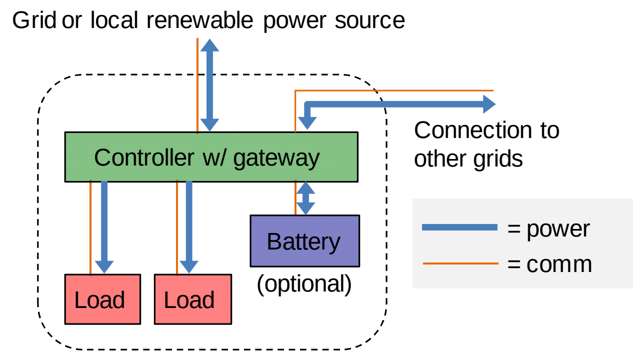

Fig. 1. Schematic of a nanogrid

the storage medium. A nanogrid may have storage and no loads; that is, storage does not exist independent of a nanogrid. The controller manages the storage – the storage does not have independent decision-making capacity, and no power connection to any other entity.

D. *Gateways*

Gateways can be one-way or two-way for power. Each gateway implements communications and power exchange. The power exchange will need to be defined for a variety of voltages and capacities; a challenge is to determine what the best sets of these is, but certainly the DC voltages already in common use today, including 5V, 12V, 24V, 48V, and 380V, are good candidates, as well as traditional AC voltages. The semantics of what is communicated across gateways – the upper layer protocol of nanogrid communications – must be common to all nanogrids. Defining this upper layer protocol, to create standard interfaces between nanogrids, is a key subject for future work. Gateway communication is further considered later in this paper.

The nanogrid does not "know" what is on the other side of a gateway beyond a common interface to exchange information on price, capacity, and availability. Minimizing communication is key to increasing security and privacy, and a stark difference between the distributed approach to power distribution and that implicit in many Smart Grid designs.

E. *Setting electricity price and operation of nanogrids*

The local price may be either the current price of electricity only, or it may include a time series forecast of future prices (with a one day time horizon likely to be most common). The forecast is not a guarantee, just a best effort guess. Each nanogrid has an internal local price for loads, as well as a buy and sell price offered for each gateway. A nanogrid uses price as a way for loads to express preferences about their relative importance. The local price may affect decisions to store or withdraw energy from storage. The controller may raise or lower the local price when supply and demand are not in balance, to move them closer to balance.

A nanogrid may have a power capacity limit, and it can raise the local price when this is neared. The price of power available through gateways may serve as a practical floor for the local price until such time as it is so expensive that switching to local storage makes more sense. Once the nanogrid is operating off of stored power, it will set the price to try to ensure that the storage is not exhausted before it recommences using external source power. The price set when using stored power can take into account the cost of the power eventually needed to replenish it, as well as losses into and out of storage.

Across gateways, grids can offer to sell power, offer to buy it, or both. When one grid wants to buy power at a price greater than or equal to that another grid wants to sell they may agree to exchange power. This way, the nanogrid can seek optimal behavior for a larger system comprised of many grids. To account for energy losses through gateways, in wires, and in possible voltage conversions and/or conversions between AC and DC, the grid buy and sell prices will usually be different. The actual price and supply/demand rules implemented in a nanogrid are internal to it, so they do not need to be commonly defined; only the gateway definitions and behavior need to be standard.

Gateway connections and loads may vary over time as connections are established and severed such as when a nanogrid is moved. The controller reassesses its situation each time an event occurs and adjusts its behavior as needed. Whether costs for exchanged electricity are actually paid in a monetary sense is not the point – there is no barrier to doing that, but within a single building there may not be a reason to do so. Both gateways at a connection can track accumulated electricity and costs, protecting nanogrids from malfunctioning or nefarious other grids. Any time that two grids cease to agree on price or power, they can stop exchanging power.

F. *Local Power Distribution*

The entire topic of managing the distribution of power within buildings we call *Local Power Distribution*. This term mirrors the term Local Area Network from communications. It covers microgrids, nanogrids, local sources, and loads. Technologies for Local Power Distribution are not part of the utility grid, and any building type is in scope: residential, commercial, industrial, vehicles, and so on.

III. ORIGINS OF THE NANOGRID

In this section we explore the origins of the nanogrid with respect to the grid (or "megagrid") and microgrids. We also describe the relationship of nanogrids with related work.

A. *Megagrid and microgrids*

The megagrid (the commonplace utility grid) is highly reliable with little direct coordination between sources and loads. That megagrids work as well as they do without coordination with loads is remarkable. Balancing the megagrid 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. Utility grids typically incorporate spinning reserve capacity that can be quickly brought on-line when needed to balance supply and demand. These and other ancillary services are expensive.

Microgrids create domains of electricity use separate from the megagrid. Features of microgrids [20][4][13][15] 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 both independently of ("islanded from") or connected to the megagrid
- Optimize multiple-output energy systems (for example, combined heat and power)
- Hide microgrid details from the megagrid

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. Microgrids have open problems related to electrical compatibility and control [13][15][3]. The emergence of electronic power converters may be critical to attaining efficiency and other advantages not possible through prior technology alternatives [3]. Our view is that many residential and commercial buildings will become microgrids over the next few decades, with multiple nanogrids and local generation [16]. At gateways between microgrids and the megagrid, building operators can choose to value carbon and/or other environmental externalities of grid power and incorporate this into the microgrid local price. All nanogrids which consume that power will then incorporate this into their local price.

B. *Why nanogrids*

The nanogrid concept arose from the need to meet several key needs/goals.

- Enable "plug-and-play" integration of local renewables (this is a US DOE goal [27]).
- Enable "plug-and-play" integration of local storage, and optimal management of the storage.
- Provide the correct local indication of electricity scarcity to each device.
- Support a layered architecture for communication among energy-using devices, to obtain the value that layering provides.
- Provide a network architecture that lends itself to scaling of complexity, as well as the power and reliability inherent in distributed control.
- Create a universal technology, to be applicable regardless of geography, building type, or income level, to drive down prices and drive up availability as much as possible.

The combination of these needs led to the nanogrid architecture that we describe in this paper.

While nanogrids can be AC, several features lend themselves to DC power. One is the existence today of standard managed power technologies (for example, PoE and

USB). Another is the fact that storage is inherently DC. A third key feature of DC is that it enables “Direct DC” – directly using locally generated renewable power for devices that are natively DC (or could be); this has been shown to save 5 to 13% of electricity in residential applications [6].

A nanogrid builds on many of the principles of microgrids with some key limitations; nanogrids provide only a single voltage and level of quality/reliability; they do not address systems with complex optimization such as combined heat and power; nanogrids do not contain power sources; they have only one entity that controls power distribution within it; and they exchange power with only adjacent grids.

C. *The LoCal project*

LoCal [8] was a project at University of California, Berkeley that explored how to interconnect electricity systems at various scales. The LoCal proposal for an Intelligent Power Switch (IPS) was a significant inspiration for the nanogrid concept. One difference between data networking (in the Internet) and “grid networking” is that in the former it is necessary to have a consistent architecture across the entire network to enable end-to-end connectivity. LoCal envisioned a hierarchy of IPSes in the network, eventually spanning the entire grid, analogous to the end-to-end connectivity of the Internet. In the nanogrid concept connectivity is only needed between adjacent grids as communication only extends to adjacent grids.

LoCal placed the IPS intermediate among loads, generation, and storage. In contrast, with nanogrids one controlling authority is tightly coupled to its loads and storage with the links between nanogrids much looser. The internal links of a nanogrid are very different than the external links. LoCal began from an overall concept that could eventually be applied to large-scale electricity systems and scaled down to specific implementations. Nanogrids start from existing technologies for local connectivity and explore how these can be connected to each other at increasingly large scales.

D. *Relationship to the Internet*

Many discussions of the “Smart Grid” observe how digital communications can help transform our electricity system. However, they generally take the structure of the grid as it is, and use technology to improve how it operates. An alternate approach is to model the actual structure of the electricity system on network architectures and principles [24][3]. LoCal and other projects [20][1] have the concept of “packetizing” electricity, much as data is packetized on the Internet. Nanogrids lack this explicitly, however the negotiated timing of changes in loads and associated exchanges of power provides a limited notion of blocks rather than a continuous flow of power. Using the Internet analogy for power distribution does not require packetizing electricity, however it does not preclude it.

The term “Nanogrids” had been previously used in [18] and [3], but in a very different context from our usage. The context of military needs for energy gave rise to the concept of “scalable energy networks” [24]. When local grids are connected to each other, and to “wide area grids”, the notion of the “intergrid” follows naturally as a “network of grids” [17][3].

IV. Existing Nanogrid Technologies

In this section we survey examples of existing nanogrids. The examples cover a range from minimal and unmanaged to highly capable and managed. One purpose of reviewing existing technologies is to understand how well the generic nanogrid architecture described previously in this paper maps to existing technologies. We also seek to derive common principles and terminology.

A. *Universal Serial Bus (USB)*

A USB hub and devices connected to it form a nanogrid. A USB port supplies power and if the connected device takes power it is a load. Multiple USB ports on the same PC or same hub are part of the same nanogrid. Unpowered USB hubs enable connecting more devices to a single port. A powered USB hub becomes its own nanogrid, independent (for power) from the upstream PC. Notebook PCs can operate on-grid or off-grid due to their local storage.

The original USB specification [26] provided for 2.5 W of power that connected devices could share (any device is 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. The USB Power Delivery Specification for USB 2.0 and 3.0, finalized late in 2012, raises the per-port power limit to 100 W [25]. When a USB master device goes to sleep it can provide a reduced amount of power to its connected devices.

B. *Power over Ethernet (PoE)*

IEEE 802 standards define how standard Ethernet cables can carry power. The latest version, 802.3at [9] provides for up to 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, using the Link Layer Discovery Protocol (LLDP) for devices to request additional power over a 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. The HDBaseT standard, for audio/video data, increases the power ceiling for Ethernet cables to 100 W [12].

For both USB and PoE, the general data communications part of the technology (which is their original purpose) is separate from the power distribution features, even as the same cabling is used for both.

C. UPAMD

The Universal Power Adapter for Mobile Devices (UPAMD, IEEE P1823) standards project defines a power delivery connection between a power adapter and power using devices in the 10 W to 240 W range [10]. The standard covers a 21 V DC feature, and optional features for additional voltages and distribution to multiple devices. UPAMD is exploring how to use communications to allocate power to devices.

D. EMerge

The EMerge Alliance has defined a technology to distribute 24 V DC power for use in commercial buildings [5]. It provides up to 100 W on each distribution channel. Lighting is a key application, but any device could be powered. A high-voltage version of EMerge uses 380 V DC and was originally designed with data centers in mind but can be applied in commercial buildings for lighting, DC power distribution, HVAC, and many other purposes.

E. Selected proprietary solutions

Nextek Power Systems sells devices that interface between the megagrid, local renewables, local storage, and AC and DC building loads (including the 24 V DC EMerge standard) [21]. These implement several interconnected (though unmanaged) nanogrids, and the Nextek hardware serves as a central controller, with several gateways. Some companies such as Redwood Systems [22] have technologies for distributing DC power and providing communications, also intended for commercial buildings. These systems begin with LED lighting but could be extended.

F. Vehicles

Many components of a car (such as lights, radio, etc.) are powered by the 12 V battery used to start the car and maintain its electrical stability. The cigarette lighter has long been a standard outlet in cars to plug in accessory devices. Modern cars have a significant amount of entertainment electronics, and increasingly provide Wi-Fi inside; these need high-speed communications wires, which may be able to also provide power. An increasing number of cars also have 115 V AC outlets; this is essentially a second nanogrid. With electric cars and plug-in hybrids, we will have many more road vehicles that connect intermittently to the grid. Cars today are unmanaged nanogrids.

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

G. High-reliability contexts

A variety of building types require higher reliability than the ordinary grid can deliver. These include data centers, communications facilities, and hospitals. Military facilities also require reliable power and can be highly mobile and dynamic with a great diversity of loads of very different scales (single person to aircraft carrier) that may want to interconnect and share power in ways not planned for in advance [24]. These can all be seen as examples of "resilient control systems" that are not only hardened to resist failures or threats, but also continue to operate as best they can in the face of adverse conditions in order to maximize the existence and quality of their functioning [23]. A characteristic of high-reliability IT devices, such as those in data centers, is the prevalence of multiple power supplies for individual devices supplied by different circuits. Managing this power distribution topology is much easier with nanogrids.

H. Off-grid households in developing nations

A large portion of humanity, about 1.3 billion people, lacks grid electricity for their homes [7][29]. 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. Section VII of this paper addresses developing nations.

V. Implementation of Nanogrids

Nanogrids take from microgrids their primary goals: making available power with diverse characteristics; better matching power supply to the needs of the devices being supplied; enabling distributed generation and storage; and energy efficiency opportunities. Nanogrids merit attention for energy efficiency research and policy to understand how they can be used and promoted where they do save energy. Nanogrids may also get increasing use for their other benefits (regardless of their energy impact) so it is worth making them as efficient as feasible. Energy efficiency will likely not be a primary reason for adoption of nanogrid technologies, so any efficiency gains will be "free". Nanogrids enable optimum use of price signals from the utility grid as they are introduced.

As nanogrids are already relatively inexpensive to purchase and install, they could see rapid adoption and deployment. This enables price reductions of components to make them even more accessible. USB is a primary example of a widely used technology for which components are inexpensive due to large production volumes.

A. Interconnecting nanogrids

Most nanogrids are connected to the megagrid at least some of the time (vehicles are mostly an exception, but plug-in vehicles may change this). Usually this is only for power, not communication, and usually power only flows into the nanogrid. If a nanogrid has access to non-dispatchable power (for example solar or wind), and all storage is full, then it can export any excess power, but this alone is a simplistic and limiting notion of when sharing power might make sense. By adding the price characteristic to nanogrid gateways, grids can exchange power any time when their offered and bid prices are compatible. As with any normal economic transaction, both parties are better off (assuming that they have correctly specified their price preferences). Without a concept of local price, this cannot be done.

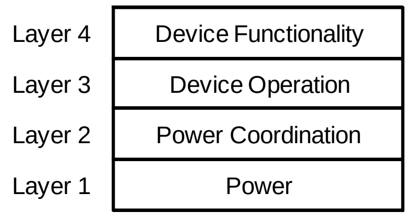

Fig. 2. Layered model of a nanogrid

Gateways between nanogrids have some economic cost to purchase and maintain. They also have some efficiency loss between nanogrids and for conversion if they are at different voltages. Gateways 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 and correct. Such a price difference also inserts friction into the system which should enhance stability.

B. Communication standards and layering

Interoperations of nanogrids with each other and with the megagrid all require communication across the gateways. Managed nanogrids also require communication between the controller and loads. Some nanogrid technologies are built on data or network communications methods, and so naturally have one available for internal use. For interconnecting grids it seems unlikely that a single physical layer could be agreed upon, but the number 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 from 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 internal behavior in the abstract, with each particular technology implementing it in its own way. A key point for nanogrids is not to consider creating any standards for interoperation of products for functional purposes. There are already many standards for this. Nanogrids need to be kept to power distribution only.

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. Figure 2 shows a layered model for nanogrids. The first layer is power distribution and is concerned with cabling, connectors, voltage levels, current, and other electrical characteristics. The second layer is the core nanogrid communications layer related to exchange of price, availability, and other power distribution information. In the third layer the device combines its functional goals with the price information to decide how to operate. The fourth layer is for functional coordination. The controller implements the first through third layers, and may reside inside of an entity that also implements the fourth layer. Devices can implement layers one through three (managed) or only the first layer (unmanaged).

VI. Rule-Based Operation of Nanogrids

Sources and loads have behaviors that are intrinsic to their nature. For example, a solar panel will have varying availability of electricity as a function of time of day, time of year, and local cloud cover. Loads will have varying demand as a function of their use and the current price of electricity. We envision that some loads may request electricity independently of price (for example, high priority refrigerators that are used to keep medicines cold) whereas others will adjust their demand to price (for example, lighting or cooling). A nanogrid controller is governed by rules. These rules determine the local price of electricity and when a battery should charge or discharge its stored electricity. The local price of electricity, as determined by controller rules, is the key to nanogrid operation. Local electricity price is used to modulate load demand in order to match the current electricity supply. Rules determine how effectively a nanogrid uses available electricity. For example, good rules can maintain battery charge for later use during temporary periods of insufficient external electricity supply. Poor rules may result in sub-optimal use of battery charge and the possibility that loads could be starved of needed electricity during temporary periods of insufficient electricity supply. Determining good rules is future work.

VII. Nanogrids and Developing nations

Consider the example of an off-grid household in a developing country with a car battery and a solar panel, and a number of devices of varying priority (such as lighting, refrigeration, communications devices, and so on). This nanogrid can operate in isolation or could connect to adjacent houses and other structures (for example, to a school, medical clinic, or local business). A school will have days off, during which its excess power can be sold to its neighbors; on school days the reverse may occur. A medical clinic may have devices with extremely high need for power continuity such as those providing critical life services, or refrigeration of vaccines and antibiotics. 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 interconnections. Electricity production capacity expansion is much more flexible with this system, allowing for the easy sharing of surplus power. Critically, nanogrids allow for the prioritization of electricity use during periods when electricity becomes scarce.

A village could have dozens of nanogrids (and perhaps a few microgrids) interconnected in an ad hoc manner as shown in Figure 3. There could often be power flow across many "links" of the grid, with many nanogrids simultaneously buying and selling power on different "ports". 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

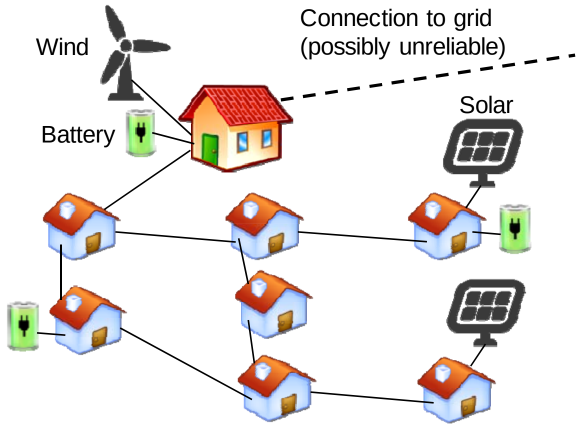

Fig. 3. A village-scale network of nanogrids

desired, and prices. While an ad hoc nanogrid is most common today, there are solutions with standard controllers, some for more critical applications like medical clinics [28].

Many have observed that the telecommunications infrastructure in some developing nations is not passing through the same technology stages as in industrialized countries, but instead, going from nothing to modern cellular-based mobile technology. This provides more and better services than the traditional land-line services could have provided. Nanogrids offer the same potential for power distribution technology. Rather than invest large amounts of money in traditional central-station generation facilities and high-capacity transmission and distribution systems, developing nations could rely mostly on distributed generation and low-capacity electricity exchange lines.

VIII. The Way Forward: Our Position

Nanogrids will continue to evolve on their own as people find them useful, but with an active research and development agenda we can make better use of them. Our position is that additional work is needed in the following areas.

A. Build nanogrid testbeds

An urgent near-term need is to build hardware platforms that fully implement nanogrid technology, both to show that it works by an existence proof, and to assess efficiency and control algorithms. A software platform is also needed to be able to test arbitrary networks of nanogrids, storage, and loads, to explore system behavior and how well different rules perform including key measures of energy used by loads, cost of energy used by loads, and energy wasted.

B. Understand use and capabilities of existing 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. This estimate should distinguish between managed and unmanaged nanogrids. It would be helpful to have a survey of all existing technologies which support communication about power distribution. In USB and PoE this is clearly differentiated from functional communication. In other technologies, it is grouped with functional communication but could be analyzed separately.

C. Define a standard nanogrid architecture

Harmonization in the basic structure, common concepts, and features can enable greater interoperability between nanogrids, with microgrids, and with the megagrid. Nanogrid standards are yet to be defined, so there is still time to drive necessary and useful commonality.

Devices that connect to a nanogrid 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. Devices also need to receive standard price signals. This information could be in a meta-standard, and then incorporated into individual technology standards for power distribution to individual loads as well as for gateways.

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 [2], which is now being pursued in the IETF [11].

D. 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 should address only communication. Communication will include how prices are treated, how frequently conditions are renegotiated, and the capacities of various parts of the systems. Related specifications will address physical-layer power distribution; these will be diverse and will evolve over time.

E. Keep power and functionality as separate layers

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 in USB or PoE) on the same wires cannot be used for functional purposes, but those should be separate mechanisms.

F. Identify promising applications

Companies that sell hardware for nanogrids have an interest in presenting them as highly beneficial for energy savings 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 can do so with confidence.

G. 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. Most nanogrids will likely be grid-connected most of the time.

H. Bring nanogrids to developing nations

Nanogrids hold great promise for bringing basic electricity services to people who 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.

IX. Summary

Nanogrids are already with us and can be expected to grow significantly in number, usefulness, and total energy distributed. They will enable some capabilities and energy savings not otherwise possible. They are highly complementary to top-down approaches and they are a useful and effective way to introduce price-responsiveness. Nanogrids isolate complexity to enable interoperability within and between nanogrids. Nanogrids need further research, development, implementation, and evaluation. They offer an opportunity for developing nations to "leap frog" past old power distribution technologies into a new technology. More research is needed.

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