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A Grid as Smart as the Internet

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ABSTRACT

A new era of electricity is dawning that combines the decarbonization of the grid with the extensive electrification of all sectors of society. A grid as smart as the internet is needed to harness the full potential of renewables, accommodate technology disruptions, embrace the rise of prosumers, and seamlessly integrate nano-, mini-, and micro-grids. The internet is built upon a layered architecture that facilitates technology innovations, and its intelligence is distributed throughout a hierarchy of networks. Fundamental differences between data flows and power flows are examined. The current operating paradigm of the grid is based on the conviction that a centralized grid operator is necessary to maintain instantaneous power balance on the grid. A new distributed paradigm can be realized by distributing this responsibility to sub-grids and requiring each sub-grid to maintain its net power balance. A grid as smart as the internet based on this new paradigm, as well as a hierarchical network structure and a layered architecture of operating principles, is presented.

1. Introduction

Global climate change, largely due to greenhouse gases from human burning of fossil fuels, is already taking place. The concentration of greenhouse gases (primarily carbon dioxide) in the atmosphere has increased to levels unprecedented on earth in about a million years. The world is currently 1 °C warmer than preindustrial levels. Greenhouse gases remain in the atmosphere unabated, causing the warming effect to be cumulative. Leaders from around the world collectively agreed in 2015 in Paris that human behavior-induced climate change is a threat to all of humanity and global action is needed to substantially reduce greenhouse gas emissions in an effort to limit the temperature increase in this century to 2 °C, while pursuing means to limit the increase to 1.5 °C. The world's leading climate scientists recently warned [1] that the half a degree difference between 1.5 and 2 °C will significantly worsen the risk of severe droughts, floods, extreme heat, and poverty for hundreds of millions of people, and that actions must commence immediately to limit the temperature rise to within 1.5 °C before the window of opportunity closes around 2030. Every citizen of the world in every profession has the responsibility to do whatever he or she can, in large or small measures, immediately and urgently, to combat global climate change in order to save humanity for future generations.

Economic development is accompanied by higher energy consumption. Improvement in living standards is propelled by the increased use of energy. Most of the world's population still lives in countries that are considered to be developing, where the average energy consumption per person is very low. In the next decade or so, billions of people—a large proportion of which are in Asia—will be lifted either from poverty or from low-income levels to mid-income levels. Global energy demand will rise. In its Sustainable Development Goals, the United Nations (UN) has explicitly recognized that ending poverty and building economic growth must go hand-in-hand with tackling climate change and environmental protection. To put it simply, the world will need more energy but less carbon.

The decarbonization of electricity by switching from fossil fuels to renewable and other non-fossil sources, coupled with the increased electrification of other sectors of the economy, is considered to be an effective pathway to sustainable development [2,3]. However, the introduction of new renewable sources fundamentally changes the characteristics of the electric energy system, commonly referred to as *the grid*. Wind and solar generation is best located in regions where the environmental conditions (i.e., wind

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speed, solar radiation) favor it. It possesses little economy of scale; hence, it is mostly deployed in a dispersed and distributed manner, and can be installed and used on the consumer's premises. As a result of these changes, the characteristics of the new electric grid will be more like those of the internet, where information, vis-à-vis energy, is generated and shared everywhere and anytime throughout the network. This apparent similarity has inspired some people to envision a future electric grid in which hundreds of millions of people produce their own energy from renewables, store it locally in batteries in their homes, offices, and factories, and then share it with others through the grid [4]. The internet is smart. Will the grid be as smart as the internet to facilitate the massive sharing of energy?

This paper addresses the following issues:

- Why would we like the grid to be as smart as the internet?
- What makes the internet smart?
- Why are previous attempts to make electric grids internet-like unsuccessful?
- How to make the grid as smart as the internet?

2. The future is electric

A new era of electricity is coming. The step-by-step decarbonization of electricity with renewables will provide humanity with more energy and less carbon, and will place the power sector in the vanguard of emissions reduction efforts. Further intensified electrification of other sectors of the economy will lead to a fast-track pathway to combat global climate change.

Government policies and technology advancements have made tremendous cost reductions in renewable energy. Data from 2017 shows that 179 countries have set renewable energy targets and 57 countries have set 100% renewable electricity targets [5]. At the 2019 UN Climate Action Summit, 77 countries and more than 100 cities committed to net-zero carbon emissions by 2050. Hopefully, other countries, including India, China, and the United States, will soon follow suit. China—the largest carbon emitter in the world—is well on the way to fulfilling the commitment of reaching at least 20% non-fossil energy by 2030. Although the United States—the second largest emitter—is walking away from the Paris Agreement under the Trump administration, many states and private sectors are nevertheless aggressively trying to meet the goals of Paris and beyond. For example, California signed a bill in 2018 mandating 60% of the state's electricity to be powered by renewable resources by 2030, while calling for a path toward 100% zero-carbon sources for electricity by 2045. The state of New York is pushing to reach 100% zero carbon five years earlier. Various government policies aiming at providing encouragement and incentives for renewable energy development and utilization have stimulated intensive research and development (R&D), technology innovation, and business entrepreneurship. The resulting technology advancements, economies of scale, and increasingly automated production processes have driven the cost of renewable energy down drastically.

Wind energy is currently one of the cheapest sources of electricity, and it is getting cheaper [6]. Progress in materials research has resulted in astonishing cost reduction in solar panels—more than 99% decline in 40 years, from 77 USD per watt in 1977 to 0.64 USD in 2017 [7]. The average installed cost of residential solar generation in the United States has dropped by 60% and that of utility-scale solar generation has dropped by 77% from 2010 to 2017 [8]. The costs of renewable power are forecasted to continue declining. Renewables accounted for two thirds of the new power added to the world's grids in 2017 (of which half is in China) [9], including both rich and poor countries. The share of generation from renewables may rise to become the world's main power source as early as 2040 [10].

At present, about a fifth of the world's total energy use goes through electricity and more than three quarters of the energy used by key non-power sectors (i.e., transport, buildings, and industry) comes from fossil fuels. Decarbonization of the power supply coupled with greater electrification of these sectors holds the potential to significantly reduce fossil fuel use and carbon emissions [2,3]. The transport sector presents the most sizeable near-term electrification opportunity. Electric vehicles (EVs) have progressed rapidly in the last couple of years and more than 3 million EVs are on the road worldwide, although the market share of EVs is still low. China alone added more than 500 000 EVs in 2017—a 72% increase over 2016—in addition to 370 000 electric buses and 250 million electric two-wheelers. The emergence of low-cost shared mobility services with autonomous (i.e., driverless) vehicles is expected to be predominately based on EVs. The International Energy Agency (IEA) forecasts that the number of EVs on the road could reach 125 million, or even as high as 220 million, in 2030 [11]. Buildings are already electrified to some extent. The industry sector, which is the biggest consumer of fossil fuels beyond power, is more difficult to electrify due to the heterogeneity of its users. Aggressive government policies, technology innovation, and business entrepreneurship, similar to the cases of renewables and EVs, hold the keys to drive down costs for further electrification of these sectors.

Conventional fossil fuel generation is controllable to supply fluctuating load demands on the grid. Variable renewable energy (VRE), which depends on wind and solar radiation, is intermittent, variable, and stochastic. The massive introduction of VRE is changing the landscape of the grid. A variety of new energy storage systems, including batteries, flywheels, compressed air, thermal storage, and hydrogen storage, are swiftly developed in recent years to smooth out the variability of renewables and to assist in the instantaneous power balance required by the grid. In particular, battery technologies have advanced tremendously, thanks to technology innovations and market expansion due a large extent to the demand of batteries for EVs. Battery costs have decreased by more than a factor of four from 2010 to 2016 [12]. Batteries can be deployed both on the grid and at individual consumer premises. Large-scale installation of batteries in front of the meter assists grid operators in maintaining power balance and a variety of other applications. Local solar panels and batteries behind the meter, on the other hand, may lead to grid defection, leaving less controllability for grid operators. From the grid perspective, coupling battery storage with renewable generation is a weak substitute for conventional fossil fuel plants [13]. The magnitude and quality that are required solely of energy storage systems to accommodate fast-growing levels of VRE are deemed to be technically and economically exorbitant.

Another option to help deal with the variability of renewable generation is to shift consumption to other periods when supply is more abundant, such as when the sun shines and the wind blows. This kind of *demand response* can be considered as a virtual energy storage system, where customers' energy demand is used as "storage." Digital connectivity allows appliances and equipment (e.g., smart home appliances, smart thermostats, building energy management systems, smart industry boilers, etc.) to be monitored and controlled continuously in order to shape demand to optimally match it with available supply. Greater automation, the diffusion of internet-of-Things (IoT) devices in the residential and commercial sectors, and higher deployment of EVs and smart charging systems will expand the demand response capability. Some estimates reckon that 20% of electricity consumption in 2040 will be technically available for demand response [14].

For over 100 years, since Thomas Edison lit up the homes in New York, the grid is delivering electricity to 6 billion people every day to enjoy the economic benefits and opportunities.

For the remaining 1 billion people on the planet today who lack electricity, most of whom are very poor and live in remote villages, the cost of connections is prohibitive and their governments are too poor to subsidize them. The rise of new technologies in the last decade, coupled with the emergence of private-sector entrepreneurship, has radically changed the economics of energy delivery to remote rural dwellers, allowing poorer and more remote people to have access to electricity faster and cheaper than has previously been possible. As mentioned earlier, the colossal drop in the costs of solar panels and batteries has spurred the localized generation and storage of electricity in homes or communities. Other technological mega-trends, such as more energy-efficient appliances (e.g., light-emitting diode (LED) lighting and mobile phones), the IoT for remote monitoring and servicing, and mobile money, have enabled entrepreneurs to provide viable energy services, such as selling generation/storage kits that range from a few watts to a couple of hundred watts, commercialized through the pay-as-you-go (PAYG) business model. An increasing number of entrepreneurs are actively testing a range of business models and helping to move renewable-based *mini-grid* sector to maturity. In India alone, more than 200 mini-grids were installed during 2016–2017. Through the deployment of either off-grid solar systems or renewable-based mini-grids, these distributed renewables for energy access (DREA) systems are providing electricity access to more than 360 million people worldwide [5,15].

The combined demand for electricity access in developing countries and for further electrification for emission reduction in developed countries could result in a staggering 60%–90% global growth in electricity by 2040 [3]. This is happening at a time when the electrical energy system itself is experiencing its most dramatic transformation since its creation more than a century ago. Major changes include:

(1) **Increasing share of VRE.** The more successful decarbonization of the grid is, the more electrification will come, resulting in more global carbon reduction. Grid operation must endeavor to accommodate a continually increasing share of VRE, and increasingly improve its utilization of VRE.

(2) **Rise of prosumers.** Today, residential customers own about one third of global solar photovoltaic (PV) capacity. Battery storage will likely be similar. This continuing trend has two implications: First, there will be thousands or even millions of small-generation sources that are dispersed and distributed throughout the system; second, users of the grid will be both producers and consumers, or will become *prosumers.*

(3) **Intelligent periphery.** In the digital era, data, analytics, and connectivity are abundantly available to prosumers at the *periphery* of the grid (i.e., distribution system and beyond) to intelligently schedule, manage, and control their own variable renewable generation, battery storage systems, EV charging, various demand response systems, and so forth. Controllability and intelligence are no longer the monopoly of grid operators.

(4) **Proliferation of nano-, mini-, and micro-grids.** Micro-grids that are largely self-sufficient have become popular [16]. Renewable-based mini-grids and off-grid nano-grids (with combined solar and battery) in the developing countries are mushrooming. At the same time, an increasing amount of grid defection of prosumers in developed countries who possess their own solar and battery storage systems is threatening the survival of power companies (the so-called "utility death spiral").

(5) **Fast pace of technology innovation.** Explosive advancements of solar PV and battery technologies in recent years are hard-pressed on conventional grid operations. More new and innovative technologies, some of which will be disruptive, will emerge at some point in the future. Grid operation must take full and timely advantage of available innovations.

The physical composition and characteristics of the grid are changing significantly, especially on the periphery [17]. But the operating paradigm of the grid remains unchanged. The operating principles, control architecture, and basic tools that are used for grid operation today were developed in the middle of the 20th century, during the last great grid expansion. Intelligence was enhanced in control centers when the first generation of digital computers came along. It is a tall order to ask the same operating paradigm to work in a new and different environment.

How well is the grid coping with the changes so far? Let us first look at how well it handles the integration of VRE into the grid. In 2016, China—the country with the largest installed VRE capacity in the world—had much more solar and wind capacity in terms of percentage (13.7%) than in terms of the energy it generated (5.3%). The United States—the second largest country in VRE installation—was slightly better (10.7% in capacity and 6.9% in energy) [18]. These numbers indicate that the utilization (i.e., energy generated) of the VRE asset (i.e., capacity) is lower than the average of today's grid (which consists of mostly a conventional base and peaking units). The data from Ref. [19], summarized in Table 1, is even more telling, as it shows that the utilization of wind energy in terms of the capacity factor (i.e., percentage of energy output to what could have generated if available around the clock) worldwide is fairly low and does not improve with greater capacity.

It is common knowledge in grid operation that VRE resources are frequently subject to curtailment due to constraints imposed by the grid [20–22]. Curtailment rate is defined as the percentage of energy curtailed to the energy generated. The curtailment rate of wind, for example, could be 10% or more, which means that tens of terawatt hours of energy are wasted annually. These constraints are brought about by the conventional grid operation protocols, even in cases where the transmission capacity is adequately sized. The grid was built to facilitate the transmission of energy from sources to consumers. In the era of VRE, the grid is no longer an enabler; it becomes a blocker.

The electric grid is considered to be the greatest invention of the last century, while the internet is the greatest innovation of this century. The internet is smart and can readily accommodate fast-changing landscapes of continuous disruptive information revolutions. In the new era of electricity, we would like the grid to be as smart as the internet! A grid as smart as the internet should be able to harness the full potential of renewables, incorporate technology innovations, embrace the rise of prosumers, and integrate nano-, mini-, and micro-grids.

3. The internet

To the users of the grid and the internet, both networks are ubiquitous (available everywhere and all the time) and heterogeneous (passing through any form of energy/data). The internet is smarter because of the way the intelligence is deployed.

3.1. Distributed intelligence

Any form of data—text, voice, or video—is transmitted through the internet without central control or coordinating facilities, relying solely on the endpoints of transmissions at local nodes that handle the processing to complete the job. There is no extended

Table 1
Wind energy capacity and capacity factor.

Country/region	Wind capacity (GW)	Capacity factor (%)
United States	82.2	32.0
European Union	153.0	22.5
China	168.7	16.5

global reach by a single authority. Intelligence is distributed throughout the network and the responsibility of ensuring successful transmission—as well as data integrity, reliability, and authentication—is shared among the nodes. Distributed intelligence and decentralized control render the internet resilient to disturbances and disruptions. The complex system is made to work flawlessly and efficiently by the design of the network structure and a layered architecture of operational protocols [23,24].

3.2. Internet structure: A hierarchy of sub-networks

To understand the structure of the internet, let us take a simple example: User A in Tianjin wants to send an e-mail to User B in San Francisco (Fig. 1). User A's computer is connected to a local area network (LAN) and her e-mail is served by a local internet service provider (ISP) in China (Fig. 2). The e-mail may have to hop through a few intermediate points in the ISP's backbone network (e.g., local ISP to regional ISP) to reach a network service provider (NSP) of a large international network of the global internet; similarly for User B. But User A's and User B's ISPs may not belong to the same NSP network. The e-mail will have to exchange through a network access point (NAP) between the two NSP backbone networks. The point-to-point path along which the e-mail travels can be traced from A's computer in Tianjin to an LAN, an ISP (possibly more intermediate points), an NSP (or more points in between), an NAP, another NSP (or more points in between), another ISP (or more points in between), another LAN and finally to B's computer in San Francisco. The internet is a network of (sub-)networks structured in a hierarchical manner with a number of tiers. At the top is the global internet, followed by several tiers, including NSP backbones, ISP backbones, and so forth, LANs or users at the bottom.

3.3. Routers

The e-mail is routed in the internet through a number of *routers*. Routers are usually used to connect different networks. An ISP and NSP may have several routers as part of their backbone networks. The logical view of the internet is, therefore, a network of routers arranged in a hierarchy. A router is a specialized computer that directs data traffic. Each router has the knowledge of its own network and of all the sub-networks below it. When the e-mail arrives at a router, it examines the recipient's address and sends it to the next correct router according to a simple rule: If it is within its own sub-networks, it will be sent to the sub-network router; otherwise, it will be sent to a default router, which is usually one up in the hierarchy and has a larger set of sub-networks.

Since each router is associated with a sub-network to which it belongs and over which it holds responsibility, an alternative view of the path of data transmission in terms of sub-networks, which will be useful in Sections 4 and 5, is provided here. User A's computer is connected to the router of an LAN. When it is connected to the internet via an ISP router, it becomes part of the ISP network, and so on. Therefore, instead of tracing the e-mail from node to node (i.e., from router to router) in the internet, we may say that the e-mail moves from network to network. The e-mail travels from an LAN in Tianjin, to a Chinese ISP network containing the LAN, to an NSP network containing the ISP, to an NAP in the global internet, to another NSP network, to another ISP network in the United States, and finally to the LAN in San Francisco. The path of the e-mail, up and down the hierarchy of sub-networks, depends on the locations of the users and the sub-networks they belong to.

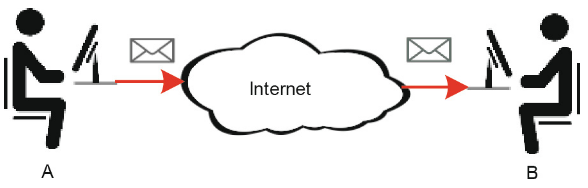

Fig. 1. An example of sending an e-mail through the internet.

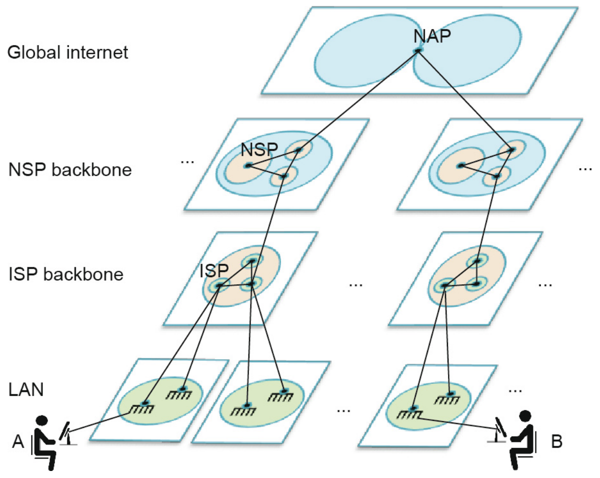

Fig. 2. The structure of the internet. NAP: network access point; NSP: network service provider.

3.4. Layered internet architecture

The e-mail from User A to User B must be translated from text into electronic signals, routed through the internet, and translated back into text. The information exchanged between routers is governed by rules and conventions that are set out in *communication protocol* specifications. In modern design, protocols are layered to form a protocol stack. *Layering* is a design principle that divides the design task into smaller steps, each of which accomplishes a specific subtask and interacts with other subtasks only in a small number of well-defined ways. It allows the decomposition of a single and complex task into simpler, clear, and cooperating subtasks. Layering is also a functional decomposition; each layer solves a distinct class of communication problems.

The International Organization for Standardization defines seven layers of networking protocols, called Open System Interconnection (OSI) reference model, which can be simplified into four layers, as shown in Fig. 3. The simplified version roughly corresponds to the protocol stack used on the internet known as the Transmission Control Protocol/Internet Protocol (TCP/IP) stack. The functions of the four layers are briefly described below:

- **Application layer.** Users interact with the application layer. Electronic mail (Simple Mail Transfer Protocol, SMTP) is one of the internet applications. Others include World Wide Web (Hypertext Transfer Protocol, HTTP) and file transfer (File Transfer Protocol, FTP). The application program passes the message to the transport layer for delivery.
- **Transport layer.** A message is usually divided into smaller packets, which are sent individually along with a destination address. The transport layer ensures that packets arrive without error and in sequence.
- **Network layer.** The network layer handles communications between machines. The packets are encapsulated in datagrams. A routing algorithm is used to determine whether the datagram should be delivered directly or sent to a router.
- **Physical layer.** The physical layer takes care of turning packets containing text into electronic signals and transmitting them over the communication channel.

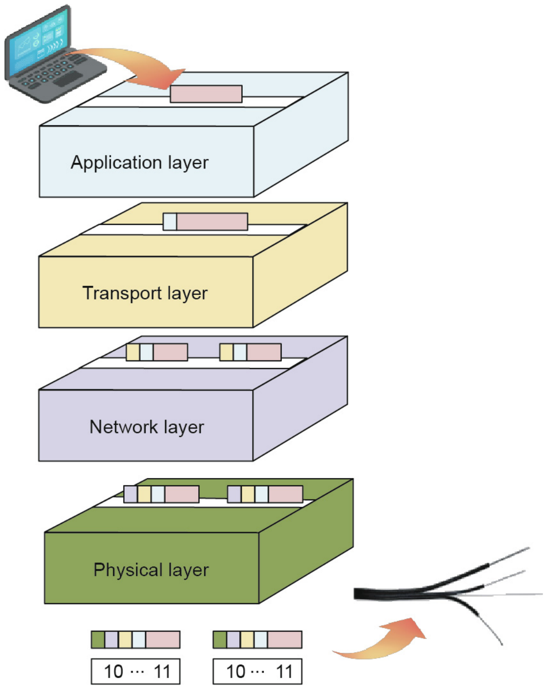

Fig. 3. Transmission Control Protocol/Internet Protocol (TCP/IP) stack.

The message—in this case, the e-mail—starts at the top of the protocol stack on the sender's computer and works its way downward (Fig. 3). An upper layer uses the functions available in the next layer and instructs the next layer what to do. The instruction is coded as a header added to the front of the message. Each layer adds a header on the way down. This process reverses on the receiving end. Each layer reads and interprets the instruction from the header and moves the message up or down after stripping the header intended for this layer from the message. Fig. 4 shows another example of the paths of an e-mail up and down the protocol stacks with two intermediate routers. Here, it is assumed that router D is the main server of the ISP and performs the store-and-forward function.

The internet is smart because the layered architecture provides division of labor and the distributed control empowers sharing of responsibility. The responsibility of sending a message from A to B is shared by a number of routers along the path. The required intelligence of each router is simple and specific, i.e., forwarding the message to the next recipient correctly. Functional decomposition in a layered architecture makes it possible for new applications or functions to be added by utilizing and configuring existing lower layer functions. Innovation becomes more readily achievable. Distributed control and layered architecture also make the internet resilient to disturbance and adaptable to technology advancement.

4. Data flow and power flow

Previous attempts to make the grid internet-like have focused on the role of the router in the internet as a "switch" in passing incoming "packets" to the next router [25–28]. A so-called "energy router" has been developed, with the help of modern power electronics, to direct or limit the power flow from a micro-grid or prosumer to the grid [26]. A different "energy router" uses alternating current (AC)/direct current (DC)/AC converters to regulate the power flow [27,28], taking advantage of the fact that power electronic circuits have better control of the power flow in the DC portion of the device, and essentially changing an AC grid into many hybrid AC–DC–AC sub-grids. All of these efforts are laudable and contribute to the advancement of power system technologies; however, they fall short of making the grid internet-like. We shall examine the underlying physics that makes data flows on the internet different from power flows on the grid.

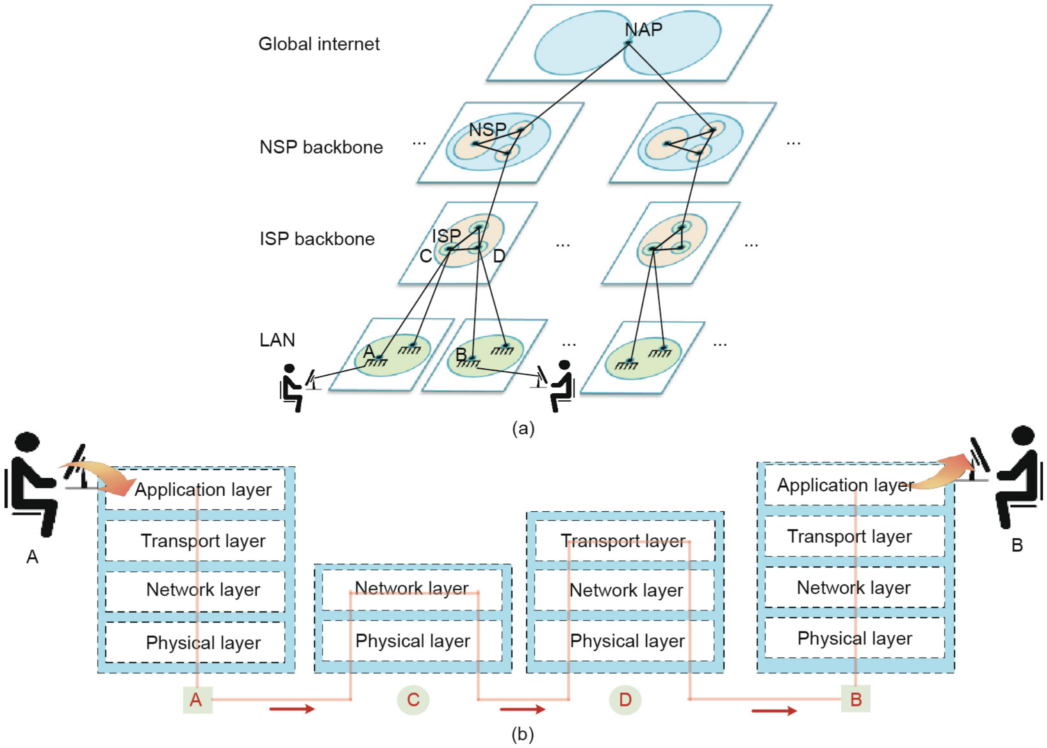

Fig. 4. An example of the data flow path (a) in the network structure and (b) in the protocol stacks.

4.1. Data flow

Voice, video, and other data signals are typically superimposed on a wave of some kind suitable for transmission over the chosen medium [29]. In communication networks, a physical *medium* is the transmission path over which a signal propagates or data flows. Many different types of communication media—wired or wireless—are used, including phone lines, cables, optical fibers, microwaves, and radio. A high-frequency sine wave is usually used as a carrier wave, but it can be DC or pulse chain depending on the application. In modern radio communications, such as orthogonal frequency-division multiplexing (OFDM) or code-division multiple access (CDMA), multiple or a spread of carrier waves of various frequencies are used. The carrier wave, be it electromagnetic, optical, or radio, involves the physical movement of electrons or photons. The process of modifying the carrier wave to carry signals from the transmitter is called *modulation*. At the receiving end, signals are recovered through *demodulation*. Modulation is important to transfer signals over long distances, since it is not possible to send low-frequency signals for longer distances. Modulated waves in communications can be considered as adding data flows onto the flow of electrons or photons of the carrier wave.

High-capacity communication media can be divided into distinct segments (i.e., bandwidths) for non-overlapping modulated carrier waves, which can then be leased to and operated independently by different companies. Moreover, multiple signals are usually combined into one signal over a shared medium for transmission. This process is called multiplexing. Multiplexing divides a communication channel further into several logical channels through frequency division, time division, or others, and allots each one to a different and independent set of data flows. Multiple transmitters and receivers can share a common medium, resulting in multiple-access channels in communications.

In summary, data flows are added to the flows of electrons or photons in communication media and can be directed to flow from one node to another node (or alternatively from one sub-network to another sub-network) in a communication network. Take the example shown in Fig. 4: The data generated in A is sent to B through intermediate routers, that is, from A to C, C to D, and D to B.

4.2. Power flow

Power is carried directly by electrons in the power flow [30]. More power means moving more electrons. The flow of power must obey physical laws—that is, Kirchhoff's and Ohm's laws. These physical laws can be summarized as the requirement that power must be balanced at all times and everywhere on the grid. Any addition or reduction of consumption of electric power must be accompanied simultaneously by the addition or reduction of generation somewhere on the grid. The distribution of power flows on the grid is the consequence of the physics of power balance. Any change in the supply and demand of electricity will result in a redistribution of power flows in the interconnected grid. From a technical perspective, one learns from the first course on power systems that power flows on the grid are calculated mathematically after solving the so-called power flow (or load flow) equations, which are the mathematical manifestation of the fact that real and reactive power must be balanced at each node of the grid. The power flow equations are derived from Ohm's law and from Kirchhoff's current and voltage laws.

It should be pointed out that in an AC power system, which is the grid we have today, the power includes both real (or active) and reactive powers. The real power is the average power that is generated or consumed. The reactive power is associated with voltage: Sufficient reactive power is necessary to maintain a desired voltage level. Moreover, power must be balanced in both steady states and transients during grid operation. A sudden change (i.e., disturbance) of power balance on the grid will cause the system to move to a new equilibrium of power balance. During the transient, no device for overload protection should trigger further disruption to the grid operation (such as a blackout). Power system *stability* refers to the ability of the grid to continuously maintain the power balance after a disturbance without causing overload or other abnormal conditions. In the following discussion, for brevity, the term "power" is used loosely to cover both real and reactive powers, while "power balance" is used to cover both steady states and transients.

As power must be balanced anywhere on the grid, for any sub-grid or area of the grid, the net power—counting the power flowing into (import) and out of (export) all lines crossing the boundary of the sub-grid—must be balanced. Conversely, if the net power is balanced on any of the sub-grids of the grid whose union covers the whole grid, power will be balanced on the whole grid.

Power cannot be directed from one node to another node, as data flows on the internet. Nevertheless, it is logically possible to trace the power flowing from generation to consumption through sub-grids, just as data flows can be traced through sub-networks, as described in Section 3.2. For example, suppose A sells power to B, where A and B are assumed to be in the same distribution substation, as shown in Fig. 5. The additional power from A to B represents a change in power balance, which will affect power flows on the parts of the grid that are connected to both A and B, i.e., the sub-grid of the distribution substation. The sub-grids to which A and B belong are defined as A and B, respectively, and are also the sub-grids of substation D. Let us assume that an additional sub-grid C is defined (see Section 5.2 for its selection) and attempt to trace out the sub-grids that are affected by the change of power flows. Since (sub-grid) A must keep its net power balance, the extra power from A must export to C, where C is the sub-grid of the feeder containing A in this example. Similarly, the extra power import to C must export to D in order for C to maintain its net power balance. D can maintain its power balance since B will consume the extra power from C, and both C and B are inside D. Of course, all of these power flows occur simultaneously and instantaneously.

5. Come to grids with intelligent periphery (GRIPs)

Energy management systems (EMSs), which are placed on high-voltage transmission systems covering hundreds of generators and

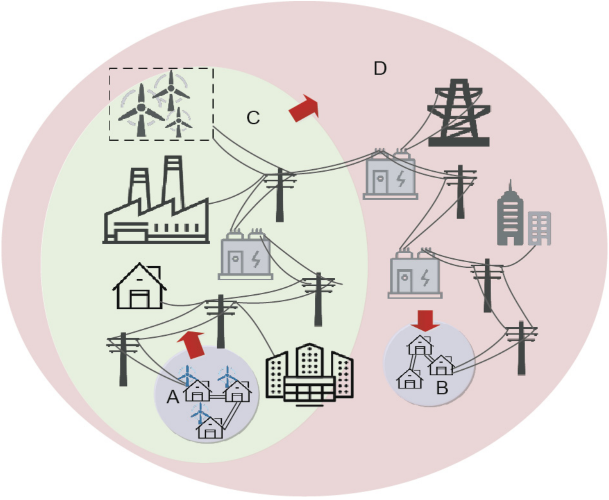

Fig. 5. Power flows from A to B.

substations, have been tremendously successful for decades in managing and controlling power systems to ensure their economical and reliable operation [31]. Extending this system, along with its underlying centralized operating paradigm, to distribution systems and beyond for thousands and millions of prosumers in future grids will stretch the limit to the point of being inefficient, unwise, and untenable. A recent study has concluded that, as the future grid becomes ever more complex, its reliability and resilience will be under tremendous stress if the current centralized operating paradigm continues [32]. The internet has demonstrated that distributed intelligence and decentralized control provide the most effective means to enhance the reliability and resilience of the system. A new operating paradigm of the grid with distributed intelligence and responsibility sharing is developed. A grid with intelligent periphery (GRIP) that makes the grid as smart as the internet by empowering the periphery of the grid to embrace the new operating paradigm is proposed [33,34]. GRIP focuses on the periphery and requires no scrapping of the successful EMS or the practices of grid operation of the transmission system that are functioning well, only to make them simpler (without the responsibility for the periphery). Nevertheless, future transmission systems have the freedom to evolve into more decentralized operation consistent with the new paradigm.

5.1. Distributed intelligence

The conventional operating paradigm leaves the fundamental responsibility of system operation, i.e., maintaining instantaneous power balance without overload and abnormal conditions of the whole grid, to a single centralized decision-maker: the grid operator. As noted in Section 4, power is balanced (with no overload and abnormal conditions) on the grid if and only if the net power is balanced (with no overload and abnormal conditions) on any of the sub-grids of the grid. The latter principle can be used as the foundation of a new distributed operating paradigm for the future grid.

Let us call a connected sub-grid of the grid, consisting of a cluster of prosumers with the intelligence to manage and control its net power balance, a *cluster*. With this definition, all of the following are examples of clusters:

- An interconnected transmission system with an independent system operator (ISO) operating an EMS to control the generation and consumption of its members in its defined jurisdiction;
- A transmission company or authority with EMS operating as a “control area” [35];
- A distribution company that has a modern distribution automation system to control power flows and voltage regulation (i.e., reactive power flows) on feeders and laterals and/or an advanced metering infrastructure (AMI) system to control customer loads;
- A micro-grid, mini-grid, or nano-grid;
- A smart community with its own EMS can be made into a cluster by adding the capability of managing and controlling its net power balance;
- A smart building with a building EMS can be made into a cluster by adding the capability of managing and controlling its net power balance;
- A smart home can also be made into a cluster by adding the capability of managing and controlling its net power balance using the smart meter;
- An aggregator can sign up a group of smart homes, smart buildings, smart communities, and micro-grids on the same distribution company to form a cluster by managing and controlling the power generation and consumption of the aggregation.

5.2. GRIP structure: A hierarchy of clusters

Two clusters cannot partially overlap because, if they do, none of them can manage their own net power balance. Therefore, two clusters are either non-overlapping or one is completely contained inside the other, just like an LAN is viewed as being inside an ISP sub-network of the internet (Fig. 2). A cluster may contain many clusters or none at all. A cluster that is itself part of a larger cluster may contain several clusters. This leads to a natural hierarchy of clusters arranged in tiers (Fig. 6). At the top of the hierarchy is the whole interconnected grid. One tier below could be a power authority, or a company with its own EMS operated as a “control area” in the interconnection. The bottom tier could be a smart home.

Let us revisit the example in Fig. 5, where A sells power to B and A, B, C, and D are all clusters. We will view the path of transaction in terms of power flow in clusters; more in tune with the perspective of data flows through a number of sub-networks associated with internet routers, as described in Section 3.3. Cluster A sees no extra power demand inside the cluster to balance the additional power generated; it exports (sends) the power to the cluster it is connected to that is one tier above—namely, cluster C. Similarly, the extra power to C is sent to D. The extra demand of B, which is inside cluster D, now balances off the extra power flowing in from C to D. The path of power flow is from A to C, C to D, and D to B. The task of managing the transfer of additional power from A to B is therefore distributed among a set of clusters; each sends the power either to the cluster one tier up in the hierarchy or to the receiver, if it is inside the cluster. Physically, A generates additional power and B simultaneously takes the same amount of power. As long as all clusters—A, B, C, and D—maintain net power balance, the transfer of power happens instantaneously.

The responsibility of maintaining the power balance of the grid is thus shared among the clusters that are affected; each has the responsibility of maintaining its own net power balance. Fig. 5 is redrawn in Fig. 7 to show the path of power flows in the hierarchy of clusters.

5.3. Energy router or cluster EMS

A cluster must have the intelligence to manage and control its net power balance. The energy management system of a cluster (CEMS), consisting of all necessary hardware and software to manage and control its net power balance, is equivalent to a router in the internet and can legitimately be called the energy router (E-router) in GRIP. An E-router, or CEMS, must have sensors to monitor power flows across the boundary of the cluster; power-conditioning devices (e.g., current limiters) to control the power

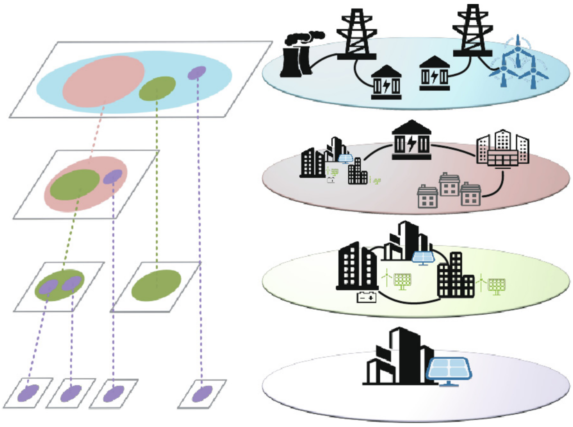

Fig. 6. The nested hierarchy of clusters.

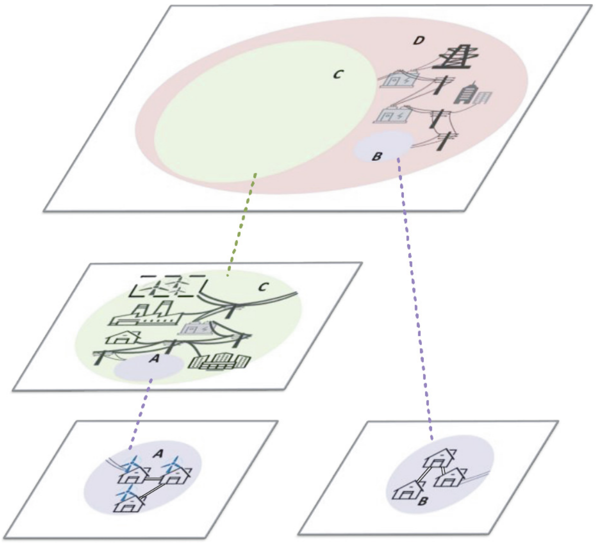

Fig. 7. Power delivery from A to B in the hierarchy of clusters.

flows; and information and communication technology (ICT) capability to manage generation and load—as well as the power flow—in the cluster.

5.4. Layered architecture of GRIP

A layered architecture of GRIP consisting of three layers—namely, market layer, scheduling layer, and balancing layer—is proposed (Fig. 8). Users of the grid—that is, prosumers—interact with the electricity market (sometimes called the power market) to share or trade electricity. The transaction must be scheduled and realized physically on the grid and the net power of the cluster must be balanced at all times.

(1) **Market layer.** Various forms of day-ahead, hour-ahead, real-time, and other types of electricity markets are operating under different rules and regulations in different countries and regions. Bilateral trading is the simplest form of market activity for energy sharing that can be accommodated in any market. Physical realizability may require a more general multilateral trading scheme [36]. Multilateral trading has been successfully implemented in an interconnected grid with five regional grids [37]. Modern blockchain technology, which provides an open and distributed ledger, may be gainfully employed to facilitate multilateral trading. The trading of electricity in the market must be realizable for implementation in the scheduling layer. Off-line analysis is used to translate cluster operating limits into constraints on acceptable transactions the clusters can engage in. For clusters on the distribution system, where the networks are mostly radial and the limits are line loading and allowable voltage bands, this may be relatively simple, compared to the heavily meshed transmission system. For complex transmission systems, time-tested standard protocols for control-area operation can be used.

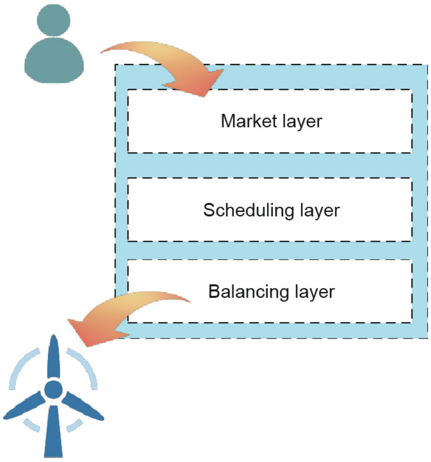

Fig. 8. Layered architecture of GRIP.

(2) **Scheduling layer.** A prosumer may participate in one or more of the day-ahead, hour-ahead, and real-time markets to maximize his/her benefit. Preparation work for scheduling must be done in advance to ensure, first of all, that the cluster has the ability to maintain net power balance at the time of execution of the transaction. Since unexpected events or disturbances, such as outages of generation or lines, happen all the time on the grid, the cluster must have the ability to withstand and have sufficient *reserve* available to fill in power imbalance caused by any credible disturbance in the cluster. A cluster's reserve is the additional controllable generation or load that is instantly available to compensate for the imbalance caused by the disturbance. The ability to withstand disturbances is called *security* in power system terminology. For a cluster with multiple generation and consumption, a *dispatch* of supply and demand may be conducted to share the resources in the most efficient and economic manner. A comprehensive tool for the scheduling function, called *risk-limiting dispatch* (RLD), which takes scheduling, dispatch, security, and economic considerations into account, is proposed [38,39]. RLD is built on a multi-stage stochastic optimization framework (Fig. 9) and has the following features:

- The stages correspond to the scheduling stages of the markets, i.e., day-ahead, hour-ahead, real-time, and so forth.
- Stochastic nature of VRE, other types of generation, and loads is considered.
- The control variables are the schedulable and dispatchable generation and demand in the cluster.
- The allowed terminal states are restricted to those states whose risk of not achieving net power balance is limited to an acceptable level (similar to risk management in the banking sector).
- Security constraints are imposed on cluster operation.
- The objective function of the optimization is the economic benefit of the cluster.

The symbols used in Fig. 9 are defined in Table 2.

RLD is thus an evolutionary extension of the long list of traditional power system operational tools, including economic dispatch, unit commitment, optimal power flow, security-constrained economic dispatch, stochastic optimal power flow, and so forth, adapted for the operation of the future grid. The adaptation of RLD by existing EMSs on the transmission system can be gradual and incremental, but simpler versions of the methodology can be developed and implemented readily in smaller clusters on the distribution system and beyond.

(3) **Balancing layer.** The scheduling layer ensures that the net power of the cluster can be balanced within the time-step of the dispatch, which may be seconds or less. Deviations from the scheduled power balance within the time-step, due to fluctuations either

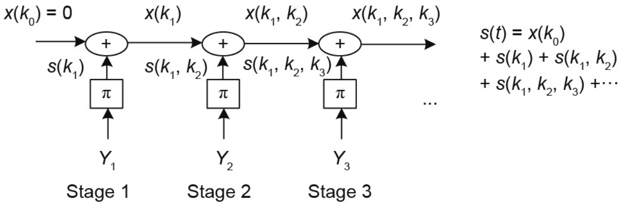

Fig. 9. Multi-stage stochastic optimization framework of RLD (represented by π).

Table 2
Symbols used in Fig. 9.

Symbol	Description
$Y_1, Y_2, Y_3, \ldots$	Available information at each stage
$k_0, k_1, k_2, k_3, \ldots$	Initial stage, stage 1, stage 2, stage 3, . . .
t	Time
$s(k_1), s(k_1, k_2), s(k_1, k_2, k_3), \ldots$	Dispatch decisions of net supply at each stage
$x(k_0), x(k_0, k_1), x(k_0, k_1, k_2), x(k_0, k_1, k_2, k_3), \ldots$	Total dispatched net supply after each stage

in generation or load in a cluster, must be smoothed out to maintain instantaneous net power balance. An electric spring (ES) for the periphery cluster, where there are no speed-governors and exciters in synchronous generators that are used in the transmission grid for smoothing out fluctuations, is invented [40,41]. ES is a power electronic device that uses load, which is prevalent in periphery clusters, to do the job. Some of the loads, such as water heaters, air conditioners, and non-essential lightings, are considered to be non-critical in the sense that they can withstand temporary reduction or increase of power with no noticeable adverse effect. The ES is connected in series with, or embedded in, non-critical loads and the combination is connected in parallel with the rest of the loads (critical loads), as shown in Fig. 10. The ES dumps temporary power imbalance to non-critical loads, i.e., when there is an over/under supply of power, the ES lets the non-critical loads consume more/less power in order to absorb the imbalance in the cluster. An ES-embedded smart load may be considered as an advanced demand response system.

To illustrate the various functions performed by different layers of the clusters, the same example in Fig. 5 (or Fig. 7) is used again in Fig. 11, where it is assumed that a re-dispatch of the generation/load in the cluster is necessary by the distribution substation cluster D.

The responsibility of maintaining power balance in a GRIP is shared among all clusters; that means that each cluster must maintain its net power balance, with all the responsibilities of scheduling, dispatching, balancing, and security. Each cluster must operate as an autonomous unit, sticking precisely to its announced schedules, even in the event of a disturbance such as generation failure in the cluster. Each cluster must be able to prevent unscheduled power flows and acquire necessary reserve from within or from the cluster one tier above. The reserve from the cluster above will be able to maintain that cluster's net power balance and prevent the effect of the disturbance from traveling further. The interconnected grid at the top of the tiers no longer serves as the last resort to supply or absorb imbalances, as is the practice today. There are no "free rides" for micro-grids or prosumers connected to the grid only for reliability assurance.

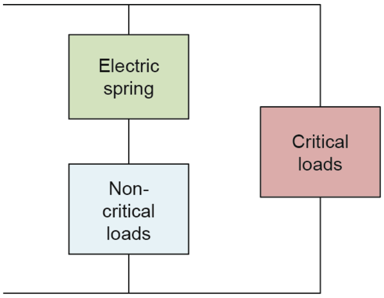

Fig. 10. An ES-embedded smart load.

In a layered architecture, the lower layer carries out tasks instructed by the upper layer, and the interface must be well defined. The market layer expects the scheduling layer to implement any transaction that is deemed acceptable by the scheduling layer. What constitutes an acceptable transaction must be well defined. The scheduling layer knows precisely the level of capability the balancing layer has in smoothing out fluctuations. There are no back-and-forth negotiations between the layers.

6. Conclusions

The fundamental requirement of grid operation is to maintain instantaneous power balance on the grid. The current operating paradigm is based on the assumption that a centralized grid operator is necessary to maintain power balance. In the coming new era, prosumers will have full controllability and digital intelligence to better manage their own resources and smart devices, and will no longer need to cede the authority to a grid operator. A new distributed operating paradigm can be realized by distributing the responsibility of power balance to sub-grids of the grid on the periphery to maintain individually their net power balance. A grid as smart as the internet based on this new paradigm—the GRIP—is presented.

A GRIP has the following features and is suitable for serving the grid of the future:

- **Better utilization of VRE.** The distributed operating paradigm will lead to maximal utilization of VRE resources because the operation of VRE will rest on the hands of local stakeholders who have better knowledge to forecast, schedule, and control the resources.
- **Empowering prosumers.** Prosumers will have complete control over the operation of their own generation and load, and will have the incentive to install and operate the most efficient and effective facilities, such as solar PV, battery storage systems, EV charging systems, and ICT hardware and software.
- **Responsibility sharing with the periphery.** In the new digital era, the periphery has a similar level of intelligence and capability as the grid operator in managing its own sub-grid, as hardware gets cheaper and software gets smarter.

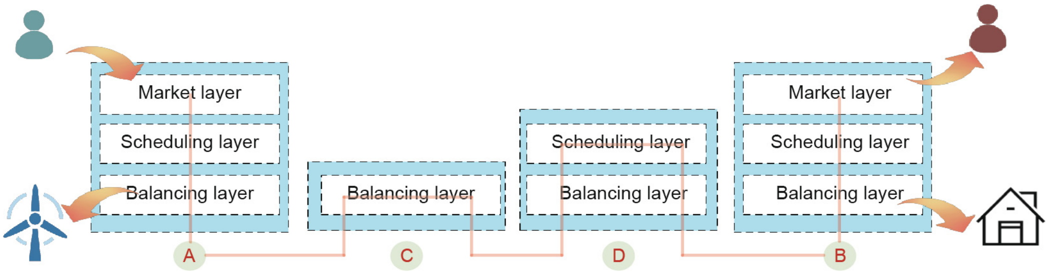

Fig. 11. Power delivery from A to B in the layered architecture of clusters.

- **Seamless integration of nano-, mini-, and micro-grids.** The responsibility-sharing feature of the new paradigm is compatible with the autonomous or semi-autonomous philosophy of today's nano-, mini-, and micro-grids, and assists their seamless integration. Moreover, the allowance of semi-autonomous operation of clusters will prevent the total grid defection of prosumers.
- **Fast adaptation of technology innovations.** The layered architecture of GRIP makes it easy to incorporate innovative new technologies.

GRIP can evolve from the existing grid at any pace once the new operating paradigm is adopted. A transmission grid with its own EMS can be the first cluster of the interconnection. More clusters of distribution companies, each covering a sub-grid of a distribution substation, can be added. Clusters of smart homes, smart buildings, smart communities, micro-grids, and so forth can also be added. Other clusters can be flexibly formed and added, since a cluster may be part of an existing cluster and may contain any number of pre-existing clusters. The GRIP requires no scrapping of successful EMS or effective traditions in the operation of the transmission grid and focuses on adding more intelligence and responsibility to currently mostly passive distribution systems and beyond. It can be built on the success of existing grid operations and strengthens the periphery of the grid to embrace innovative new technologies.

The *energy internet* is a recent trend toward integrating and managing multiple energy systems, including electricity, thermal, gas, and transport, by identifying and coordinating synergies among them in order to achieve optimal solutions for each individual sector, as well as for the overall system [42]. Using excess heat from electricity production and industry for district heating has been around for decades. Three-way conversion among electricity, thermal, and gas, as well as two-way conversion between electricity and EV batteries, adds more flexibility in energy management. Different forms of energy all have the same underlying physical law—namely, the conservation of energy. We believe that the same idea of decomposing the system into a hierarchy of clusters, each maintaining its own net energy balance, will lead to *an energy internet as smart as the internet.*

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Compliance with ethics guidelines

Yanli Liu, Yixin Yu, Ning Gao, and Felix Wu declare that they have no conflict of interest or financial conflicts to disclose.

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